CLIMATOGRAPHY MODEL FOR SUSTAINABLE URBAN BUILT ENVIRONMENT

Ph. D. THESIS

by

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INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE – 247667 (INDIA)
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Submitted in partial fulfilment of the requirements for the award of the degree

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CANDIDATE'S DECLARATION

I hereby certify that the work which is being presented in the thesis entitled **"CLIMATOGRAPHY MODEL FOR SUSTAINABLE URBAN BUILT ENVIRONMENT"** in partial fulfillment of the requirements for award of the Degree of Doctor of Philosophy and submitted in the Department of Architecture and Planning of the Indian Institute of Technology Roorkee, Roorkee is an authentic record of my own work carried out during the period from July, 2012 to July, 2017 under the supervision of Dr. Mahua Mukherjee, Associate Professor, Department of Architecture and Planning, Indian Institute of Technology Roorkee, Roorkee.

The matter presented in the thesis has not been submitted by me for the award of any other degree of this or any other Institute.

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This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

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Date: 15/12/17

ABSTRACT

Climatological information is crucial to the development of any Model for Sustainable Urban Built Environment. Traditionally the diverse geo-climatic environments prevailing in India have given rise to diverse vernacular architectural traditions, all of which are resource conserving, climatically appropriate and sustainable. In recent times though the traditional building typology as a whole has lost in popularity to the modern mass producible construction materials and fast and efficient techniques. In the effort towards economizing the building stock, the attention hitherto received by the climate responsiveness of the design solution has waned.

The role played by climate responsive attitude towards sustainable development in the building design and construction activity has been accepted widely even at international forums. Collaborative efforts between users, builders, governments, NGOs, teachers and design professionals are need; for successful implementation of strategies emerging from scientific knowledge, traditional wisdom, innovative high and low-tech building solutions; in order to reduce the rate of energy consumption and pressure on the environment. Conversely even if the buildings are designed with utmost respect to climatic consideration, they do participate in modulation of local climate to a certain extent.

Lack of climatic information pertaining to the growing number and size of urban settlements, in readily usable form acts as impedance in the generation of the scientific knowledge required for identifying strategies appropriate in those respective settlements. It is impractical for the state legislative to prescribe a separate climatic analysis for every settlement in view of the complexity entering the process due to the absence of contextual climatic data. The climatic classification map hitherto referred for prescribing design strategies is based on obsolete size of data, and as such fails to represent the diverse geo-climatic environment prevailing in India.

In the aforementioned context this research inquiry tries to answer the following questions:

- How do ambient climatic conditions provide a basis for selecting passive design strategies for achieving thermal comfort in urban built environment?
- How do thermal comfort requirements vary with geographical regions of India?

- Do existing building legislation, regulations, codes and standards support the successive modulation of ambient climatic conditions?

The proposed Climatography Model is aimed at enabling modulation of ambient climatic conditions; through incorporation of appropriate passive design strategies in building regulations for achieving a sustainable urban built environment. The objectives identified for fulfillment of this aim are as follows:

1. **To Formulate** a framework for collation of climate information useful in thermal comfort analyses, at scales of regional geography and urban built environment.
2. **To Delineate** regions within India based on prevalent thermal stresses, requiring specific combinations of responsive passive design strategies, **(a)** for standardizing mandatory compliance criteria and **(b)** for identifying appropriate urban built form.
3. **To Recommend** revisions in building byelaws, town planning and state energy conservation regulations for,
    - **(a)** including identified strategies as mandatory compliance criteria and
    - promoting built form design interventions in the context of study area
    - **(b)** standardizing building performance evaluation criteria

Having introduced the research context the First Chapter then proceeds with a discussion on Research Approach and concludes by describing the scope, limitations and thesis outline. The research approach is briefly discussed using a diagram of nested frames ranging in detail from School of Thought at the broadest scale to Strategies at the intermediate scale and then moving to Tactics at the narrowest scale. The details at the scale of School of Thought include the three domains supporting the aim of enabling a sustainable urban built environment; namely Climatology, Responsive Building Design and Building Legislation. The details at the scale of Strategies include trifurcation of the tree domains as follows. Strategies in the domain of Climatology are detailed out as analyses at 'Regional Level', 'Local Level' and 'Typical Level'. In correspondence to these strategies, the domain of Responsive Building Design is detailed out into 'Combinations of Responsive Strategies', 'Appropriate Urban Built Form' and 'Base Case for Building Performance Simulation' respectively. Whereas in the domain of Building Legislation, 'National Building Code', 'Building Byelaws' and 'Energy Conservation Building Code' have been identified as the documents which will be informed by the aforementioned strategies in the domain of Climatology and Responsive Building Design.

Chapter Two is an exposition of detailed concepts in the domains of Climatology, Responsive Building Design and Building Legislation. Concepts dealt at length in the domain of Climatology include, Climatography as a branch to Climatology; Scales of Climate Study, and Climate Data. While exploring the various scales of climate study, one gets introduced to, the basis of Koppen climate classification, the notion of geographical regions, and the concepts of Urban Climate and Local Climate Zones. A review of various concepts related to Climatic Data starts with secondary aspects such as meteorological parameters, collected vide the automatic weather station and urban climate networks, and leads to the computation of climatic normals. These aspects are a precursor to the primary aspect of diagraming and mapping, as part of which one is introduced to composite climate charts (used for representing temporal variation in multiple parameters together), geographical climate maps (used for representing composite charts of multiple cities together), and finally the development of agro-climatic zones. After the study of Agro-climatic zones one understands the use of derived parameters (based on interpolated data) in identifying spatial zones having geo-climatic conditions favorable for achieving high yield of various crops.

Concepts dealt at length in the domain of Responsive Building Design include, the frameworks for understanding the linkages between various elements involved in as well as impeding or enabling the application of climatology to various scales of built environment ranging from the region, to the settlement, and down to building element. Other concepts dealt here, include the various diagrams (called bioclimatic charts) used for identify thermal stresses experienced at a place though out the year, that help in the selection of appropriate design strategies. The finer aspects related to Climatic Suitability of Built Environment also include Psycho-Physiological model of thermo regulation related to the idea of thermal preference as well as the cyclic method in which the architectural design strategies are implemented for modulating the ambient climatic conditions.

Concepts dealt at length in the domain of Building Legislation include, the phenomenon of Urbanization, Constitutional provisions enabling urban local bodies for regulating construction activity (with the help of building codes and standards) as well as general environmental conditions (with the help of environment impact assessment of development projects), Urban and regional plan formulation and implementation guidelines. The finer aspects related to the concept of Energy Conservation Building Code, include the various compliance criteria as well as the typical weather file required in the whole building performance method of compliance. Here, the scant number of typical weather files available for India is identified as a concern. The Green rating systems discussed here are closely related to various sustainable concepts including energy conservation. Last but not the least the review deals with the standardized development control regulations at national and state level that can be targeted as vehicles for implementing responsive design strategies.

Chapter Three is a compilation and comparison of alternative case studies used for selecting components in the research framework. The climatic classification criteria available across the world are distinguished into forward analysis and backward analysis on the basis of the stage in the design process where it is to be implemented. Finer aspects in the concept of Climatic Data Modeling include, Spatial Interpolation, Physical basis of variation in Urban Climate, and Temporal Interpolation. The finer aspects in the concept of Climate Modulation Strategies include the Design Matrix of all possible strategies, Mahoney Tables criteria of prioritizing between conflicting requirements and detail exploration of specifications related to the built form, building envelope and opening design. Lastly the finer aspects related to the concept of GIS are described, including physical and human geography, continuous and discrete data, interdisciplinary subsystems.

The literature review conducted in Chapter Two and Three lays the platform for fulfillment of the First Objective achieved in Chapter Four through the formulation of analytical framework. The analytical framework consists of three inter connected analytical workflows. Second objective of this research is completed after implementing two workflows, namely Regional Climate level analysis and Local Climate level analysis.

In the Regional Climate level analysis published interpolated (temperature extremes) and modeled (relative humidity) climate data is used to perform cartographic modeling in GIS application on the basis of Mahoney Table criteria and compile thermal stress maps. In the next step the stress maps are subjected to positional notational codes to generate strategy maps. Finally the eight strategy maps are superimposed to delineate Thermal Comfort Design (TCD) Zones.

In the Local Climate level analysis on the one hand Local Climate zones (LCZ) are to be delineated in selected city by performing supervised classification on remote sensing images as per WUDAPT procedure, while on the other hand diurnal micro-meteorological measurements are to be collected from various LCZ. In the next step LCZ map and diurnal measurements are to be correlated using Energy Flux model to obtain Modeled Local Climate Data. A second iteration of regional climate level analysis is to be performed using this Local Climate data to identify Appropriate Urban Built Form.

In the Typical Climate level analysis climatic normals or collated gridded data are used as input in an automated spreadsheet based on a published algorithm to generate local typical weather file based on the paper translated from Portuguese attached as APPENDIX 3. The base case used in building performance evaluation is to be designed as per the applicable TCD Zone. Whole building simulation completed using base case designed as per TCD Zone and Local typical weather file completes part (b) of Third Objective.

The TCD Zones are assessed and discussed at length in Chapter Five. Google Earth app enables the straight forward identification of the unique combination of responsive design specifications at any location across India with the help of a pop-up that appears when one searches and clicks besides that location. All major cities (population more than 1 million) are located within 31 out of 62 TCD Zones delineated across India. Only 16 of these TCD Zones encompass 5 or more major cities. Flyers for these 16 TCD Zones containing spatial extents, duration of climatic indicators and recommended design specifications are attached as APPENDIX 1.

Spatial analysis using uniform Hexagonal grid and Thiessen Polygons around existing Typical weather file stations is useful for identifying neighborhoods with high TCD Zone variability. Generation of additional local typical weather file is recommended for cities located in these neighborhoods. Detailed spatial analysis has been done for the extents of Maharashtra State to enable regionalization of Development and Control Regulations. Out of the 12 TCD Zones found across Maharashtra, 5 TCD Zones are restricted to the Konkan region, which signifies the role of TCD Zone in identifying regional thermal comfort requirements. List of 254 ULBs of Maharashtra along with their assigned TCD Zone has been included in APPENDIX 2 along with the matrix of design strategies applicable in each zone. The matrix is useful for identifying the variation in DC&P Rules with respect to individual TCD Zone. Recommendations have been made in the Sixth Chapter for including the identified strategies as part of Building Byelaws and National Building Code, which completes part (a) of the Third Objective. Future Scope for extension of this research has been enumerated in the Conclusion Chapter.

Thus all objectives identified for achieving the aim of this research have been fulfilled.

ACKNOWLEDGEMENT

This research process was a fulfilling endeavor with a very high learning curve. It opened my mind to such an extent that now I feel like a sponge. It has made me inquisitive like a young child, but empowered with an ability to analyze huge amounts of data notionally. It has taught me to believe in intuition. This is hardly a place to put on record all the nitty - kitties that made this process wonderful; none the less I shall make an attempt to at least mention the names of people closely associated with it being so.

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I wish to thank other members of my family, Tatya, Anuja, Aniket, Gauri, Asawari, Kaka-Kaki, Abaji-Kaki, Appaji-Kaki, Sumitra, Vedant, Aadya, Nandan-Ashwini, Ivan, Tai-Bapu, Jiji-Mama, Mai, Supriya, Satyajeet; who have borne the side effects of my single-mindedness during the course of this research.

GLOSSARY OF TERMS

Fenestration: in architectural domain means the arrangement of windows in a building[i]. However for the purpose of legislating about the performance characteristics of fenestration namely, U-factor, SHGC, and VLT - Visible Light Transmittance, one needs to follow the Energy Conservation Building Code of India wherein; it is defined as all areas (including the frames) in the building envelope that let in light, including windows, plastic panels, clerestories, skylights, glass doors that are more than one-half glass, and glass block walls[ii].

(a) Skylight: a fenestration surface having a slope of less than 60 degrees from the horizontal plane. Other fenestration, even if mounted on the roof of a building, is considered vertical fenestration.

(b) Vertical fenestration: all fenestration other than skylights. Trombe wall assemblies, where glazing is installed within 300 mm of a mass wall, are considered walls, not fenestration.

India's Unique Numbering System [iii]

Term	Indian Writing Figure	No. of Zeros	Western Writing Figure	In Words
Lakh	1,00,000	5	100,000	Hundred thousand
Crore	1,00,00,000	7	10,000,000	10 million
Arab	1,00,00,00,000	9	1,000,000,000	1 billion
Kharab	1,00,00,00,00,000	11	100,000,000,000	100 billion

R-value (thermal resistance) [ii, v]*:* the reciprocal of the time rate of heat flow through a unit area induced by a unit temperature difference between two defined surfaces of material or construction under steady state conditions. Units of R-value are $m^2 \cdot °C/W$ ($h \cdot ft^2 \cdot °F/Btu$). For the prescriptive building envelope option, R-value is for the insulation alone and does not include building materials or air films.

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[i] https://en.oxforddictionaries.com/definition/fenestration

[ii] https://beeindia.gov.in/sites/default/files/ECBC%202016_Draft_V8.pdf

[iii] Kanuk, A.R., 2007, India's Unique Numbering System. In Capital Markets of India: An Investor's Guide.

SHGC [ii]: the ratio of the solar heat gain entering the space through the fenestration area to the incident solar radiation. Solar heat gain includes directly transmitted solar heat and absorbed solar radiation, which is then reradiated, conducted, or convected into the space.

Skylight roof ratio (SRR)[ii]*:* the ratio of the total skylight area of the roof, measured to the outside of the frame, to the gross exterior roof.

Thiessen Polygons: or Voronoi polygons define individual areas of influence around each of a set of points. Thiessen polygons are polygons whose boundaries define the area that is closest to each point relative to all other points. Mathematically they are defined by the perpendicular bisectors of the lines between all points.[iv]

U-factor (Thermal Transmittance) [v]*:* heat transmission in unit time through unit area of a material or construction and the boundary air films, induced by unit temperature difference between the environments on each side. Unit of U value is W/m^2·°C (Btu/h·ft^2·°F).

VLT (Visible Light Transmittance) [v]: also known as Visible Transmittance, is an optical property of a light transmitting material (e.g. window glazing, translucent sheet, etc.) that indicates the amount of visible light transmitted of the total incident light.

[iv] http://www.ian-ko.com/ET_GeoWizards/UserGuide/thiessenPolygons.htm

[v] Kumar, S. et al., 2009, Energy Conservation Building Code (ECBC) User Guide USAID ECO-III Project, ed., Bureau of Energy Efficiency

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ABBREVIATIONS AND ACRONYMS

Term / Symbol	Meaning intended in this report
%	"Percent" unit for measuring relative humidity
°C	"Celsius" Unit for measuring temperature
arc s	Smallest unit in "Degree-Minute-Second" division of earth's surface
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BEE	Bureau of Energy Efficiency
BIS	Bureau of Indian Standards
DC&PR	Development Control and Promotion Regulations
deg C	"degree Celsius" Unit for writing temperature range
$\Delta T_{x\text{-}y}$	Acronym used to annotate temperature difference between location x and y
ECBC	Energy Conservation Building Code
ENVI-met	3D CFD (i.e. three dimensional computational fluid dynamics) Software package system capable of performing high-resolution microclimate modeling and simulation.
GCN	Global Climate Network
GIS	Geographical Information System
IMD	Indian Meteorological Department
IIRS	Indian Institute of Remote Sensing Dehradun
IITR	Indian Institute of Technology Roorkee
K	"Kelvin" Unit for measuring temperature
LCZ	Local Climate Zones
LULC	Land use Land cover
MBBL	Model Building Bye Laws

Term / Symbol	Meaning intended in this report
mm	"millimeter" unit for measuring rainfall
$m^2 \cdot °C/W$ ($h \cdot ft^2 \cdot °F/Btu$)	Unit for measuring R-value (see Glossary of Terms)
NBC	National Building Code of India
NDC	National Data Center
NRSC	National Remote Sensing Center
SDCR	Standardized Development Control Regulations
TCDZ	Thermal Comfort Design Zones
TCPO	Town and Country Planning Organisation
ULB	Urban Local Body
UOPS	Online User Order Processing System - of NRSC
URDPFI	Urban and Regional Development Plan Formulation & Implementation Guidelines
$W/m^2 \cdot °C$ ($Btu/h \cdot ft^2 \cdot °F$)	Unit for measuring U value (see Glossary of Terms)

CHAPTER 1. INTRODUCTION

1.1. Preamble

For centuries indigenous (vernacular) buildings provided thermally comfortable built environments in different climatic zones in India and world over [57] [7] [74] [30]. These buildings were constructed using locally available materials and methods (local building technology) developed by trial and error over centuries in response to prevalent geo-climatic conditions. In recent decades various phenomenon like population growth and outsourcing of industrial processes by developed nations lead to a trend of influx of large populations to various old and new towns in the developing countries. The increased housing demand led to scarcity of and inflation in prices of resources like land and traditional building materials. Alternative building materials costing less and consuming lesser space gained popularity and are often outsourced from other places.

1.1.1. Earth's Finite Resources

The finiteness of earth's resources came to fore during the oil crises of 1970's. Consequently the use of fossil fuels in general for energy generation caused unprecedented environmental pollution and efforts to avert climate change were initiated. It gave an impetus to the research for assimilating the ancient knowledge about climate modulation without the use of energy driven appliances [6,110]. The ensuing debate was between reverting to improvised older construction technology and limiting the use of climatically unsuitable elements while continuing with active climate modulation [71].

1.1.2. Millennium & Sustainable Development goals

Millennium Development Goals 2000 as well as the Sustainable Development Goals adopted at the international forum acknowledge the need for a paradigm shift to climate responsive architectural design [146,147]. In order to achieve these goals, a thorough understanding of climatology needs to be developed for its appropriate application in the practice of architectural design.

1.1.3. Climate Responsive Architecture Pledge

Architects from across the world participating at an international workshop on "Sustainability through passive and low energy: climate responsive architecture" pledged commitment to the challenges of creating better performing buildings and sustainable future[71]. They acknowledged the importance of controlling the energy consumption and demands on environment through collaborative efforts between users, builders, governments, NGOs, teachers and design professionals. They held that buildings designed without using strategies emerging from scientific knowledge, traditional wisdom, innovative high and low-tech building solutions unnecessarily exert pressure on the environment.

1.2. Research Context

Legislative measures esp. the Energy Conservation Building Code [23] are in place to reduce the reliance on fossil fuels for construction and operation of buildings. In case the mandatory and tradeoff compliance criteria are not met whole building simulation approach is available, which regulates per unit area energy consumption in proposed design to be less than standard design (ECBC, clause 10.1.2). However the pattern of energy consumption changes with geo-climatic conditions within existing climate zones. Legislative measures are yet to be developed for implementation of climate responsive design strategies.

1.2.1. Sustainability is contextual

For a sustainable future, design decisions and construction practices about the built environment must go well beyond technical correctness, by their aesthetic inquiry as well as by their community responsibility[31]. Jeffrey Cook [31] emphasizes that in order to implement “design with climate” one needs to utilize a “design with place” matrix of performance expectations that matches international expertise with local resources. He also quipped; Climate zones to describe appropriate building design should be different from those invented for agriculture or aeronautics [30].

1.2.2. Successive climate modulation

Elaborate frameworks for the use of climate information in successive climate modulation by means of planning of regions, settlement and design of buildings [16] have existed since a few decades, but its practical implementation has been hindered due to certain barriers transfer of knowledge [39] from experts to other stake holders.

1.2.3. Climatic Diversity of India

India is a vast and humanly too complex a country for any facile generalization or comprehension to be meaningful, and it is difficult to grasp it and understand it in its entirety [130]. By using regionalization approach Singh et al [130] demonstrated that the dictum – the whole can be understood through its parts – holds good for India. Diverse regional climates are experienced across India – mainly due to the uneven spatial and seasonal distribution of solar radiation, moisture and precipitation over its unique terrain comprising following four macro level natural regions [130] as shown in Figure 1-1:

1. The mountain wall consisting of the Himalayan Range
2. Northern plain or the Indo-Gangetic Plain
3. Peninsular plateau consisting of Malwa, Chhota Nagpur and Deccan Plateaus and Chhattisgarh Plains
4. Coasts and islands extending from Rann of Kachch, Kathiawar Peninsula, Konkan, Malabar and Coromandel Coasts, Northern Circars, Lakshadweep and Andaman & Nicobar Islands

1.2.4. Inter-relation between Climatic Diversity and Ethnicity

Diverse regional climates are responsible for increased human ethnic diversity [27]. India's National Anthem [135] is an epitome acknowledgement of the plural ethnicity of its people – evident from religious, linguistic and regional or sectional diversities – which we as Indians have resolved to transcend [141]. Ethnic groups [142] of India built up their distinctive ways of living – including their dwellings (vernacular architecture) in response to the natural climatic and techno-cultural environments which are part of *climo-cultural determinant* of *thermopreferendum* [4].

Absence of sufficiently detailed climatic information needed for assessing comfort requirements across India and within urban settlements; impedes the implementation of strategies for successive modulation of climate that are at the disposal of respective urban local bodies, town planning departments and energy regulation authorities. In order to achieve a sustainable urban built environment it is important not only to implement the appropriate responsive passive design strategies, but also to assess their performance.

1.3. Research Framework

1.3.1. Research Questions

Traditionally the diverse geo-climatic environments prevailing in India have given rise to diverse vernacular architectural traditions all of which are resource conserving, climatically appropriate and sustainable. In this context it is important to know…

- How do ambient climatic conditions provide a basis for selecting passive design strategies for achieving thermal comfort in urban built environment?
- How do thermal comfort requirements vary with geographical regions of India?
- Do existing building legislation, regulations, codes and standards support the successive modulation of ambient climatic conditions?

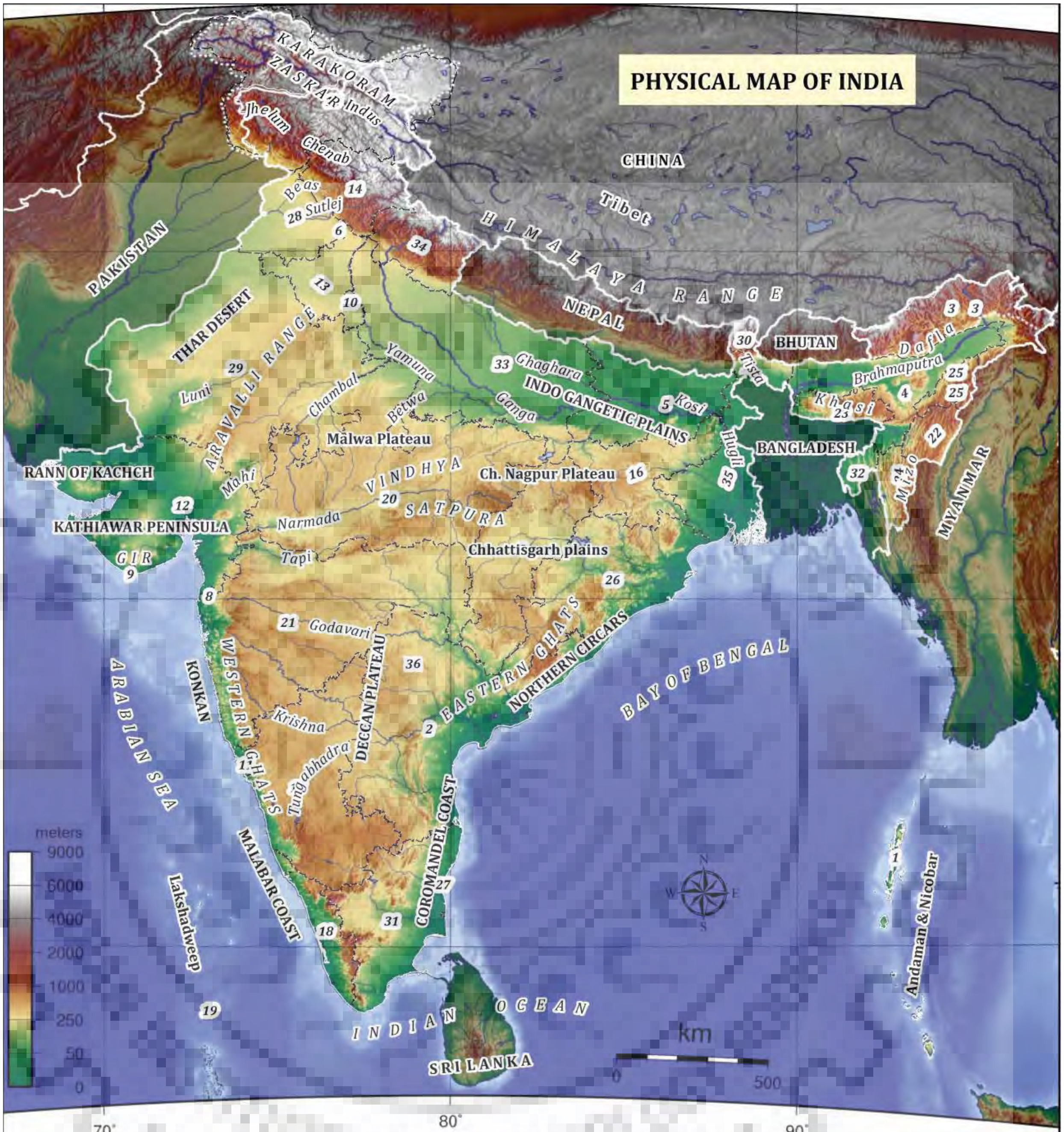
1.3.2. Aim

The proposed Climatography Model is aimed at enabling modulation of ambient climatic conditions; through incorporation of appropriate passive design strategies in building regulations for achieving a sustainable urban built environment.

1.3.3. Objectives

The following objectives were identified to enable fulfillment of the aim of this research:

1. **To Formulate** framework for collation of climate information useful in thermal comfort analyses, at scales of regional geography and urban built environment.
2. **To Delineate** regions within India based on prevalent thermal stresses, requiring specific combinations of responsive passive design strategies, **(a)** for standardizing mandatory compliance criteria and **(b)** for identifying appropriate urban built form.
3. **To Recommend** revisions in building byelaws, town planning and state energy conservation regulations for,
    - **(a)** including identified strategies as mandatory compliance criteria and
    - promoting built form design interventions in the context of study area
    - **(b)** standardizing building performance evaluation criteria



Legend numbers for States & Union Territories

1 Andaman and Nicobar	8, Dadra and Nagar Haveli	15 Jammu and Kashmir	22 Manipur	29 Rajasthan
2 Andhra Pradesh	9, Daman and Diu	16 Jharkhand	23 Meghalaya	30 Sikkim
3 Arunachal Pradesh	10, Delhi	17 Karnataka	24 Mizoram	31 Tamil Nadu
4 Assam	11, Goa	18 Kerala	25 Nagaland	32 Tripura
5 Bihar	12, Gujarat	19 Lakshadweep	26 Orissa	33 Uttar Pradesh
6 Chandigarh	13, Haryana	20 Madhya Pradesh	27 Puducherry	34 Uttarakhand
7 Chhattisgarh	14, Himachal Pradesh	21 Maharashtra	28 Punjab	35 West Bengal
				36 Telangana

Figure 1-1 Physical map of India superimposed with administrative boundaries Based on [45,153]

1.4. Research Methodology

A research methodology has been developed for sequential exploration of interlinked datasets and analytical techniques from climatology, responsive design and building legislation to achieve research objectives. Datasets and analytical methods appropriate for interlinking different levels of climate study with design sequence and existing legislative instruments are identified and put together in an analytical framework. The research approach shown in Figure 1-2 has been structured under three heads namely, system of inquiry, strategy and tactics [55] as follow:

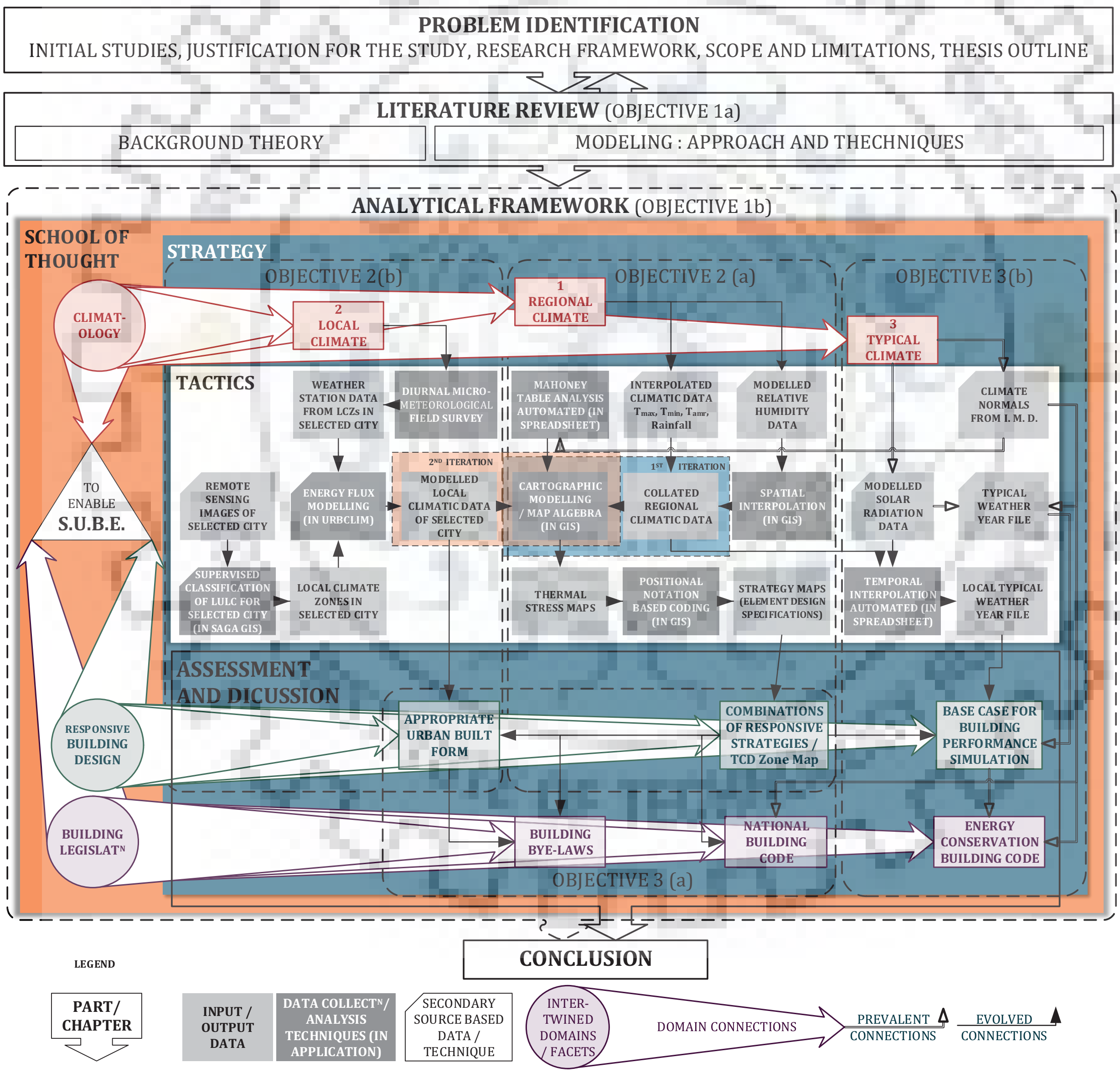


Figure 1-2 Research Approach

System of inquiry – At broader level, this research explores the synergetic interdependence between concepts of climatology, responsive design and building legislation for enabling sustainable urban built environment.

Strategy – The strategy adopted for this research is to evolve an iterative workflow of thermal comfort analyses at three levels (in order of development) regional climate, local climate and typical climate.

Tactics – The strategy of iterative analyses necessitates selection of appropriate datasets to cater a range of considerations from general to more specific. To begin it is essential to establish the climatic diversity of a country like India from thermal comfort perspective.

a. Initially various climatic datasets applicable to cross country thermal comfort analysis are collated and analyzed to identify all possible combinations of prescribed responsive building design specifications.

b. In the next iteration possibility of establishing variations – within this climate classification based on thermal comfort design prescription – due to existence of Local Climate Zones is explored. Workflow for synthesizing local climate data for a given city is developed. Energy flux modeling (based on supervised land use / cover classification using temporal satellite images) and micrometeorological field survey has been identified for use in this workflow.

c. The climate classification at two levels is used not only for stipulating prescriptions, for settlement (built form) and responsive building design but also for base cases used in whole building performance simulation. Workflow for synthesizing local typical weather year files for a given location is developed. In this workflow hitherto collated climatic datasets and modeled solar radiation data is substituted in an algorithm established for (temporal interpolation) estimation of hourly climate variables.

This analytical framework has been further elaborated in Chapter 4.

1.5. Scope and Limitations

This research is an inquiry into the causal loop of climate – adaptive comfort – responsive design – built form – (micro) climate, shown in Figure 1-3. Scope encompasses the overlap between the domains of Climatology, Responsive Design and Building Legislation (Regulations Codes and Standards), as shown in Figure 1-4.

Though various sub divisions of the domain of Climatology are found in literature [159], it has been trifurcated into levels namely, Regional, Local and Typical as shown in research approach (Figure 1-2) for establishing their linkages with various levels identified the other two domains. In the case of Regional Climate Level an in-depth review of interdisciplinary concepts has been done. Responsive Design theory has been extended to utilize interpolated climatic data and an application of the theory has been developed in GIS. While on the other hand, in the case of remaining two levels of study in Climatology exploratory review of the state of the art has been done.

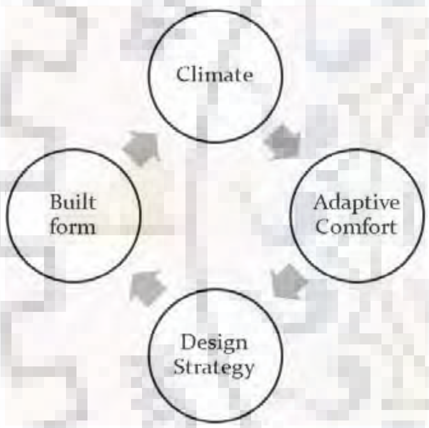


Figure 1-3: Causal Loop

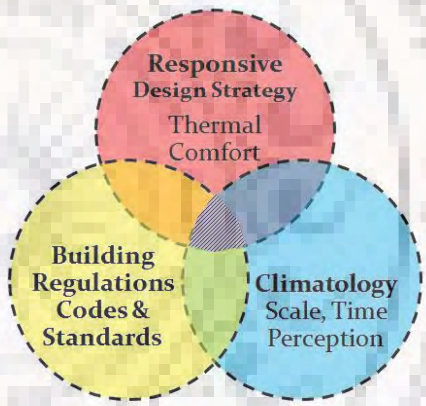


Figure 1-4: Diagram of Scope

Adaptive thermal comfort limits established in Mahoney tables for assessing monthly day time and nighttime thermal stress are dependent on factors like annual mean temperature, monthly humidity group; and as such broader in range unlike those used for energy performance assessment which are found in literature to be constantly under review [17]. Rather than establishing the suitability of various permutations and combinations of detailed element design, based on duration of stress conditions available in literature [33], the recommendation of various building design specifications has been limited to distinguished broad strategies [68,71] in order to identify the variety of combinations applicable across India.

Though a variety of building regulations codes and standards developed by organizations like Bureau of Indian Standards (BIS), Bureau of Energy Efficiency (BEE) and State

Directorate of Municipal Administration (SDMA) are in force at the national, state and urban local body levels; the scope of this research has been limited to climate responsive aspects of following Building Legislations:

1. National Building Code of India 2005 [24].
2. Energy Conservation Building Code 2007 [23].
3. Standardized Development Control and Promotion Regulation for various types of ULBs in Maharashtra 2013[150,151].

1.6. Thesis Outline

This thesis report is organized in six chapters, beginning with '**Introduction**' providing statement of research context, aim and objectives of this research and methodology follows. In the **Second chapter** titled 'Background Theory'; linkages between climatography, historical and contemporary sustainable practices for built environment and role of climatology in legislative provisions pertaining to the same have been established. The background study opens up avenues for exploring state of the art in various disciplines dealt in the next chapter.

The **Third chapter** titled 'Modeling: approach and techniques'; starts with a discussion on climate classification for building design, followed by a review of physical basis of climate variation, and explores state of the art in multi-level strategies of climate modeling. Methodologies for climatic data collection, collation and analysis pertaining to application of climatography to sustainable urban built environment have been reviewed in detail. The review lays the foundation for the development of multi level 'Analytical Framework' discussed in **Chapter Four**, wherein the advances in climatic data modeling have been extended using GIS to determine the variety of adaptive thermal comfort limits prevailing in and responsive design strategies suitable for identified regions of India in order to inform relevant building regulations, codes and standards.

The **Fifth chapter** elaborates on 'Assessment and Discussion' on efficacy of the developed analytical framework in achieving the objectives of this research. 'Conclusions' including recommendations for implementing the findings of the research through building legislations and scope for future research are discussed in **Chapter Six**.

CHAPTER 2. BACKGROUND THEORY

2.1. General

To start exposition of the background theory it is necessary to define elements of the main premise of the argument in question [19]. The central argument of this thesis is that climatography needs to be employed for regionalizing building design legislation based on forward analysis of thermal stresses and climatic indicators. In this chapter linkage between climatography, historical and contemporary sustainable practices for built environment and role of climatology in legislative provisions pertaining to the same have been established.

Bryson [22] explains that the way a segment of the world is studied not only depends on rational analysis but also on how the topic is defined relative to the expertise of the scientist and the historical precedents of the scientist's discipline. This also explains the definitions and biases that affect the study of the topic. First one must deal with various facets of *Climatology* in general and Climatography in particular from perspective of sustainable urban built form. Relevant advances and case studies from India and abroad are discussed to elucidate the research context. Later, aspects of climatology relevant to sustainable urban built environment are discussed, followed by the current legislative setup available for the implementation of the same.

2.2. Climatology

Climatology is a study of atmospheric conditions over periods of time measured in years or longer. It includes the kinds of weather that occur at a place. It is concerned not only with the most frequently occurring types, the average weather, but the infrequent and extreme events as well. Dynamic change in the atmosphere brings variation and occasional extremes that have long-term as well as short-term impacts. A recent definition states that, *climatology is the study of the processes of, and the interactions and feedbacks between, the physical and human components of the climate system at a variety of temporal and spatial scales* [143].

Until the last quarter of the twentieth century, Climatology or 'climate science' had a limited scope as a branch of meteorological science as it was dealt largely by government departments. In stark contrast to its previous role, it grew in scope due to various catalysts enumerated by Carleton [26]. These include; the revelation of an integrated climate system encompassing atmosphere, biosphere, cryosphere and hydrosphere interlinked by various feedback processes; a perceived increase in extreme weather and climate anomalies; a growing awareness of the potential and real impacts of human activities in some climate change; application of the physical and mathematical underpinnings of meteorology and atmospheric science to climate modelling; the availability of new sources of data, derived both remotely from satellites and intensively from field programs; the growing accessibility to climate-data, as well as its statistical analyses over the internet [26].

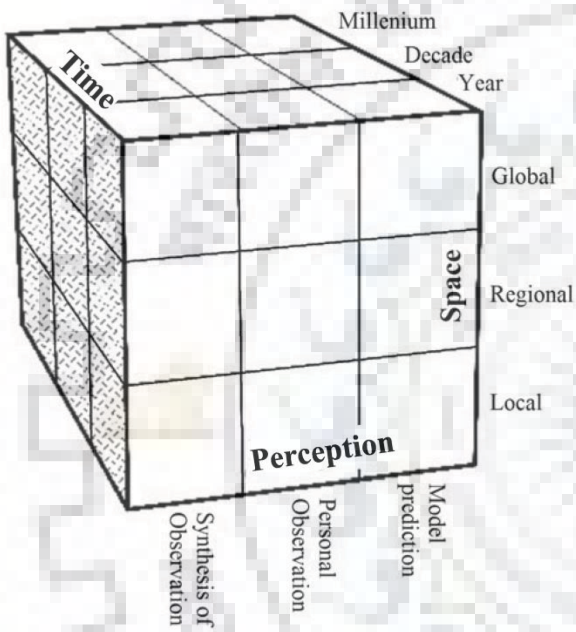


Figure 2-1 The Climate Cube
(Source: [87]**)**

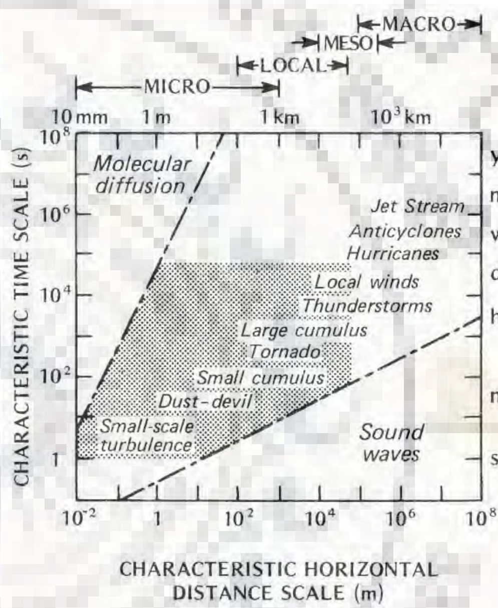


Figure 2-2 Time versus Horizontal space scales of various atmospheric phenomena
(Source: [103]**)**

2.2.1. Scales of climate study

While resolving the complexity of issues comprising climate study McGuffie and Henderson-Sellers [87] gave the analogy of a 3×3 Rubik's Cube. They (arbitrarily) divided the 3 axes representing 3 domains of climate study namely time, space and human perception, into 3 levels of detail namely fine, intermediate and coarse. As shown in Figure 2-1 they divided the domain of time into, a year, decade and millennia, while, the domain of space into, local, regional and global; whereas, the domain of human perception into, synthesis of observations, personal observations and model prediction. Oke [103] plotted various atmospheric phenomenon across a range of spatial and temporal scales as shown in Figure 2-2 where he also elaborates the role of urban built form in causing or modifying phenomenon ranging from *Small scale turbulences* to *Local winds* leading to significant variations in urban local climates as compared to rural surroundings.

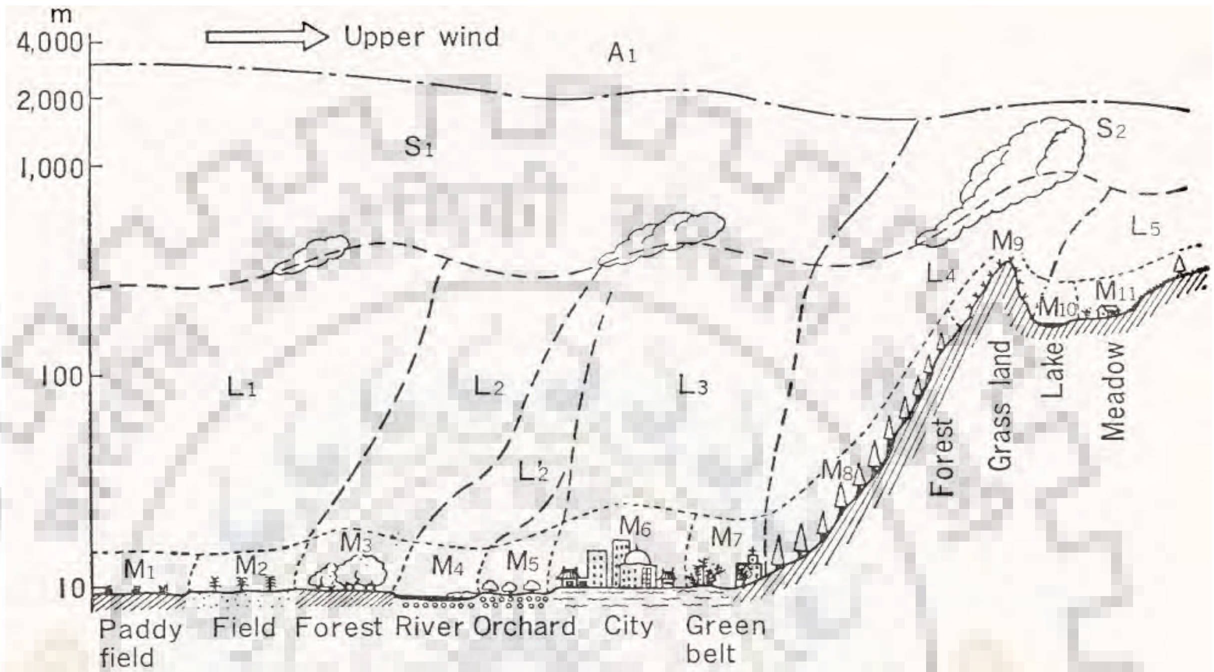


Figure 2-3 An example of micro-, local, meso-, and macroclimatic phenomena.
M_1-M_{11}: Microclimate, L_1-L_5: Local climate, S_1-S_2: Mesoclimate and A_1: Macroclimate Source:[158]

M. M. Yoshino [158] derived a general consensus regarding *nomenclature* used to define ranges of the atmospheric continuum as shown in Figure 2-3 by clarifying the confusion that existed due to its long and interdisciplinary evolution [108]. Depending upon the geographical location and extent one or more Macroclimate/s could exist across a country. Urban areas could exit in several favorable Mesoclimates developed due to proximity to geographical features such as seas, mountains, valleys, plains etc.

Multiple Local climates and Microclimates occur simultaneously in any given urban area and hence factors causing these variations also need to be studied for climate responsive design strategy adoption. Facets of various *scales of climate study* relevant to urban built form are described in the following.

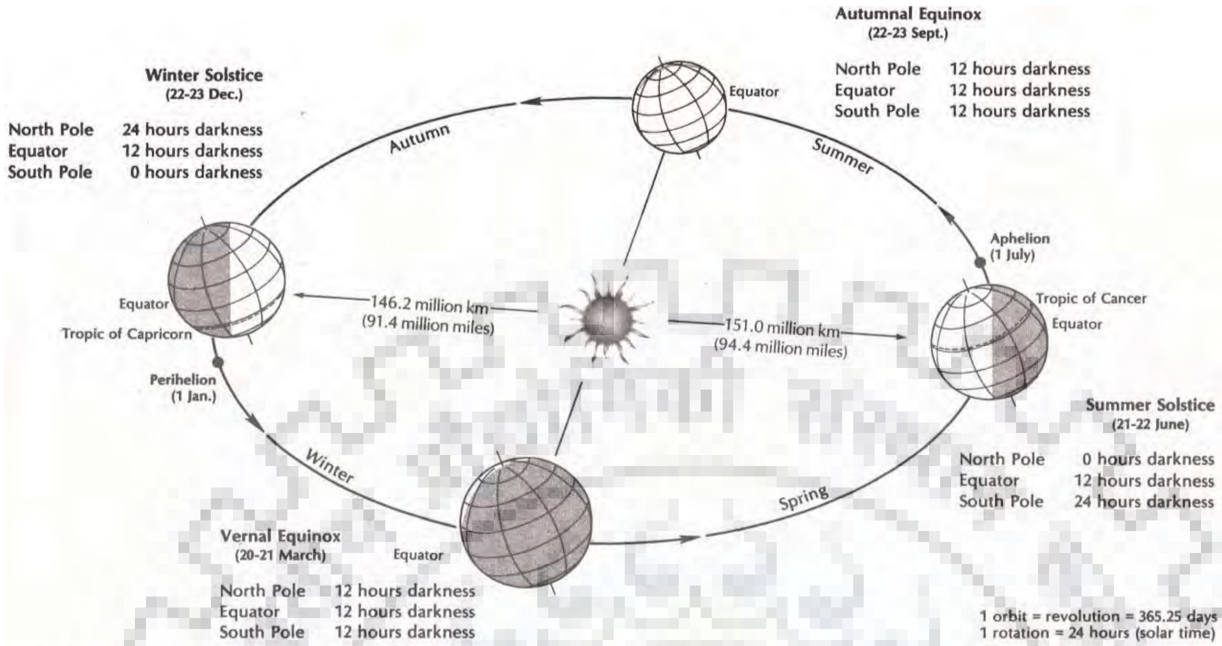


Figure 2-4 The astronomical seasons Source:[108]

2.2.1.1. Macro-scale

Macro-scale the broadest scale of study and, is used to provide an overview of the entire climate of the world [108]. Factors studied to understand phenomena at this level include planetary energy and water balance, global wind and ocean circulation patterns, nature and hazard of extreme events, etc.

There is a diurnal and seasonal pattern to the amount of solar radiation received across the earth due to its inclined axis shown in Figure 2-4, which causes seasonal variations in climate [108]. The earth's hemisphere where radiation is incident heats up and in turn the atmosphere in contact with the surface gets heated up; the differential energy flux in the atmosphere and surface drag due to rotational motion of the earth causes global wind patterns that are seasonal in nature as shown in Figure 2-5.

Seventy per cent of the earth's surface is covered with water, and solar heat gain results in evaporation and formation of clouds; when global or local winds travel inland they carry these clouds with them. The uplift of air with clouds causes adiabatic heat loss resulting in precipitation, completing the atmospheric leg of hydrological cycle as shown in Figure 2-6.

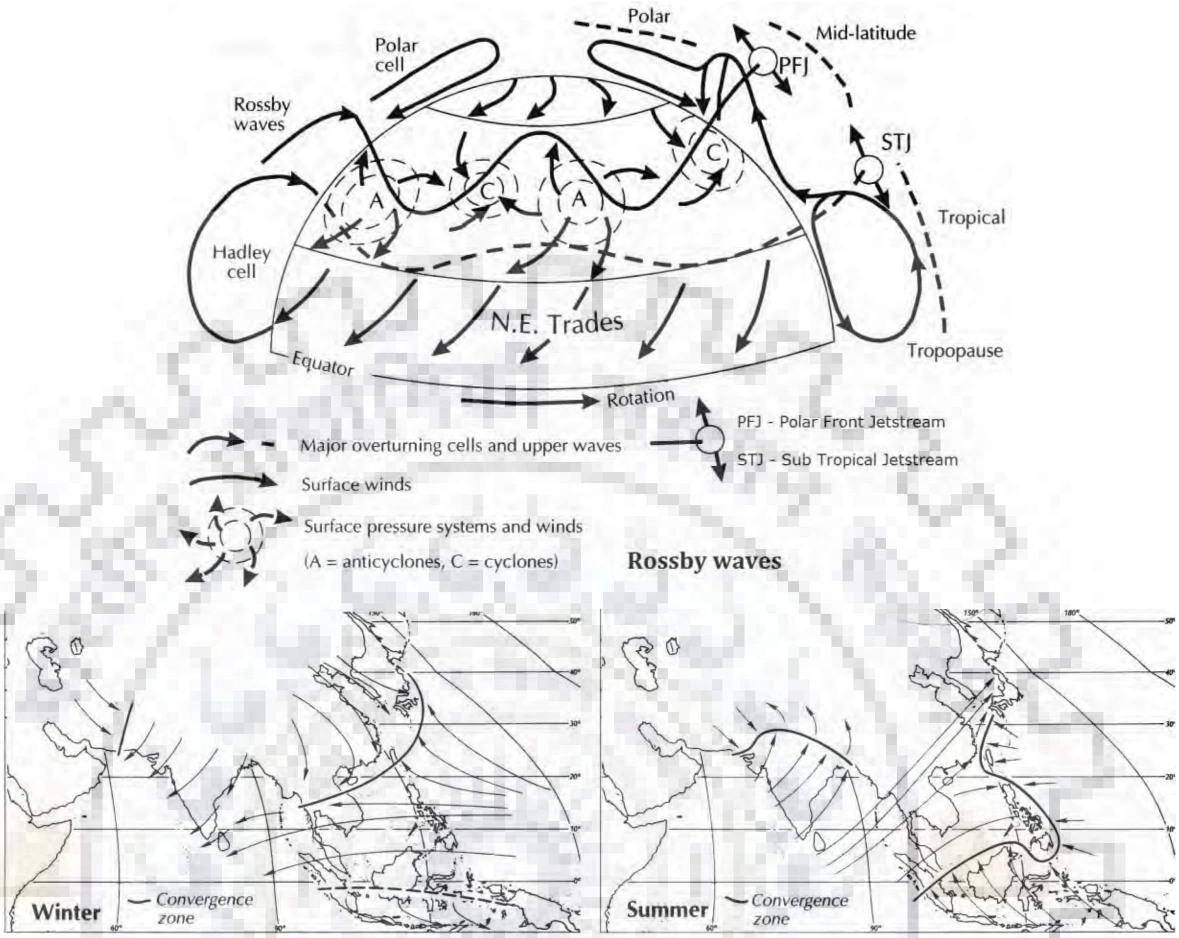


Figure 2-5 Patterns of global wind circulation and seasonal reversal Source:[108]

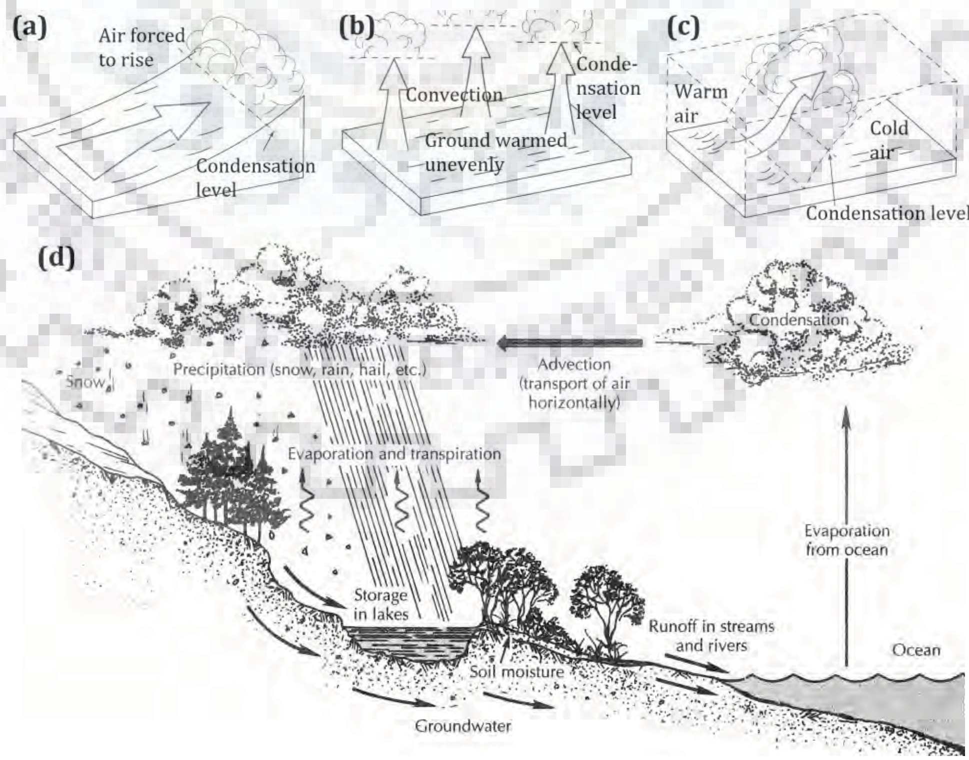


Figure 2-6 Cloud uplift (a) orographic, (b) convective, or (c) cyclonic and (d) hydrological cycle Source: [108]

2.2.1.2. Mesoscale

At the intermediate level, Meso scale climates are frequently identified with a distinctive geographic region. In such a region, the physical controls of climate are similar and not modified by major differences within the region [108].

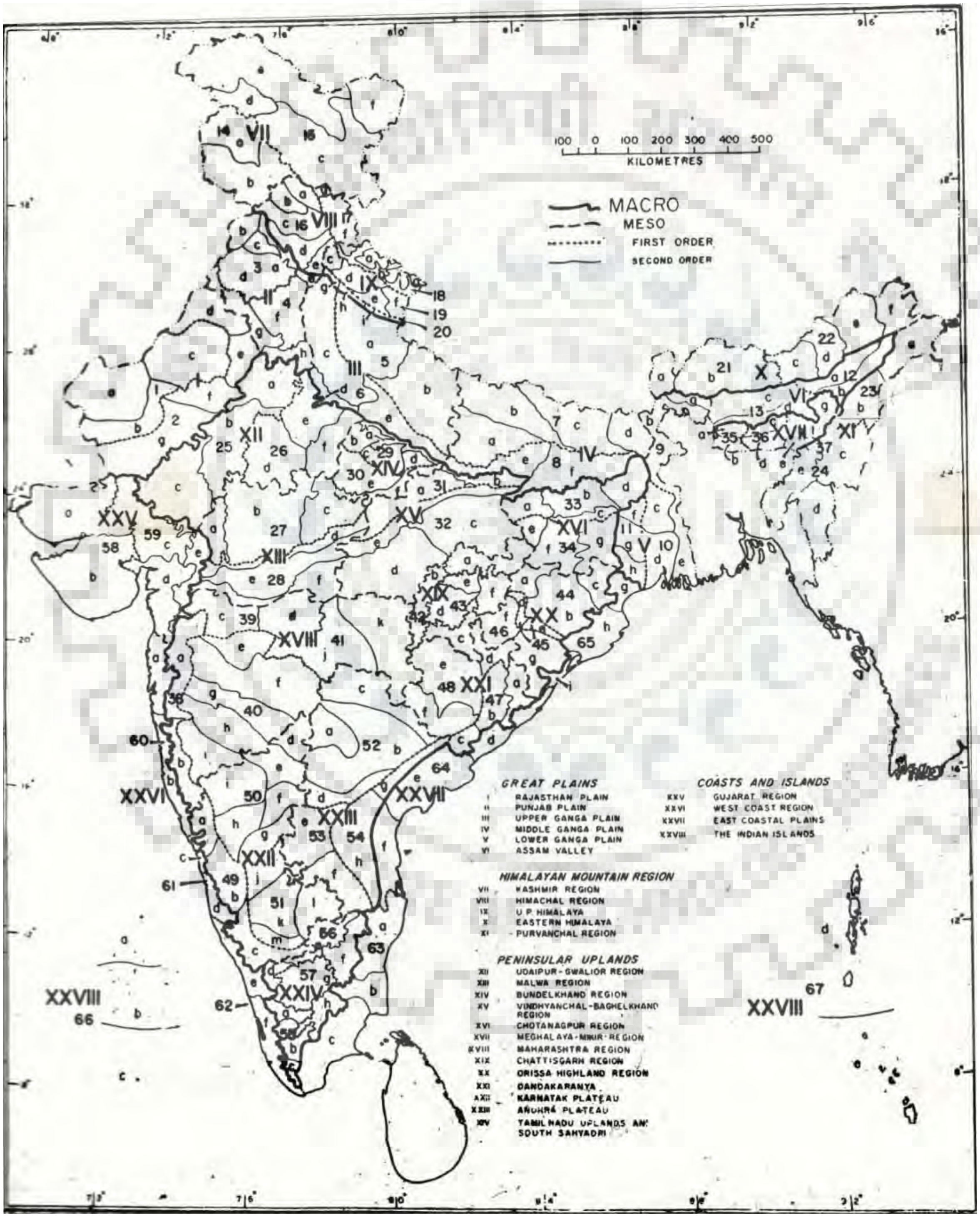


Figure 2-7 Geographic regions of India Source: [130]

Table 2-1 Geographic regions of India Source:[130]

MACRO REGIONS	MESO LEVEL REGIONS	FIRST ORDER	SECOND ORDER
A. Great Plains:			
	I. Rajasthan Plain		
		1. Marusthali	
			a. Jaisalmer Marusthali
			b. Barmer Marusthali
			c. Bikaner-Churu Marusthali
		2. Rajasthan Bagar	
			d. Hoshiarpur-Chandigarh Plain (Sub-Mountain belt)
			e. Shekhawati Region
			f. Nagaur Region
			g. Luni Basin
	II. Punjab Plain		
		3. Punjab Plain North	
			a. Hoshiapur-Chandigarh Plain
			b. Upper Bari Doab
			c. Jullundur Plain
			d. Punjab Malwa
		4. Punjab Plain South	
			e. Ambala Plain (Sub-Mountain belt)
			f. Estern Haryana (Kurukshetra Plain)
			g. Western Haryana
			h. Southern Haryana
	III. Upper Ganga Plain		
		5. Upper Ganga Plain North	
			a. Rohilkhand Plain
			b. Awadh Plain
		6. Upper Ganga Plain South	
			c. Upper Ganga-Yamuna Doab
			d. Trans-Yamuna Plain
			e. Lower Ganga-Yamuna Doab
	IV Middle Ganga Plain		
		7. Middle Ganga Plain North	
			a. Ganga-Ghaghara Divide
			b. Saryupar plain
			c. Mithila Plain
			d. Kosi Plain
		8. Middle Ganga Plain South	
			e. Son-Ganga Divide
			f. Magadh-Anga Plain
	V. Lower Gnaga Plain		
		9. North Bengal Plain	
			a. Duars (Barind Tract)
			b. Tista Flood Plain
		10. Delta Proper	
			c. Moribund Delta
			d. Mature Delta
			e. Active Delta
		11. Rarh Plain	
			f. Mayurakshi Plain
			g. Bankura Upland
			h. Midnapur Upland
	VI. Assam Valley		
		12. Upper Assam Valey	
			a. Upper Assam Valley North
			b. Upper Assam Valley South
		13. Lower Assam Valley	
			c. Lower Assam Valley North
			d. Lower Assam Valley South
B. Himalayan Mountain:			
	VII. Kashmir Region		
		14. Kashmir Region South	
			a. Kashmir Valley
			b. Jammu-Mirpur Region
		15. Kashmir Region North	
			c. Zaskar-Ladakh Region
			d. Deosai-Skardu Region
			e. Gilgit-Baltistan Region
			f. Aksaichin Region
	VIII. Himachal Region		
		16. Himalayan Himachal	
			a. Chandra Bhaga Basin
			b. Ravi Basin
			c. Beas Basin
			d. Himalayan Sutlej Basin
			e. UpperYamuna Tributary Basin
		17. Trans Himalayan Himachal	
			f. Spiti-kalpa-Sutlej Basin
			g. Malung Basin
	IX. U.P. Himalayan		
		18. Himadri	
			a. Himadri Ranges
			b.Himadri Valleys
		19. Himanchal	
			c. Trans-Yamuna Basin
			d. Bhagirathi-Alaknanda Basin
			e. Ramganga-Kosi Basin
			f. Saryu-Kali Basin
		20. Siwaliks	
			g. Yamuna-Ganga Tract
			h. Ganga-Ramganga Tract
			i. Ramganga-Kali Tract
	X. Eastern Himalaya		
		21. Darjeeling-Sikkim-Bhutan-Himalaya	
			a.Darjeeling-Sikkim Himalaya
			b. Bhutan Himalaya
		22. Assam Himalaya	
			c. Dafla Region
			d. Mir Region
			e. Abor Region
			f. Mishmi Region
	XI. Purvanchal Region		
		23. Purvanchal North	
			a. Lohit Tirap Region
			b. Nagaland
		24. Purvanchal South	
			c. Manipur Region
			d. Mizo Region
			e. Tripura-Cachhar Region
C. Peninsular Uplands			
	XII. Udaipur-Gwalior		
		25. Aravalli Uplands	
			a. North Aravalli Region
			b. Central Aravalli Region
			c. Southern Aravalli Region
		26. Chambal-Sindh Plains	
			d. Middle Chambal Basin
			e. Lower Chambal Basin
			f. Sindh Basin
	XIII. Malwa Region		
		27. Malwa Region North	
			a. Estern Mahi Basin
			b. Upper Chambal Basin
			c. Upper Betwa Basin
		28. Malwa Region South	
			d. Western- Vindhyan
			e. Middle Narmada Trough
			f. Western Satpura
	XIV. Bundelkhand Region		
		29. Bundelkhand Plain	
			a. Ravine Belt
			b. Jalaun Plains
			c. Hamirpur Pains
			d. Banda Plains
		30. Bundelkhand Uplands	
			e. Bundelkhand Genissic Region
			f. Bundekhand Vindhyan Plateau
	XV. Vindhyanchal-Baghelkhand Region		
		31. Vindhyanchal-Baghelkhand Region N	
			a. Rewa-Panna Plateau
			b. Mirzapur-Rohtasgarh Plateau
		32. Vindhyanchal-Baghelkhand Region S	
			c. Baghelkhand
			d. Chindwara-Maikal Plateau
			e. Natmada-Son Trough
	XVI. Chotanagpur Region		
		33. Chotanagpur Region-North	
			a. Palamau Uplands
			b. Hazaribagh Plateau
			c. Damodar Valley
			d. Santhal Pargana Uplands
		34. Chotanagpur Region-South	
			e. Pat Lands
			f. Ranchi Plateau
			g. South-Eastern Chotanagpur or Singhbhum Region
	XVII. Meghalaya-Mikir Region		
		35. Meghalaya-Mikir Region West	
			a. Garo Region North
			b. Garo Region South
		36. Meghalaya-Mikir Region Central	
			c. Khasi Region North
			d. Khasi Region South
		37. Meghalaya-Mikir Region East	
			e. Jaintia Region
			f. Mikir Region West
	XVIII. Maharashtra Region		
		38. Maharashtra sahydr	
			a. Maharashtra Sahyadri North
			b. Maharashtra Sahyadri South
		39. Tapti-Purna Valley	
			c. Tapti-Pura Valley west
			d. Tapti-Purna Valley East
		40. Maharashtra Plateau	
			e. Ajanta Hills
			f. Godavari Valley
			g. Balaghat Bhima Valley
			h. Upper Bhima Valley
			i. Mahadeo Upland
		41. Vidarbha Plains	
			j. Wardha-Penganga Plain
			k. Wainganga Plain
	XIX. Chattisgarh Region		
		42. Rim Land	
			a. Northern Rim Land
			b. Western Rim Land
			c. Southern Rim Land
		43. Chattigarh Plains	
			d. Raipur-Durg Plain
			e. Bilaspur Plain
			f. Raigarh Plain
	XX. Orissa Highland Region		
		44. North-Eastern Hill Region	
			a. North-Western Upland or Gangapur-Jharsuguda Basin
			b. Garhjat Hills
			c. North-Eastern Plateau
		45. Middle Mahandi Valley Region	
			d. Hirakund-Sonepur Valley
			e. Baudh Valley Region
		46. South-Western Hill Region	
			f. Hirakund-Bolangir Basin
			g. Orissa Ghats Region
	XXI. Dandakaranya		
		47. Dandakaranya Ghats	
			a. Dandakaraya Ghats East
			b. Dandakaraya Ghats Central
			c. Dandakaraya Ghats West
		48. Dandakaranya Uplands	
			d.Tel-Jonk Valley Region
			c. Baster Upland
			f. Indravati-Sabari Plain
	XXII. Karnataka Plateau		
		49. Maland (Central Sahyadri)	
			a. North Maland
			b. Central Maland
			c. South Malnad
		50. Maidan North	
			d. Bidar Plateau
			e. Gulbarga Plain
			f. Raichur Plain
			g. Bellary Plain
			h. Dharwar Plateau
			i. Bijapur Region
		51. Maidan South	
			j. Chitradurga Region
			k. Tumkur Region
			l. Bangalore Region
			m. Mysore Region
	XXIII. Andhra Plateau		
		52. Telangana	
			a. Hyderabad Plateau
			b. Telangana Peneplain
			c. Godavari Valley
			d. Krishna Valley
		53. Rayalaseema	
			e. Rayalasema Peneplain
			f. Rayalaseema Plateau
		54. Andhra Ghats	
			g. Northern Andhra Ghats
			h. Southern Andhra Ghats
	XXIV. Tamilnadu Uplands & South Sahyadri		
		55. South Sahyadri	
			a. Anaimalai-Palni Hills
			b. Cardamom Hills
			c. Agastyamali Hills
		56. Tamilnadu Ghats	
			d. Nilgiris
			e. Mettur Vellore Region
			f. Tamilnandu Hills
		57. Coimbatire-Madurai Uplands	
			g. Coimbatore
			h. Madurai Uplands
D. The Indian Coasts And Island			
	XXV Gujarat Region		
		58. Gujarat Region West	
			a. Bhuj Region
			b. Kathiwar Region
		59. Gujarat Region East	
			c. Ahmedabad Region
			d. Khumbat Region (Cambay Region)
			e. Eastern Hilly Region
	XXVI. West Coast Region		
		60. Konkan Coast	
			a. Konkan Coasty North
			b. Konkan Coast South
		61. Karnataka	
			c. North Kanara
			d. South Kanara
		62. Malabar Coast	
			e. Malabar Coast North
			f. Malabar Coast South
	XXVII. East coastal Plains		
		63. Tamilnadu Coastal Plain	
			a. Southern Plain Vaigai Tambraparni Region
			b. Delta Region
			c. Palar-Ponnaiyar Plain Region
		64. Andhra Coastal Plain	
			d. Pennar (Nellore) Region
			e. Krishna-Godacari Delta
			f. Vishakhapatnam Region
		65. Utkal Coastal Plain	
			g. Chailka Region
			h. Mahanadi Region
			i. Balasore Plain
	XXVIII. The Indian Island		
		66. Arabian sea Island	
			a. Amindive Islands
			b. Laccadive Island
			c. Minicoy Island
		67. Bay Island	
			d. Andaman Island
			e. Nicobar Island

India has been divided into four macro regions as shown in Figure 2-7. These Macro regions are further sub divided based on distinct geology, structure, & physiographic relief, together with the positional factor (longitude, altitude & continentality) [130] into 28 Meso level regions, 67 Ist order regions and 191 IInd order regions listed in Table 2-1.

The geographical context is also a significant factor in the selection of architectural design strategies as it governs the availability of raw materials for building construction as well as the climatic conditions to which it will be subjected. As will be discussed at length in section 2.5.5.2, Huang et al. [61] selected meteorological observatories (see Figure 2-12) that were representative of various geographical regions, considering meso scale variability of climate; while developing "Typical Year" weather files required in building performance assessment.

2.2.1.3. Local scale

The next level of climate study shown in Figure 2-3 is Local-Scale. Variety of Local climates are formed due to occurrence of micro-climates in close proximity to each other; under the influence of a variety of natural and man-made land covers such as forests and urban areas [108]. Simple comparison of the conventional meteorological elements (temperature, humidity, wind, precipitation) measured in a town and at an outlaying airport, has long been pointed out to be an inadequate analytical tool to establish local urban climatic difference [79]. Best practices for the selection of sites, the installation of a meteorological station and the interpretation of data from an urban area have since been established [105].

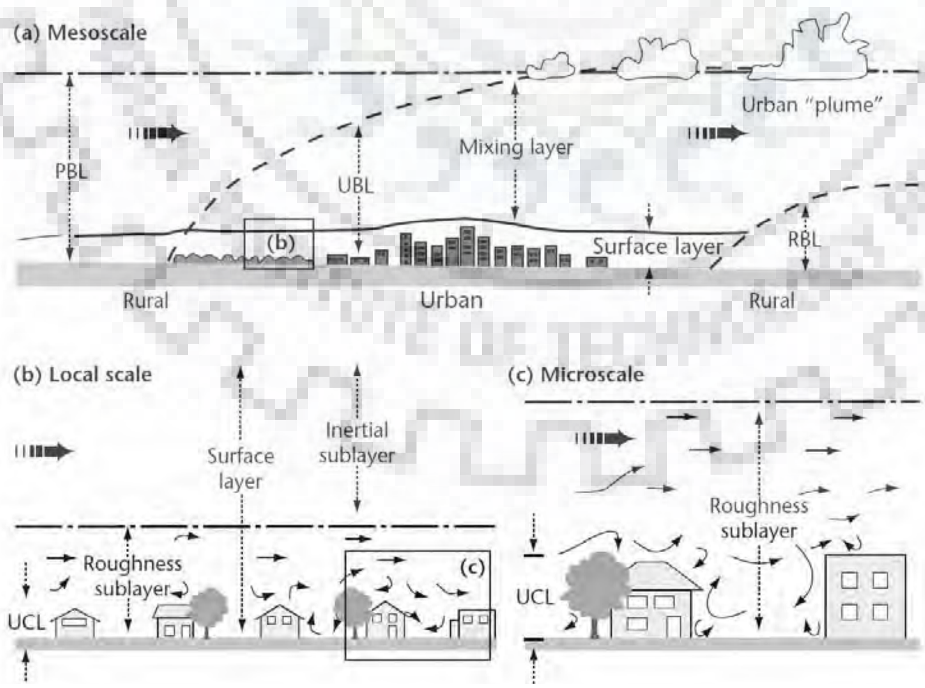


Figure 2-8 Schematic of climatic scales & vertical layers found in urban areas: planetary boundary Source: [105]

Considering a time period of one day the energy exchange near the earth's surface is restricted to a shallower layer of atmosphere called (planetary) boundary layer. In urban areas the (urban) boundary layer is sub-divided into surface layer, roughness sub layer and urban canopy layer as shown in Figure 2-8 [105]. Accordingly methodology was developed for detailed classification of natural and manmade elements affecting mixing in the roughness sub layer for differentiating between varieties of local climates [131].

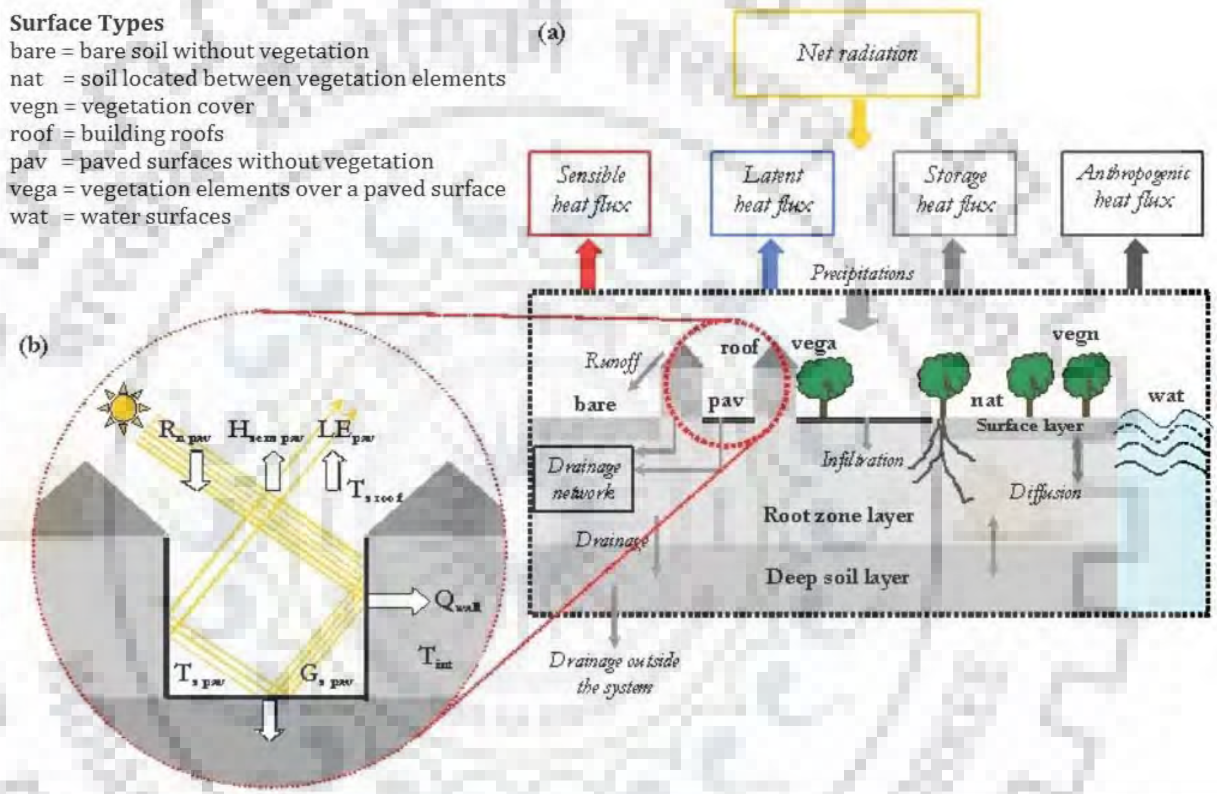


Figure 2-9 Scheme of the SM2-U energy and water budget models Source: [5]
(a) 7 surface types and 3 soil layers. (b) Energy budget of paved surfaces.

2.2.1.4. Micro scale

Micro-scale is the finest level of climate study shown in Figure 2-3. At this scale phenomenon of heat exchange occurring within the urban canopy layer (shown in Figure 2-8) may be analyzed on a sub-hourly basis. The participation of various land cover types and canyon geometry in the energy and water balance are measured and simulated at this scale as shown in Figure 2-9 [5]. At micro climate scale energy balance is studied in terms of four types of heat fluxes namely, sensible, latent, storage and anthropogenic; whereas water balance is studied in terms of precipitation, runoff, infiltration, diffusion and drainage outside the system. Physical properties of various surfaces and soil types play a role in the net radiation and hydrological budget at a given study area.

2.2.2. *Climatography*

The study of the actual distribution of climates over the earth, as distinguished from that of climate in general, is sometimes called climatography [136]. A later definition states, *climatography consists of the basic presentation of climatic data and its verbal or cartographic description* [107]. Climatography has been applied widely in the preparation of climate zone maps for policy formulation regarding various human concerns including but not limited to health [94], agriculture [84], water resource planning [118], solar energy resource planning [128], energy conservation in building industry [3,7,17,58,102,125], urban planning [1,2,38,44,48,86,121], and disaster mitigation [67,80]. A combination of climatic variables, derived indices, land form, soil types, land use - land cover, etc may be used as classifiers in the various climate zone maps [95].

Table 2-2 Description of Köppen climate symbols and defining criteria Source: [115]

1st	2nd	3rd	Description	Criteria*
A			Tropical	$T_{cold} \geq 18$
	f		- Rainforest	$P_{dry} \geq 60$
	m		- Monsoon	Not (Af) & $P_{dry} \geq 100 - MAP/25$
	w		- Savannah	Not (Af) & $P_{dry} < 100 - MAP/25$
B			Arid	$MAP < 10 \times P_{threshold}$
	W		- Desert	$MAP < 5 \times P_{threshold}$
	S		- Steppe	$MAP \geq 5 \times P_{threshold}$
		h	- Hot	$MAT \geq 18$
		k	- Cold	$MAT < 18$
C			Temperate	$T_{hot} > 10$ & $0 < T_{cold} < 18$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Cs) or (Cw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a or b) & $1 \leq T_{mon10} < 4$
D			Cold	$T_{hot} > 10$ & $T_{cold} \leq 0$
	s		- Dry Summer	$P_{sdry} < 40$ & $P_{sdry} < P_{wwet}/3$
	w		- Dry Winter	$P_{wdry} < P_{swet}/10$
	f		- Without dry season	Not (Ds) or (Dw)
		a	- Hot Summer	$T_{hot} \geq 22$
		b	- Warm Summer	Not (a) & $T_{mon10} \geq 4$
		c	- Cold Summer	Not (a, b or d)
		d	- Very Cold Winter	Not (a or b) & $T_{cold} < -38$
E			Polar	$T_{hot} < 10$
	T		- Tundra	$T_{hot} > 0$
	F		- Frost	$T_{hot} \leq 0$

* **Pthreshold** = varies according to the following rules (if 70% of MAP occurs in winter then **Pthreshold** = 2 x MAT, if 70% of MAP occurs in summer then **Pthreshold** = 2 x MAT + 28, otherwise **Pthreshold** = 2 x MAT + 14).

*__MAP__ = mean annual precipitation, **MAT** = mean annual temperature, **Thot** = temperature of the hottest month, **Tcold** = temperature of the coldest month, **Tmon10** = number of months where the temperature is above 10, **Pdry** = precipitation of the driest month, **Psdry** = precipitation of the driest month in summer, **Pwdry** = precipitation of the driest month in winter, **Pswet** = precipitation of the wettest month in summer, **Pwwet** = precipitation of the wettest month in winter, Summer (& winter) is defined as the warmer (& cooler) six month period of **ONDJFM** or **AMJJAS**.

2.2.2.1. Köppen classification system

Climatography at the macro climate scale can be recognized essentially as an orderly description of world climates based on quantitative methods to categories distribution of climatic elements like say monthly mean temperature, monthly mean precipitation and mean annual temperature.Köppen classification map shown in Figure 3-7 is an example of macro scale climatography. The classification system was initially developed based on temperature observations, in relation to plant growth. It was established as a quantitative method after being proposed, modified and re-modified over decades of research. Köppen intended to provide a triple order world pattern of climates using simple observations of selected climatic elements listed in Table 2-2 [108].

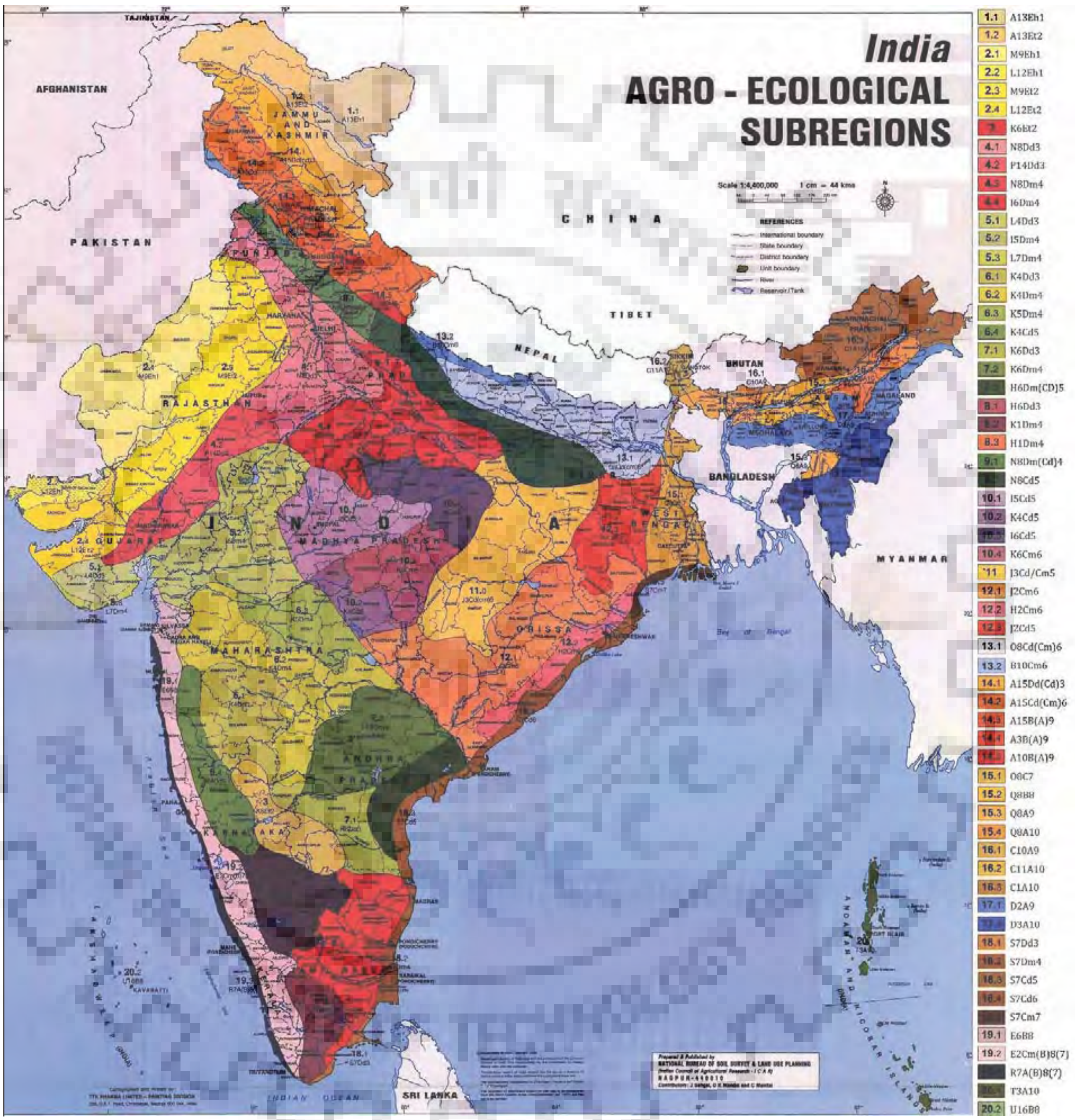


Figure 2-10 Agro-Ecological Sub-regions of India Based on: [39,127]

2.2.2.2. Geographic Regions

Climatography for delineating Agro-Ecological regions [84,127] and development of "Typical Year" weather file for 59 locations in India [61] are examples of studies at the meso climate scale.

For the purpose of practical crop planning; Agro-Ecological regions were delineated as shown in Figure 2-10. These regions were based on geographic regions of India grouped, as shown in Table 2-3 and superimposed with soil types, bio-climate and length of growing period (LGP) grouped, as shown in Table 2-4. State of the art in criteria for Agro-ecological classification system has been discussed in section 2.3.2.3.

Table 2-3 Letter Codes used for grouping of regions in Agro Ecological studies Source: [39,127]

PHYSIOGRAPHIC REGIONS (1st Letter) **A – Western Himalayas** Ladakh Plateau North Kashmir Himalayas South Kashmir Himalayas Punjab Himalayas Kumaun Himalayas **B – Central Himalayas** Foothills of Central Himalayas Bhutan Himalayas Darjiling and Sikkim Himalayas **C – Eastern Himalayas** Subdued Eastern Himalayas (Arunachal Pradesh) **D – North-Eastern Hills** Meghalayas Plateau and Nagaland Range Purvachal Range	**E – Western Ghats** North Sahyadris Central Sahyadris South Sahyadris **H – Eastern Ghats & TN Uplands** North Eastern Ghats South Eastern Ghats **I – Central Highlands** Aravali Range Eastern Rajasthan Upland Madhya Bharat Pathar Bundelkhand Upland Malwa Plateau Vindhyan Scarpland Vindhyan Range Narmada Valley **J – Eastern Plateau** Banghelkhand Plateau Chhotanagpur Plateau Mahanadi Basin Garjat Hills Dandakaranya	**K – Deccan Plateau** Maharashtra Plateau Satpura Range Karnataka Plateau Telangana Plateau **L – Kachchh & Kathiawar Peninsula** North Kachchh South Kachchh Kathiawar Peninsula **M – Western Plain** Marusthali Rajasthan Bagar **N – Northern Plain** Punjab Plain Ganga - Yamuna Doab Rohilkhand Plain Avadh Plain **O – Eastern Plain** North Bihar Plain South Bihar Plain Bengal Basin	**P – Gujarat Plain** Gujarat Plain **Q – Assam & Teesta Valley** Upper Brahmaputra Valley Middle Brahmaputra Valley Lower Brahmaputra Valley Teesta & Barak Valleys **R – West Coastal Plain** Konkan Coast Karnataka Coast Kerala Coast **S – East Coastal Plain** Tamil Nadu Plain Andhra Plain Gangetic Delta Utkal Plain **T – Islands** Andaman and Nicobar (Eastern) Islands Lakshadweep (Western) Islands

Table 2-4 Ordered Letter & Numeral Codes used in delineation of AER Source: [39,127]

SOILS (1st Numeral)

1. Red Loamy Soils
2. Red and Lateritic Soils
3. Red and Yellow Soils
4. Shallow Black Soils (with medium and deep Black Soils as inclusion)
5. Deep Black soils (with shallow and medium Black Soils as inclusion)
6. Mixed Red and Black Soils
7. Coastal and Deltaic Alluvium-derived Soils
8. Alluvial-derived Soils (with saline phases)
9. Desert (saline) Soils
10. Tarai Soils
11. Brown and Red Hill Soils
12. Saline and Sodic Soils
13. Skeletal Soils
14. Grey Brown Soils
15. Brown Forest and Podzolic Soils
16. Sandy and Littoral Soils

CLIMATE (2nd Letter)

E	— **Arid**
Eh	— Arid (hyper)
Et	— Arid (typic)
D	— **Semi-arid**
Dd	— Semi-arid (dry)
Dm	— Semi-arid (moist)
C	— **Subhumid**
Cd	— Subhumid (dry)
Cm	— Subhumid (moist)
B	— **Humid**
A	— **Perhumid**

GROWING PERIOD (2nd Numeral): days

Region	Map symbols	Subregions
<90	1	0 - 60
	2	60 - 90
90 - 150	3	90 - 120
	4	120 - 150
150 - 180	5	150 - 180
180 - 210	6	180 - 210
>210	7	210 - 240
	8	240 - 270
	9	270 - 300
	10	>300

SOIL QUALITY

Available Water Capacity (AWC) (mm/m)

Very low	<50 mm
Low	50 - 100 mm
Medium	100 - 150 mm
High	150 - 200 mm
Very High	>200 mm

SOIL QUALITY ATTRIBUTES

Soil Depth

Shallow	<50 cm
Medium	50 - 100 cm
Deep	>100 cm

Soil Texture (Family)

Sandy	: clay	<15%
Loamy	: clay	15 - <35%
Fine loamy	: clay	18 - 35%
Fine*	: clay	35 - 60%
Very fine	: clay	>60%

*For vertisol 30 to 60 percent

MINERALOGICAL CLASS

Particle size classes	AWC mm / m (for non-gravelly* in dominant clay minerals)		
	Montmorillonite	Mixed	Kaolinite
Sandy	50	50**	50
Coarse loamy	150	120	80
Fine loamy / Silty	200+	150	100
Fine	200+	150	120

* For skeletal soil, AWC is reduced by 50%
** Figures are for deep soil; it can be reduced according to soil depth.

TEMPERATURE (mean annual)

Frigid (warmer summers)	<8°C
Cryic (cooler summers)	<8°C
Mesic (cool)	8° - 15°C
Thermic (warm)	15° - 22°C
Hyperthermic (hot)	22° - 28°c
Megathermic (very hot)	>28°C

2.2.2.3. Local Climate Zones

Local climate zone (LCZ) classification has been developed for assisting detailed assessment of measurements recorded in urban climate studies [131]. LCZ is based on 10 types of built structures, 7 types of vegetation found in urban areas and 4 types of land cover properties occurring due to seasonal changes as shown in Figure 2-11.

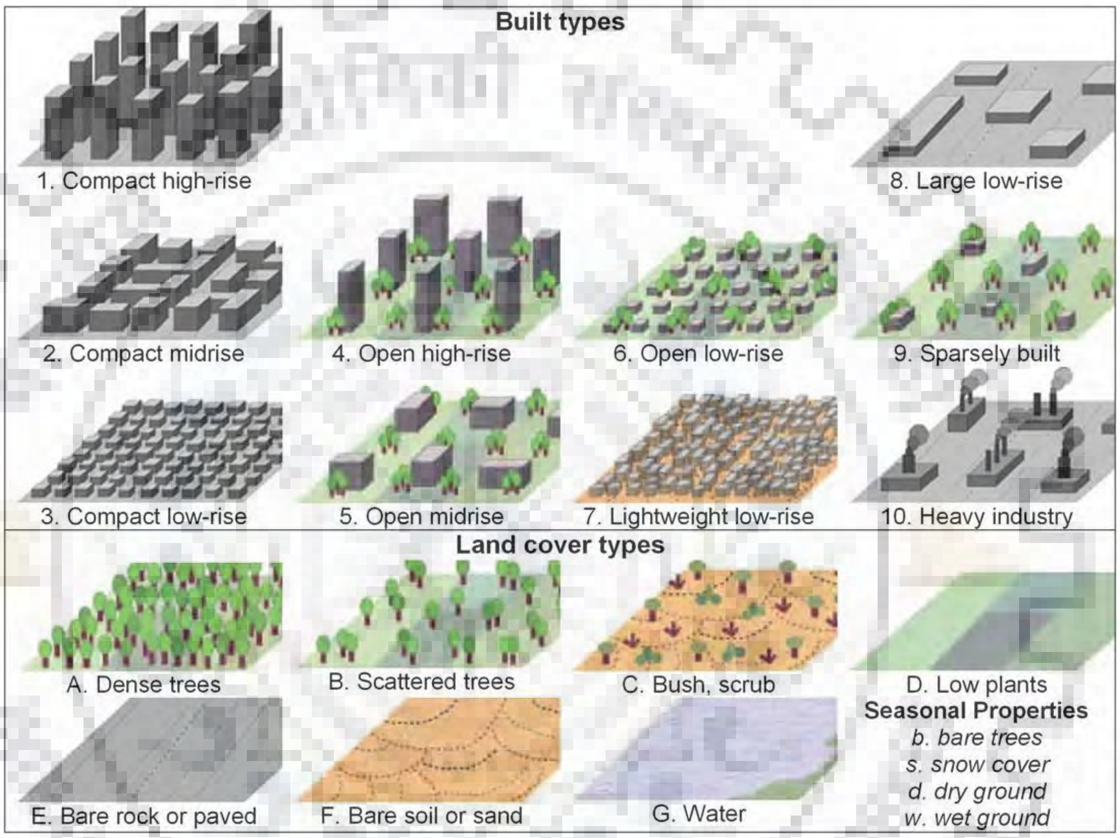


Figure 2-11 Built-up, land cover and surface typologies for LCZ classification Source: [131]

2.2.2.4. Microclimate modeling

As discussed in section 2.2.1.4 the differences in micro climatic conditions may be found around buildings depending on whether the measurement is done on the windward-leeward side, exposed-shaded from radiation, Albedo of the horizontal and vertical surfaces in the vicinity, sky exposure, pervious-impervious surfaces, type of vegetation cover etc. Well ventilated spaces may not have distinct micro-climates, due to frequent air changes. It is the obstruction of air movement that primarily leads to creation of micro-climates in urban areas. Variation in afternoon air temperatures (see Figure 3-11) across five built forms combined with three different vegetation types (see Figure 3-10) has been modeled using CFD software discussed in section 3.3.2.2.

2.3. Climatic Data

Unlike meteorology, climatology involves a study of meteorological parameters, measured at a place, over long periods. Though most parameters are measured / read on sub hourly basis, they may be recorded and reported as hourly measurements, daily extremes or monthly normals. Meteorological stations collect and publish a great deal of information on the weather of a region. Only a small part of it is required for building design. the choice is dominated by the need to obtain a picture of typical weather conditions to be expected at different seasons [144].

A structural engineer must base his calculations on the worst possible case of structural load. However it is not practicable for an architect to design for the worst possible climatic stress; it would result in buildings that are uninhabitable during normal weather conditions or lead to completely uneconomical installations for heating and cooling. Climatic design of building must be based on typical or normal, not on extreme conditions. Monthly means of daily maxima and minima of parameters listed in Table 2-5 are enough for the purpose [144].

Table 2-5 List of parameters required in climatic design of buildings Source: [144]

Air Temperature °C	**Relative Humidity %**	**Precipitation and Wind**
Monthly mean maximum Monthly mean minimum Monthly mean range Annual mean temperature	Monthly mean maximum a.m. Monthly mean minimum p.m. Monthly average	Rainfall, mm Wind direction prevailing Wind direction secondary (from 8 cardinal directions)

2.3.1.1. Meteorological Parameters

The parameters reported by meteorological stations include, air temperature, humidity, cloud amount, rainfall, mean wind speed and direction, weather phenomenon and visibility. A combination of climatic variables, derived indices, land form, soil types, land use - land cover, etc may be used as classifiers in the various climate zone maps [95].

Data on air temperature and humidity provide an idea of the climatic stress to be expected. Information on the daily and annual ranges of temperature and measurements of rain and wind complete the picture and, at the same time, indicate possible sources of relief [144].

2.3.1.2. Climatic normals used in climatology

Meteorological observations aggregated using typically 30 year long data are called Climate Normals and are used in climatic studies. Climatological Normals are long term statistical averages of atmospheric parameters measured at Weather Stations. Every 10 years IMD revises charts of climatological normals prepared by analyzing past 30years of meteorological data. A recently published dataset [63] contains data from 417 weather stations across India marked in Figure 2-12. The weather stations used for preparation of typical weather files [61] are indicated separately and *Thiessen Polygons* around each of these stations show the area of its neighborhood.

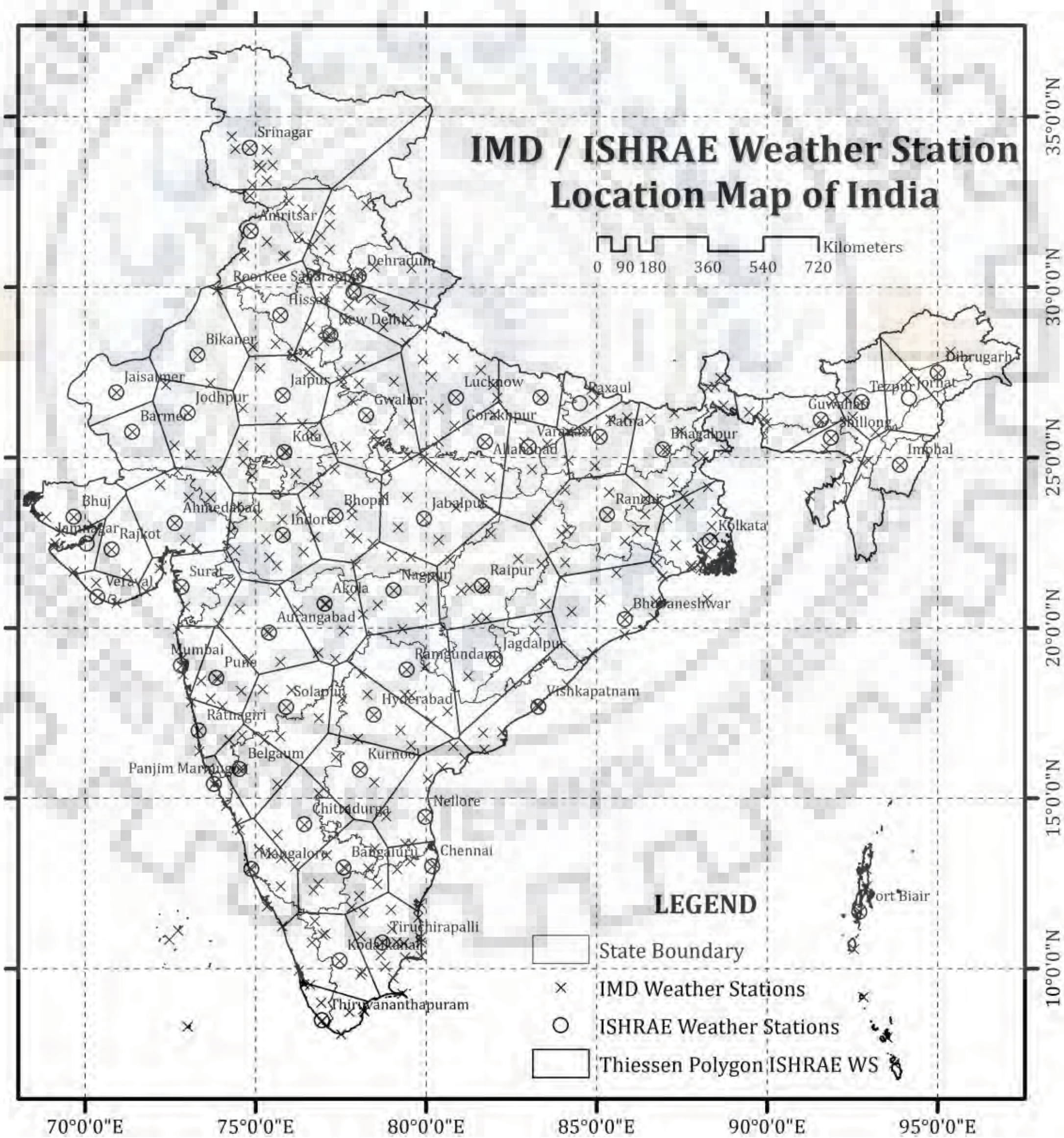


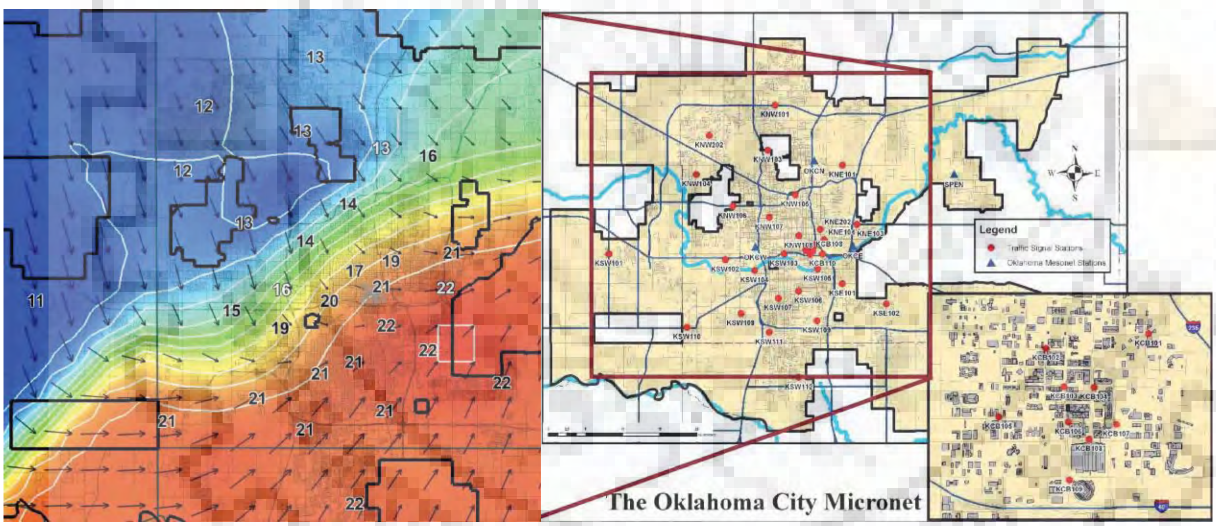
Figure 2-12 IMD / ISHRAE Weather Station Location Map of India based on [61,63]

2.3.1.3. Automatic Weather Stations

World Meteorological Organization guidelines govern the positioning of automatic weather stations installed for the measurement of regional meteorological data [154]. The instruments are usually located at a place where readings are not affected by special topographical features, nearby buildings or vegetation.

2.3.1.4. Urban Climate Network

In order to enable location of sufficient number of weather stations required for studying spatial variation in urban climate; placement criteria were adapted for urban areas by WMO [104]. Permanent urban - atmospheric monitoring programs such as the Oklahoma City Micronet (OKCNET) deployed across the Oklahoma City metropolitan area have resulted in improved understanding of the impacts of urban areas on atmospheric processes, as shown in Figure 2-13[8].



The temperature values (in °C) from traffic signal sites (& Oklahoma Mesonet sites at 9 m) are displayed in black (& white). Analyzed wind vectors are displayed as black arrows, and analyzed temperature are represented as color contours with (white) contoured isotherms every 0.5 degC.

Figure 2-13 OKCNET observations from 14 December 2008 at 1940 UTC as a strong cold front propagated through Oklahoma City Source: [8]

Installation of permanent instrumentation for urban micro climate monitoring being rare and time consuming [8], most researchers seem to rely on temporary stationary instrumentation and mobile surveys using instruments mounted on vehicles [54,66,117].

2.3.2. Climate diagrams & maps

Distribution of one or more climatic parameters may be analyzed with reference to time, w.r.t. each other or w.r.t. geographic location using various Climatographs, Climographs / Climograms and Climate maps [95]. Climographs used to show the influence of climatic conditions on human activity are also known as Bio-climatic charts and are discussed in section 2.4.3. Relevant climate maps are discussed in the following.

2.3.2.1. Composite Charts

Composite graphs of precipitation and temperature drawn in combination with climatic maps serve the purpose of understanding effects of seasonal phenomenon; like the macro-scale reversal of wind patterns occurring in June and December, collectively called the Asian Australian Monsoon. Unlike simpler wind maps shown in Figure 2-5 (b) and (c); maps of atmospheric pressure (isobars) combined with seasonal wind directions across Asia and Australia shown in Figure 2-14 help to explain the moisture and temperature regimes experienced in Calcutta and Thursday Island [159].

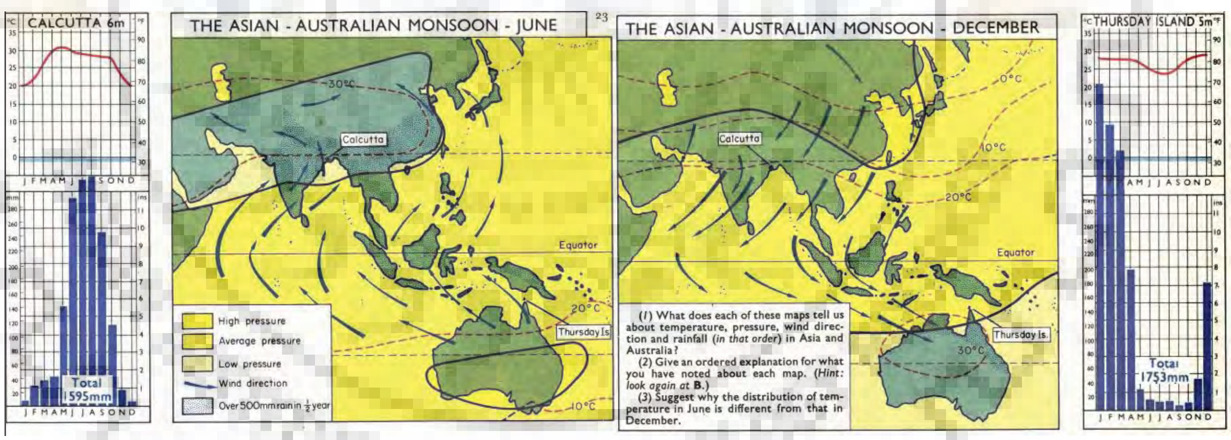


Figure 2-14 Climate Map explaining the Asian Australian Monsoon Source: [159]

2.3.2.2. Geographical Climate Maps

The monthly variation in climatic parameters viz. temperature extremes, mean relative humidity and rainfall, used to be shown in the form of composite charts at floating near the city location on a geographical map of the country.

Figure 2-15 describes variation in climate normals across India, in terms of graphs [130].

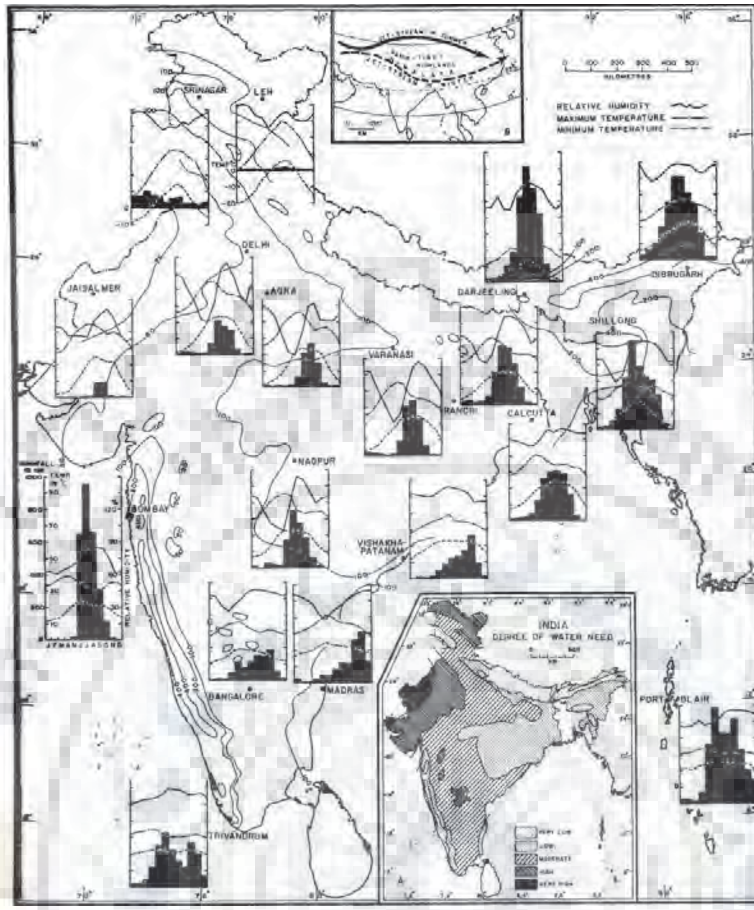


Figure 2-15 India Climatic Condition Source:[130]

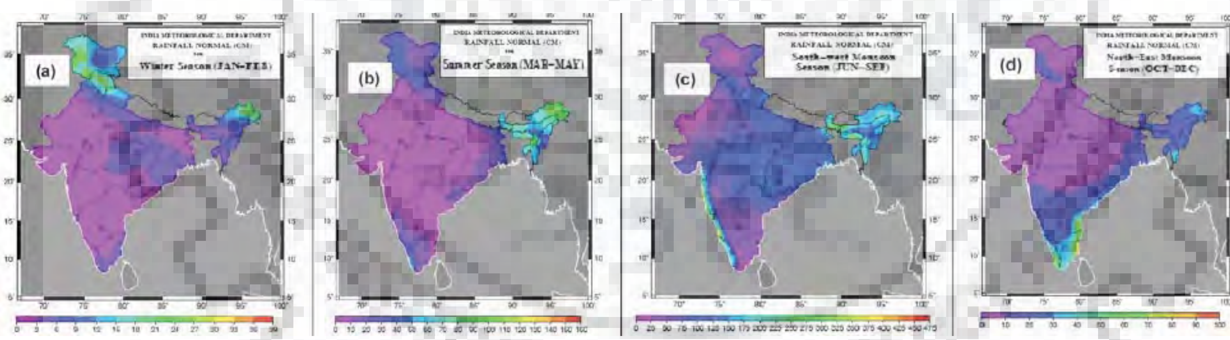


Figure 2-16 Normal rainfall pattern over India during 4 seasons Source: [64]

Figure 2-17 Seasonal temperature distribution over India Source: [64]

Interpolated patterns of normal rainfall during different seasons and monthly temperature isopleths are also being superimposed with points of interest as shown in Figure 2-16 and Figure 2-17.

These types of maps are especially useful for describing climatic normals across growing number of city locations or cumulatively across states [64].

2.3.2.3. Development of Agro-Climatic Zones

Various Agro-climatic zones were developed for agricultural planning in India. The Planning Commission of India identified 15 Agro-Climatic Resource Development Regions during the VIIth Plan 1985-90, as shown in Figure 2-18. The Indian Council for Agricultural Research (ICAR) delineated 127 Agro-climatic zones, under the National Agricultural Research Project as shown in Figure 2-19. The classifications have been done, using an indirect method based on soil type, climate (temperature), rainfall and other agro meteorological characteristics[96,97].

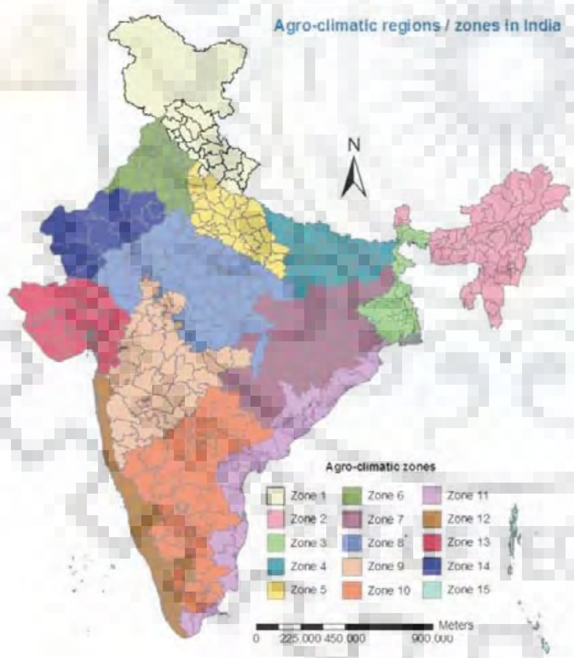


Figure 2-18 Agro-Climatic Regions as per Planning Commission Source: [97]

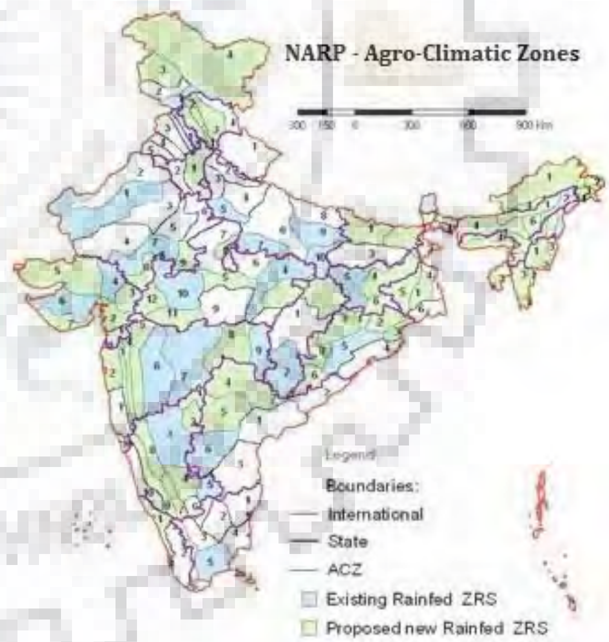


Figure 2-19 Agro-Climatic Zones as per ICAR Source: [96]

Later ICAR established 20 Agro-Ecological Regions and 60 Agro-Ecological sub-regions shown in Figure 2-10 by superimposing geographical regions with natural resources; like soils, climate and length of growing period for crops and other associated parameters classified into broad and narrow categories respectively [46,127]. To reach near the ground reality of crop performance by utilizing improved knowledge base on natural resources Figure 2-20 and analytical tools Figure 2-21, the Agro-ecological classification system is further being revised as shown in Figure 2-22 [84].

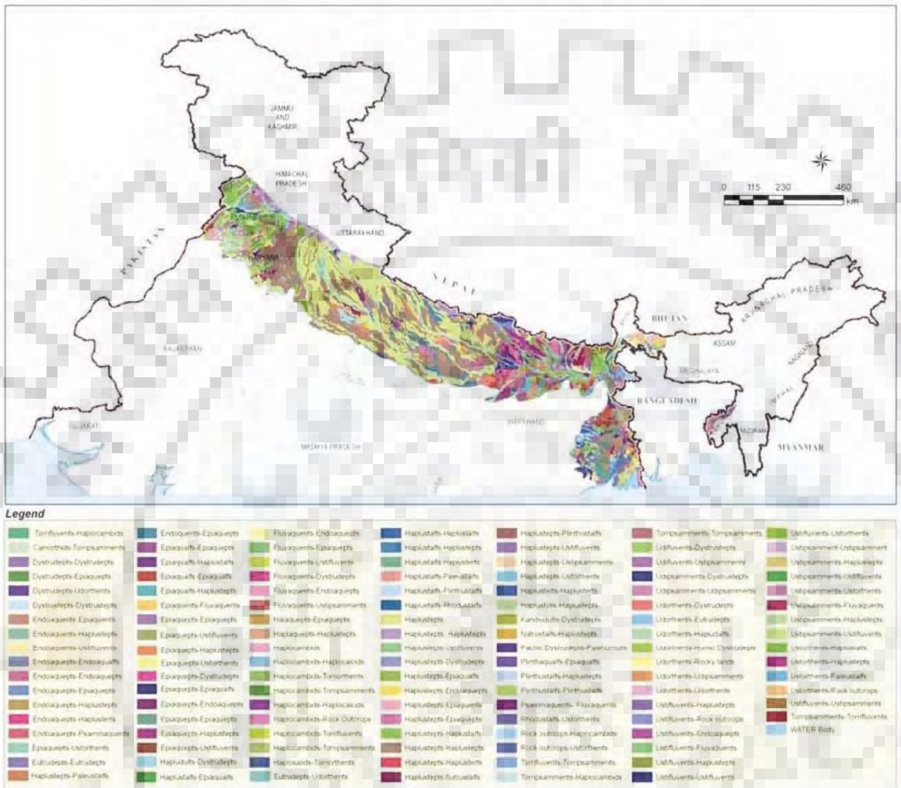


Figure 2-20 Updated soil map of IGP region Source: [84]

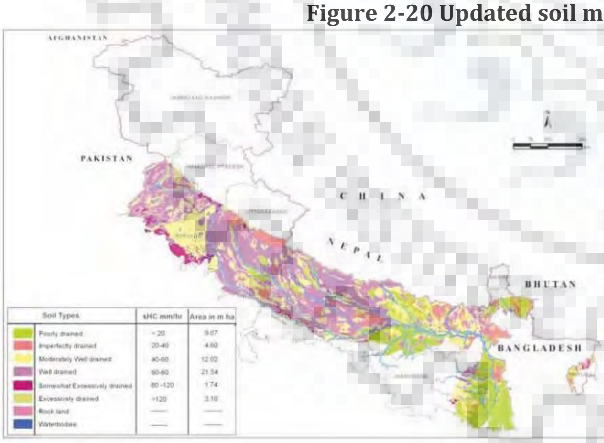


Figure 2-21 Reanalyzed hydraulic conductivity of IGP region Source: [84]

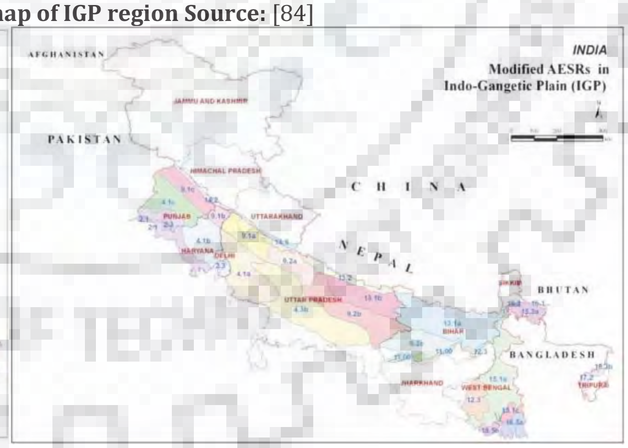


Figure 2-22 Revised Agro-Ecological Sub-Regions of IGP Source: [84]

Similarly, for achieving a sustainable built environment improvisation with respect to latest available datasets and analytical tools is necessary for improving the climatic classification for building design as discussed in section 2.5.5.2.

2.4. Sustainable Urban Built Environment

2.4.1. General

Goals pertaining to the Built Environment adopted in UN's 2030 agenda for sustainable development [146] are listed in Table 2-6. Among others the identified targets include development of technological expertise for, *building sustainable and resilient buildings using local materials*; and achieving *more sustainable patterns of* (energy) *consumption*.

Table 2-6 Sustainable Development Goals 11 & 12 Source:[146]

Goals	*Facts and Figures*	*Targets*
Goal 11: *Make cities inclusive, safe, resilient and sustainable*	○ *Half of humanity – 3.5 billion people – lives in cities today.* ○ *By 2030, almost 60 per cent of the world's population will live in urban areas* ○ *95 per cent of urban expansion in the next decades will take place in developing world* ○ *But the high density of cities can bring efficiency gains and technological innovation while reducing resource and energy consumption*	✓ *Support least developed countries, including through financial and technical assistance, in building sustainable and resilient buildings utilizing local materials*
Goal 12: *Ensure sustainable consumption and production patterns*	○ *Despite technological advances that have promoted energy efficiency gains, energy use in OECD countries will continue to grow another 35 per cent by 2020. Commercial and residential energy use is the second most rapidly growing area of global energy use after transport. Households consume 29 per cent of global energy and consequently contribute to 21 per cent of resultant CO2 emissions.*	✓ *Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production*

There has been a shift in focus of applied climatology from earlier concern of statistical distribution of climates to the interaction between physical and human components of climate system [143]. In order to reduce human impacts on the climate system, building planning, design and construction practices need to be informed according to prevailing climatic conditions.

2.4.2. Climatology Applied to Built Environment

Methodologies have been developed for effective implementation of climate knowledge in the planning, design and construction of built environment [15], and status of application have been evaluated [37].

Bitan [15] provided a methodology for applying climate knowledge to planning and building at the levels of region, settlement and building as shown in Figure 2-23. The methodology lists bioclimatic strategies to be implemented at all levels based on pertinent climatic analysis.

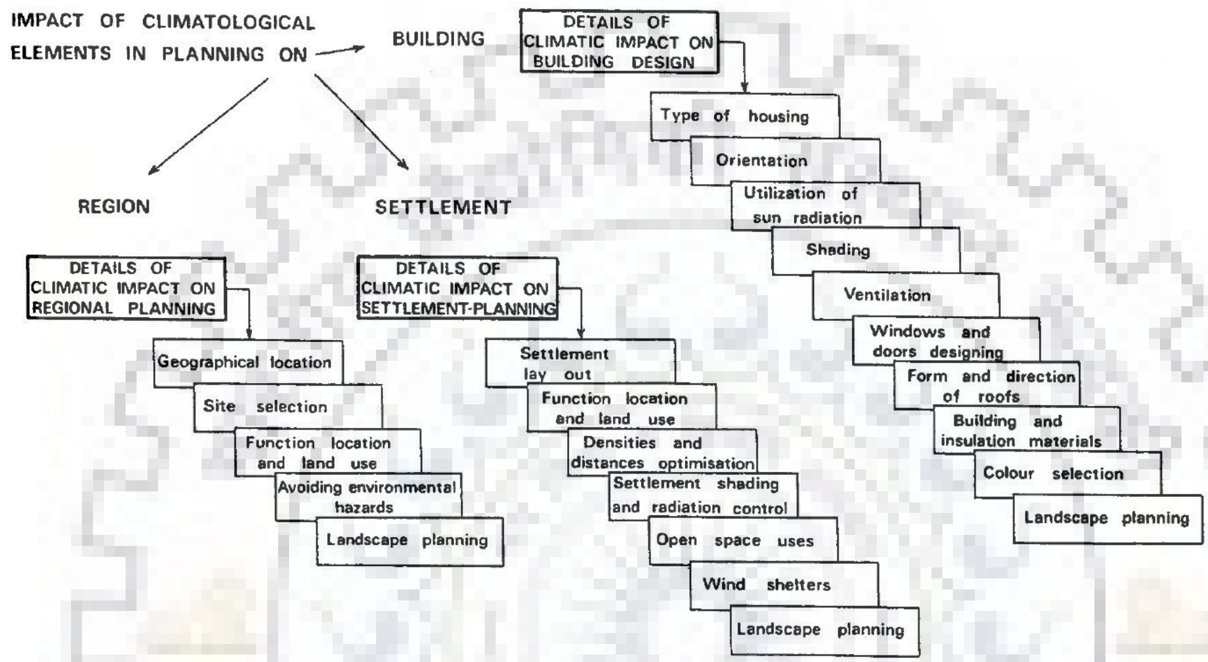


Figure 2-23 Methodology for applying climatology to planning and building design

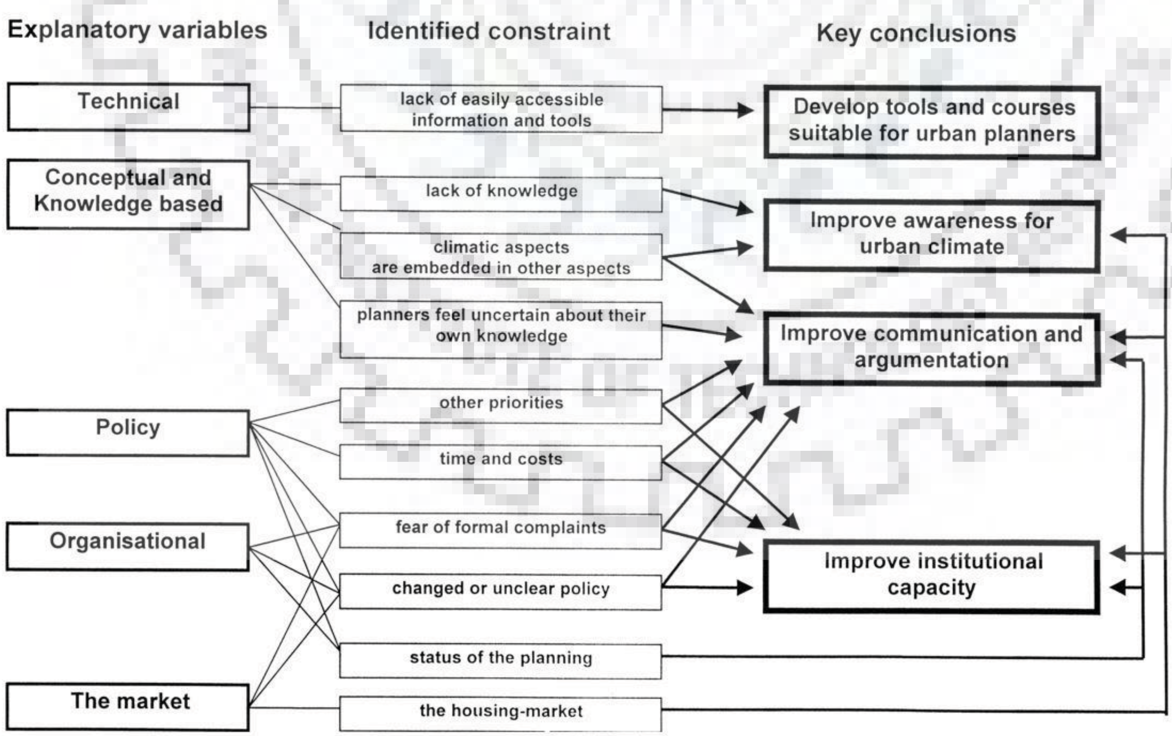


Figure 2-24 Scope for improvement in application of climate knowledge to planning and building design

Eliasson [37] linked explanatory variables and identified constraints governing the precursory "state of application" of climate knowledge in urban planning and building, and proposed actions as shown in Figure 2-24 for improving the same. She enumerates the need to improve communication, of existing climate knowledge (available with climatologists) to all concerned stake holders, and argumentation for supporting its use. Mills [89] cautions that sustainable built environment requires a coherent strategy that applies planning and design tools at the appropriate scale and ensures that actions at one scale are not counteracted at another scale [156]. Bioclimatic charts are often used in argumentation in support of implementing climate responsive best practices [125].

2.4.3. Bioclimatic Charts

Climograms used in thermal comfort analyses are called Bioclimatic charts. In a bioclimatic chart physiological effects of climate on man are indicated by plotting relative-humidity values in relation to temperature[95].

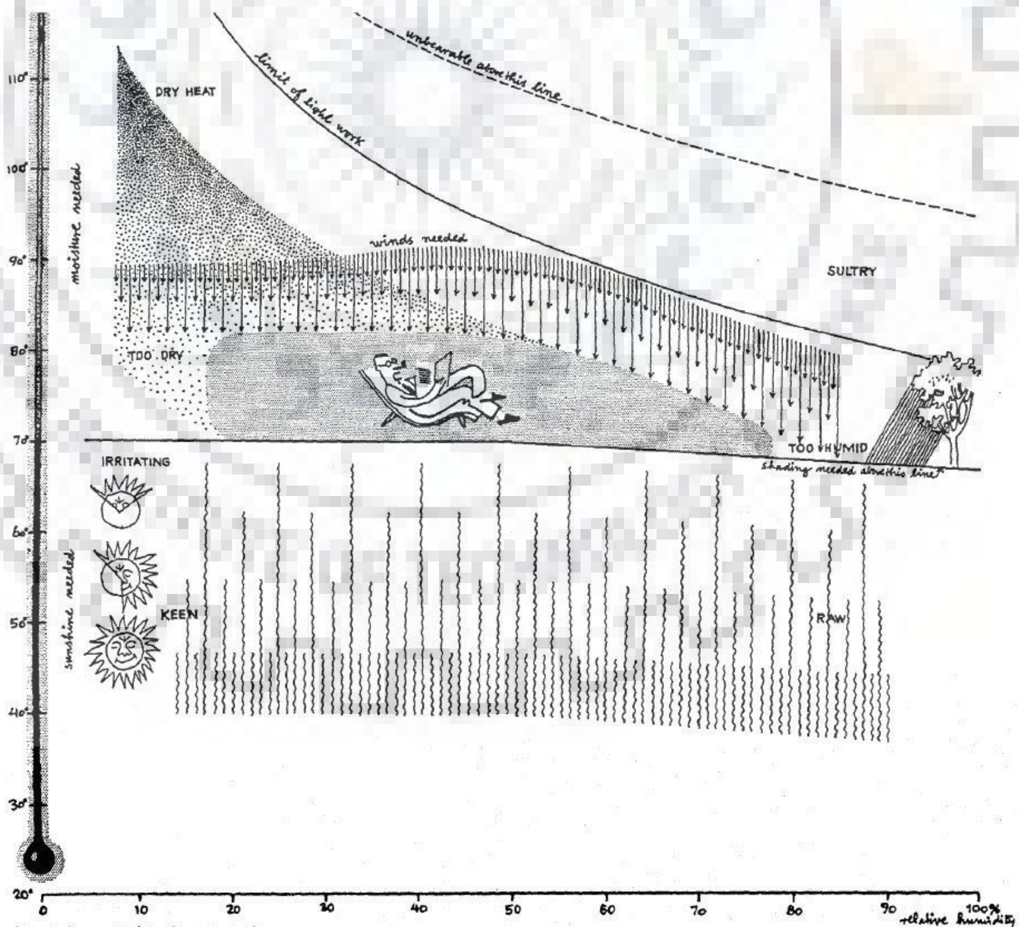


Figure 2-25 Schematic bioclimatic index Source: [106]

Thermal comfort zone and corrective measures are established on the bioclimatic chart. Olgyay and Givoni developed such bioclimatic charts to identify thermal stresses prevailing at a place and suggest corrective actions referred to as climate responsive passive design or bioclimatic design strategies [106] [47].

Olgyay[106] assembled the effects of wind, moisture and solar radiation around the comfort zone plotted on a graph built up with DBT as ordinate and relative humidity as abscissa as shown in Figure 2-25 .

Givoni's chart was first published in 1969[47]. In this chart a psychometric chart depicting Absolute humidity, relative humidity and dry-bulb temperature (DBT) is used as base. The psychometric chart has been marked with polygons where four different bioclimatic strategies used to achieve thermal comfort (natural ventilation, high mass, high mass with night ventilation and evaporative cooling) are effective. The bioclimatic strategies can be recommended for a place by plotting the outdoor climatic conditions prevailing around the year on Givoni's chart.

Various researchers developed & adapted these charts into variants that require variety of time steps and formats of input data, and that cater variety of design strategy assignment criteria and various mediums of output recommendations [78,91,125].

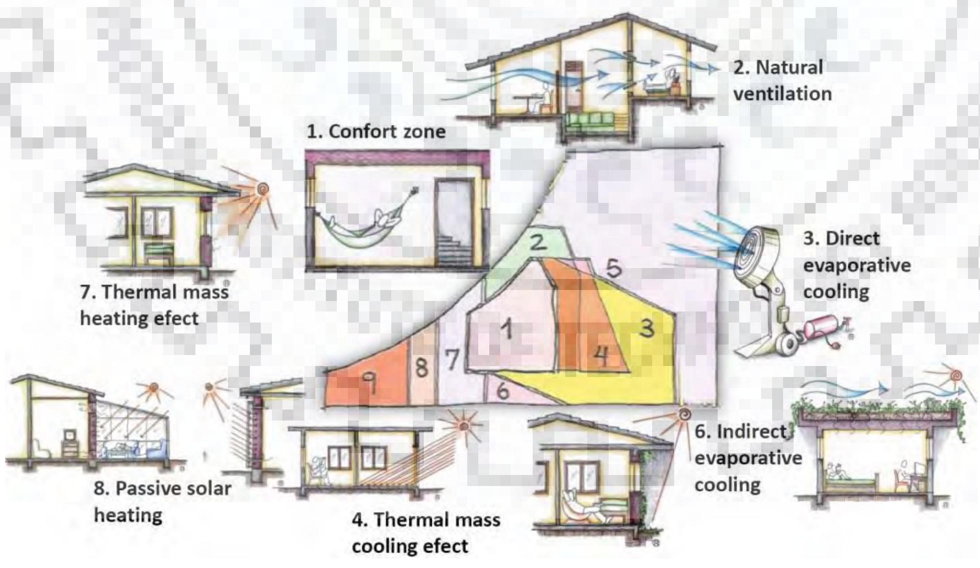


Figure 2-26 Givoni chart with strategies illustrated for Brazilian building legislation Source: [78] **as cited in** [77]

Lamberts [78] used the charts as shown in Figure 2-26 to illustrate bioclimatic design strategies in support of Brazilian building legislation. While delineating bio-climatic regions across Brazil Roriz et al. [125] adjusted the criteria for design strategy selection as shown in Figure 2-27.

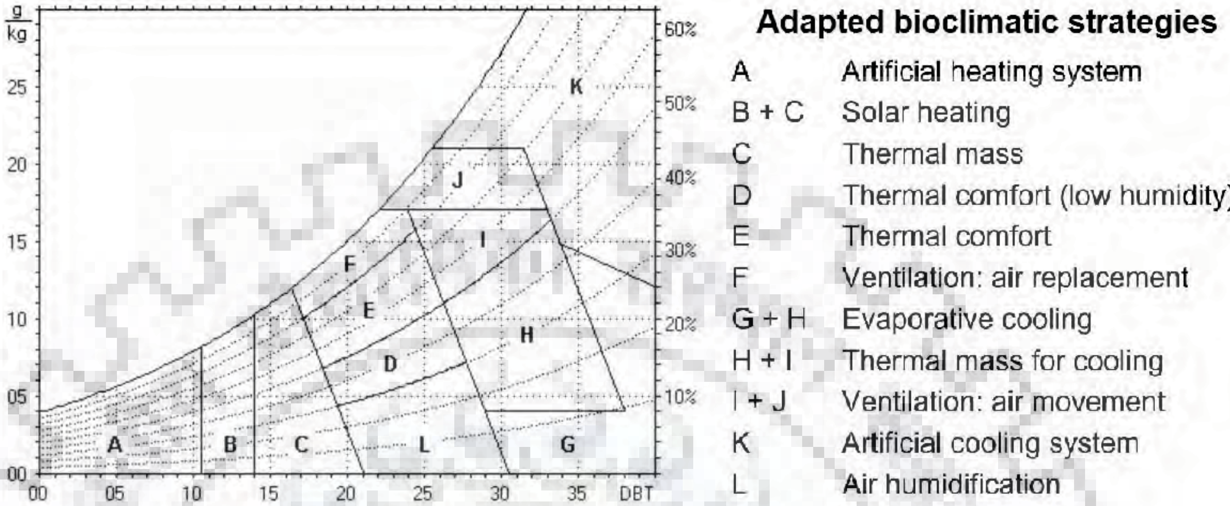


Figure 2-27 Givoni chart adapted for Brazilian bioclimatic zone delineation Source: [125]

Hourly readings of temperature and humidity can be plot on a Givoni (psychometric) chart using Climate Consultant software [91] as shown in Figure 2-28, to assess the effective duration of recommended bioclimatic strategies throughout the year.

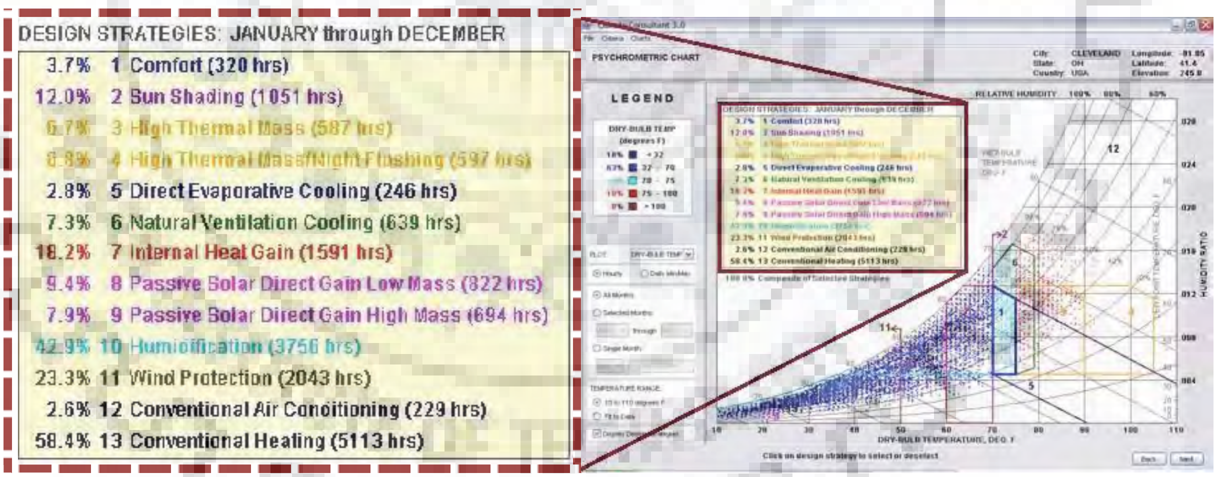


Figure 2-28 Climate_Consultant_3.0 interface for identifying bioclimatic strategies on hourly basis Source: [91]

Evans [42] proposed a graphic tool called 'Comfort Triangles' to identify and select bioclimatic strategies according to climate conditions and comfort requirements for a particular space. The Comfort Triangle use two key variables, average daily temperatures and temperature swings, to relate outdoor daily temperature variations with the modification of thermal performance achieved indoors. The four different comfort zones identified, for sedentary activities, sleeping, circulation and extended circulation have been labeled as A, B, C and D, respectively in Figure 2-29. This tool is useful for evaluating the need for implementing strategies in spaces assigned to specific uses.

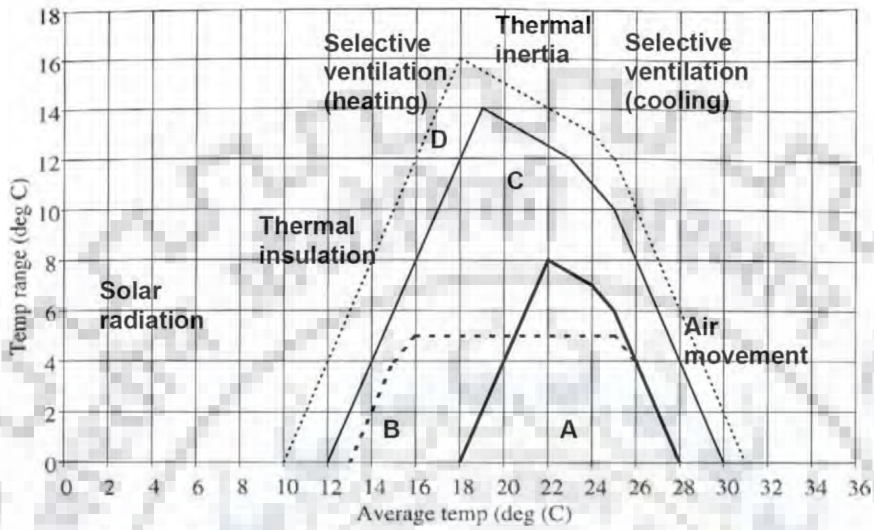


Figure 2-29 The comfort triangle with zones for identified activities Source: [42]

2.4.4. Climatic Suitability of Built Environment

Ratti et al. corroborate Oke's view that climate analysis for comfort requirement also referred to as forward analysis, shall precede any built form performance analysis [119] referred to as backward analysis. The choice of comfort requirement is dependent on the behavioral thermoregulation in various geographical regions.

2.4.4.1. Psycho-Physiological Model of Thermoregulation

Auliciems states that the natural climatic and techno-cultural environments collectively termed climo-cultural determinants, determine the thermal expectation and – as a consequence feeling of dis/satisfied with thermal affect leading to – thermopreferendum (see Figure 2-30) of people residing in different geographical regions [4].

2.4.4.2. Thermal Preference

Earlier Bedford [10] had reported variation in the thermal preference or 'comfort zone' based on average monthly outdoor temperature, called adaptive comfort range which was further investigated by Humphrey and Nicole[62], Evans [40] and Brager & Dear [16]. The Adaptive comfort range shown in Figure 2-31 has been part of the ASHRAE Standard 55 since 2004.

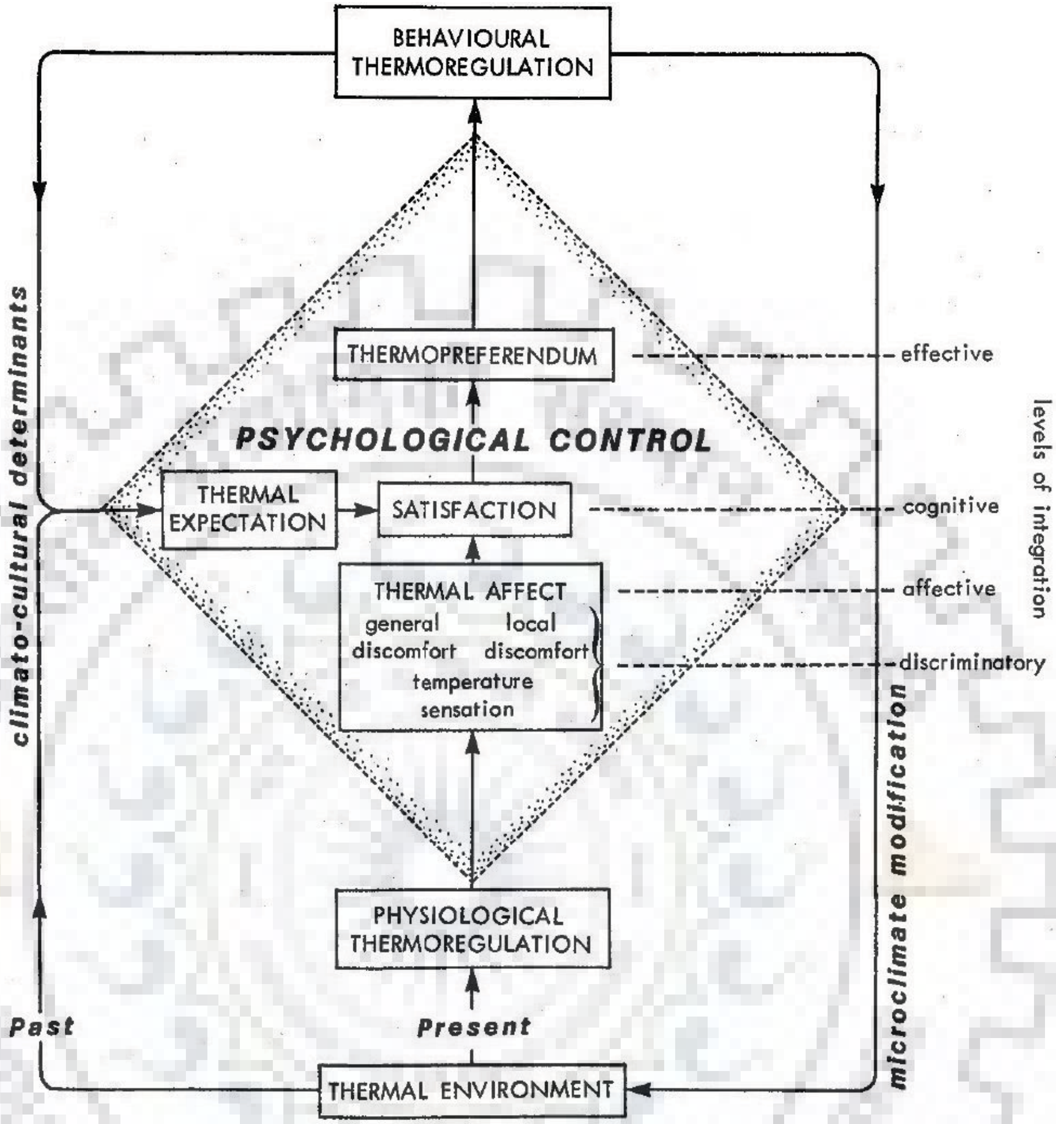


Figure 2-30 Psycho-Physiological Model of Thermoregulation Source:[4]

It has been pointed out that despite the extreme subjectivity expected in the concept of comfort, analysis of comfort votes – taken from large number of people subjected to identical conditions – produced remarkable agreement on the limits beyond which at least 70 per cent of the test subjects complained of discomfort [69]. The area between these limits is referred to as 'comfort zone'. Since these limits vary with annual mean temperature and humidity group of a particular month due to thermopreferendum; and during daytime and nighttime, due to variation in activity, metabolic rate and clothing; as illustrated in Figure 2-32; these are referred to as adaptive comfort limits. Koenigsberger et al [69] used adaptive comfort limits as selection criteria while formulating climate responsive design strategies.

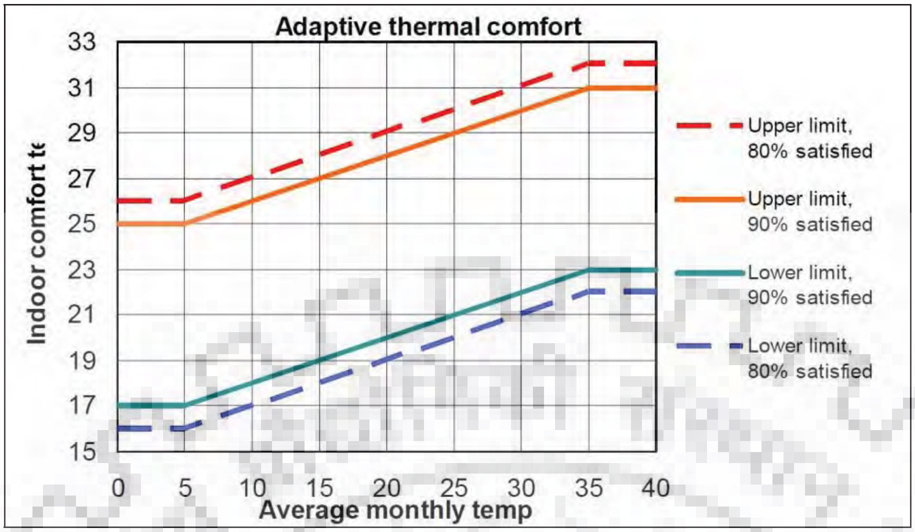


Figure 2-31 Adaptive Comfort Limits as per ASHRAE Standard 55

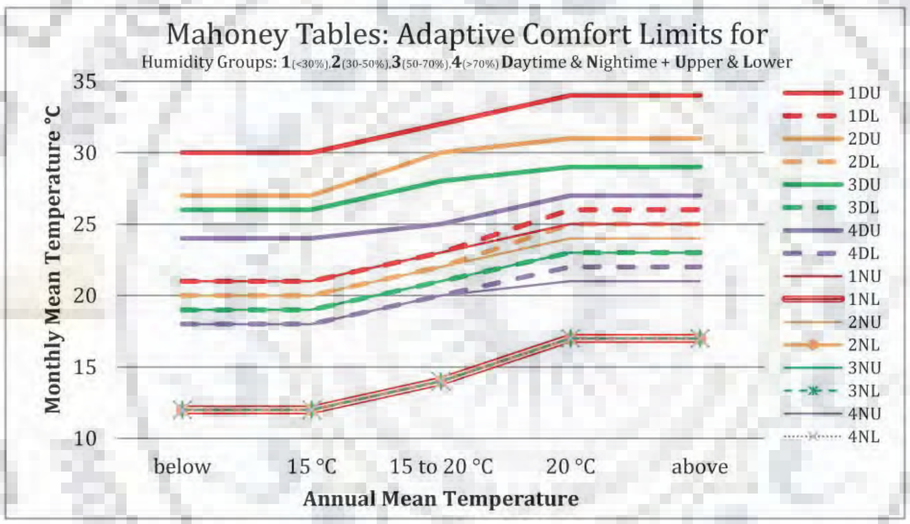
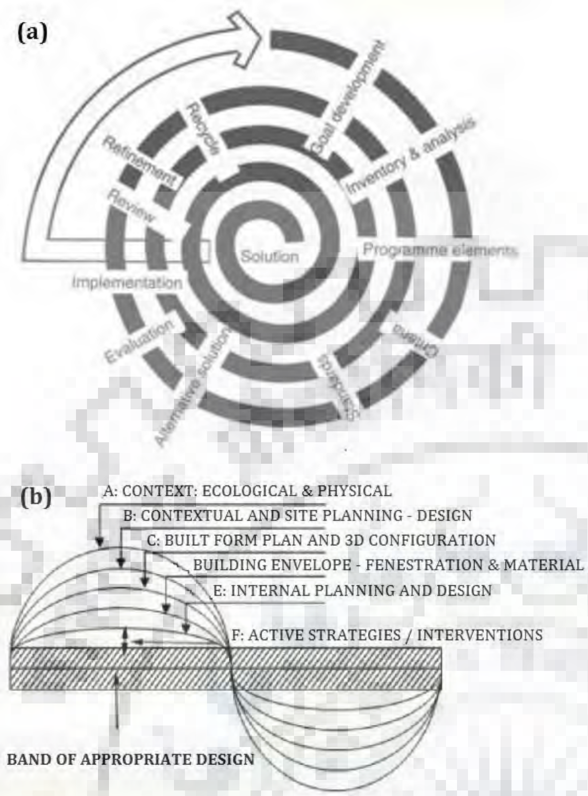


Figure 2-32 Adaptive Comfort Limits as per Mahoney Tables

2.4.4.3. Climate Responsive Process of Architectural Design

Use of relevant climatic data and information for carrying out built form analysis in the architectural design process at all stages, is of interest both from the ethical and from the practical points of view [134]. The method of environmental control is to rely on structural (passive) controls, which may obviate the need for any mechanical (active) controls, to ensure best possible indoor thermal conditions; even if mechanical controls do have to be resorted to, their task will thereby be reduced to a minimum [68]. Szokolay [134] proposed the responsive design approach using Koenigsberger et al.'s [68] successive climate modulation strategies including settlement pattern and site planning, passive design strategies, day lighting and natural ventilation and building envelope design.



(c)	Constituent Elements of Design	
B	i.	Land form: topography and slope orientation
	ii.	Vegetation type and pattern
	iii.	Water bodes
C	iv.	Street width and orientation
	v.	Open and built spaces
	vi.	Ground character
	vii.	Plan form
	viii.	Plan elements
	ix.	Building orientation
	x.	Surface area to volume ratio
	xi.	Roof form
D	xii.	Fenestration pattern and configuration
	xiii.	Fenestration orientation
	xiv.	Fenestration controls
	xv.	External colours and textures
	xvi.	Roof materials
	xvii.	Walls
E	viii.	Internal layouts and partitions
	xix.	Internal materials
	xx.	Internal finishes

Figure 2-33 Design Process (a) cyclic manner represented graphically (b) iterative levels of interventions (c) constituent elements Source: [71]

Krishan et al. [71] developed a scientific method shown in Figure 2-33 (a) to align the architectural design process with environmental concerns in a cyclic manner. For bringing the diurnal range of ambient climate within comfort limits six iterative levels of responsive design decisions have been identified as shown in Figure 2-33 (b). Krishan et al [71] considered every aspect of building and environment in a logical sequence listed in Figure 2-33(c), while discussing climate as a parameter for design of individual design constituent.

Level A of architectural design intervention at the broadest scale is termed 'Ecological and Physical Context'. The second level B termed 'Site Planning-Design' comprises of design entities such as land from, vegetation and water bodies. Next level C termed 'Built Form' comprises of eight design constituents namely; Streets, open-built spaces, Ground characteristics, Plan form, Plan elements, Building orientation, Surface area to volume ratio, and Roof form. The fourth level D termed 'Building Envelope' comprises of six design constituents namely; Fenestration pattern & configuration, Fenestration orientation, Fenestration controls, External colours and textures, Roof materials and

Walls. The second last level E termed 'Internal planning and design' comprises of internal layouts and partitions, material, and finishes, Last level F of architectural design intervention at the finest scale is termed 'active strategies' and comprise of electromechanical means of achieving thermal comfort. Criteria for selection of particular strategy in response to ambient climatic stress in case of individual design constituent from level B to level E have been illustrate in Figures 3-16 through 3-23.

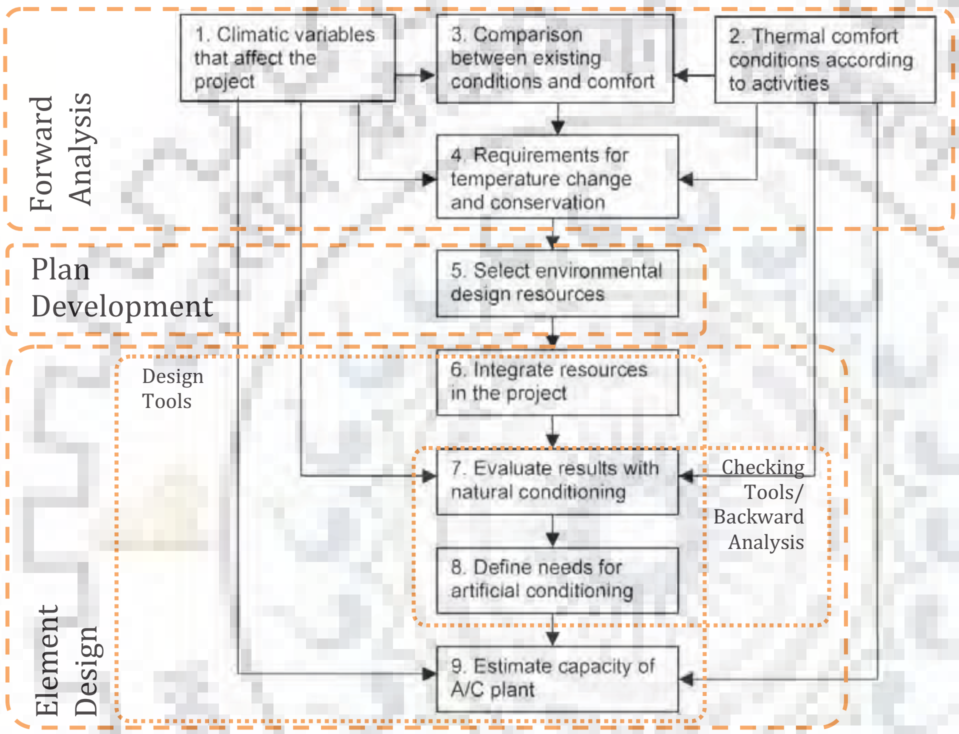


Figure 2-34 Stages for bioclimatic intervention in design process in three iterative stages Based on: [42]

2.4.4.4. Stages of Bioclimatic Intervention

Evans [42] classified 9 steps of design process as shown in Figure 2-34 to explain how climate variables and thermal comfort requirements should inform the bioclimatic design process.. These 9 steps can be distinguished into three stages where the trio of "analysis-synthesis-evaluation" proposed by Koenigsberger et al [68] is repeated. The first stage termed 'Forward analysis' consists of steps 1 to 4. The second stage termed 'Plan development' consists of step 5. While the last stage termed 'Element design' includes design tools i.e. steps 6 to 9 and checking tools i.e. steps 7 & 8 also called backward analysis.

2.5. Building Legislation: Regulations, Codes and Standards

The potential for energy conservation and reducing greenhouse gas emission from the building sector especially in urban settlements has been well documented by Intergovernmental Panel on Climate Change [65]. Though urban settlements are engines of growth, they are deficient in resources like land water and energy, they also lay tremendous stress on the environment. Following the Millennium Development Goals (MDG) and Sustainable Development Goals (SDG), Indian government has been promoting the use of Climate Knowledge in planning and building through Building Codes, Standards, including NBC, ECBC, MoEF EIA. The building codes and standards currently address the building envelope specifications and mechanical thermal comfort interventions, and their efficacy can be improved by incorporating climate knowledge on responsive design strategies.

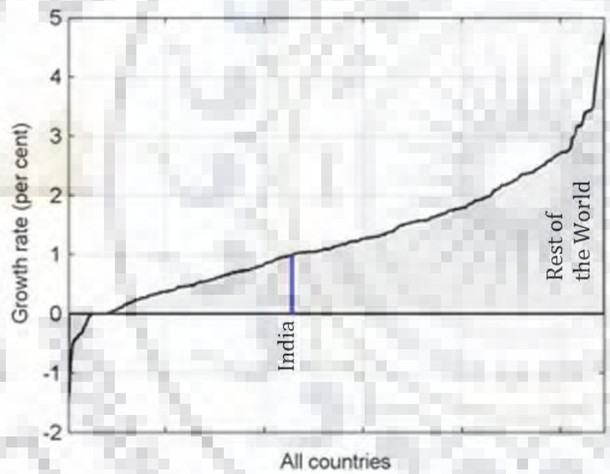


Figure 2-35 Average annual growth rate of urban population across all countries Based on: [145]

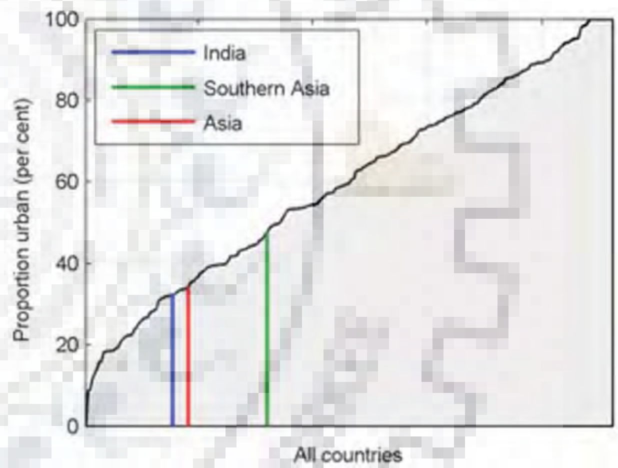


Figure 2-36 Percent urban population of World Based on: [145]

2.5.1. Urbanization

As will be seen in this section population growth and outsourcing of industrial processes by developed nations lead to a trend of influx of large populations to various old and new towns in the developing countries like India. Figure 2-35 describes average annual growth rate of the urban population of India (blue line) between 1950 and 2014, as compared with the average annual growth rates of the urban population of all countries of the world (gray area) [145]. The figure illustrates that urban growth rates between 1950 and 2014 were positive in the great majority of the countries of the world. Only a few countries had negative urban growth rates, indicating that their urban population declined between 1950 and 2014.

Figure 2-36 illustrates, Proportion of urban population in 2014 – what level of urbanization – India (blue line) has, compared to Southern Asia (red line) and Asia (green line), as well as compared to all other countries of the world (gray area).

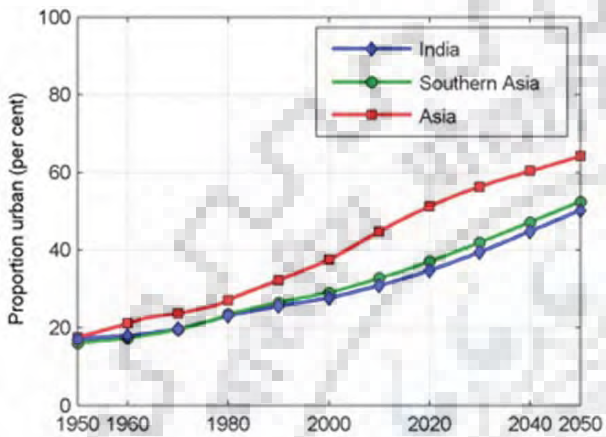


Figure 2-37 Percent urban population of India compared to Asia Source: [145]

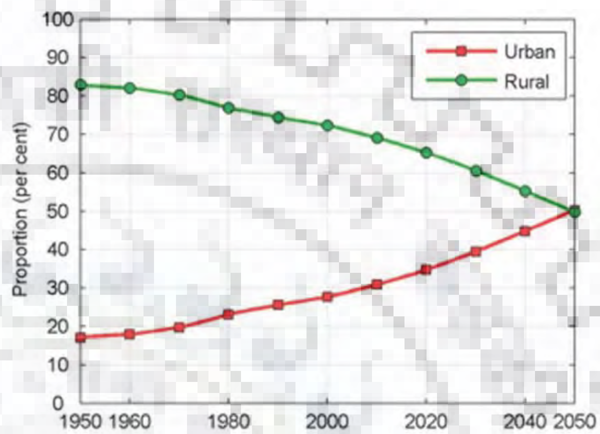


Figure 2-38 Percent urban versus rural population in India Source: [145]

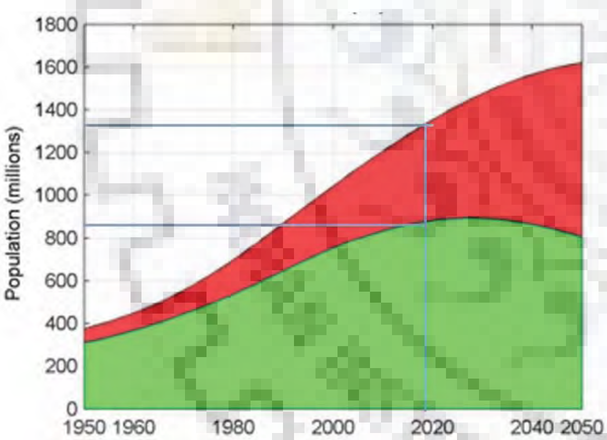


Figure 2-39 Rural versus urban population size Source:[145]

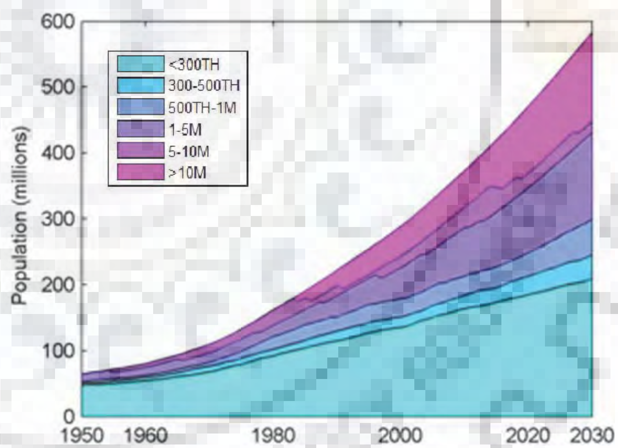


Figure 2-40 Urban population size by city size class Source: [145]

2.5.1.1. Trend of Urbanization

Figure 2-37 describes proportions of urban population in India as compared to Southern Asia and Asia. The proportion is expressed in per cent of the population between 1950 and 2050 [145]. As can be seen though India was as much urbanized as South Asia and Asia in 1950; the growth of urban populations in the other regions has been faster than that in India.

Proportions of urban and rural population in India in per cent of the total population, for the period 1950 to 2050 are described in Figure 2-38 [145]. As may be seen, the estimated Indian urban population will exceed 35 percent in 2020 and equal the rural population by the year 2050.

Plot in Figure 2-39 describes urban and rural population size in India for the period 1950 to 2050 [145]. As can be seen by the year 2020, while 850 million people are estimated to live in rural India, another 500 million people will be living in urban areas. Plot in Figure 2-40 describes urban population of India by size class of its urban agglomerations for the period 1950 to 2030 [145]. The light blue area is a residual category, which includes all cities and urban agglomerations (UA) with a population of less than 300,000 inhabitants.

Table 2-7 Definition of Urban Settlement Source: [99]

	Type of Towns /UAs/OGs	Definition	Number of towns 2011 Census	Number of towns 2001 Census
1	**Statutory Towns**	All places notified under law by the concerned State/UT Government and having local bodies like a municipality, corporation, cantonment board or notified town area committee, etc.	4,041	3,799
2	**Census Towns**	All other places which satisfied the following criteria as per the Census 2001 data: i) A minimum population of 5,000; ii) At least 75 per cent of the male main working population engaged in non-agricultural pursuits; and iii) A density of population of at least 400 persons per sq. km.	3,894	1,362
3	**Urban Agglomerations**	A continuous urban spread constituting a town and its adjoining outgrowths (OGs), or two or more physically contiguous towns together with or without outgrowths of such towns. An Urban Agglomeration (UA) must consist of at least a statutory town and its total population (i.e. all the constituents put together) should not be less than 20,000 as per the Census 2001 data. Each such town together with its outgrowth(s) is treated as an integrated urban area and is designated as an 'urban agglomeration'.	475	384
4	**Out Growths**	A viable unit such as a village or a hamlet or an enumeration block made up of such village or hamlet and clearly identifiable in terms of its boundaries and location. Outgrowth of a town, must possesses the urban features in terms of infrastructure and amenities and be physically contiguous with the core town of the UA. Some of the examples are railway colony, university campus, port area, military camps, etc., which have come up near a statutory town outside its statutory limits but within the revenue limits of a village or villages contiguous to the town.	981	962

2.5.1.2. Class-I Urban Settlements in India

The definition of urban area as per Census of India 2011 [99] is given in Table 2-7. The total urban population in the country as per Census 2011 is more than 377 million constituting 31.16% of the total population. The 468 UAs/Towns which have population of at least 1,00,000 persons as per Census 2011 are categorized as Class I UA/Town. The corresponding number in Census 2001 was 394. 264.9 million persons, constituting 70% of the total urban population, live in these Class I UAs/Towns. The proportion has increased considerable over the last Census. In the remaining classes of towns the growth has been nominal. The locations of these UAs/Towns have been taken shown in Figure 2-41.

2.5.1.1. Distribution of urban population

As shown in Figure 2-42 Maharashtra has the highest urban population size among the states and UTs, followed by Uttar Pradesh and Tamil Nadu [100]Being created in the year 1960 [28] by consolidating territories from the erstwhile Bombay, Hyderabad and Madhya Pradesh States, Maharashtra also has the earliest legal structure for urban governance in the form of Bombay Municipal Act 1888 and MRT&P Act 1966. Like all other states the building construction practice in Maharashtra too is govern by various legislative provisions starting from the Constitution and other acts at national level, to the standardized development control and promotion regulations (DC&PR) at national as well as state level, up to the DC&PR notified as part of Development Plans formulated by urban local bodies.

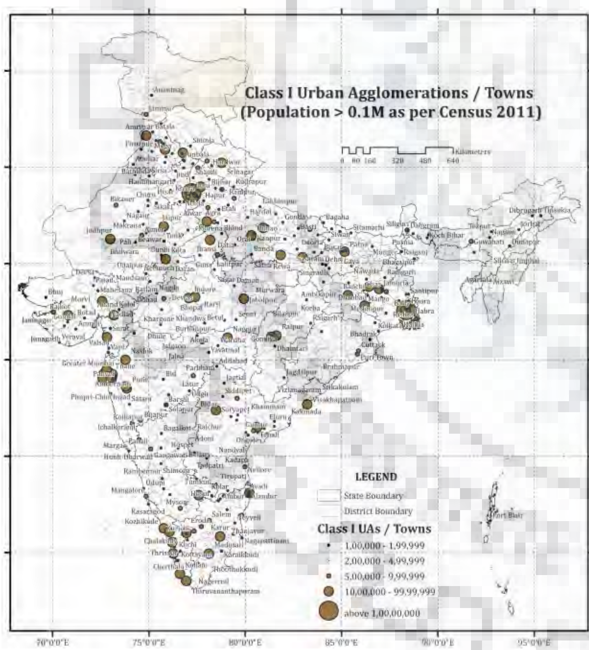


Figure 2-41 Class - I UAs / Towns in India Source: [101]

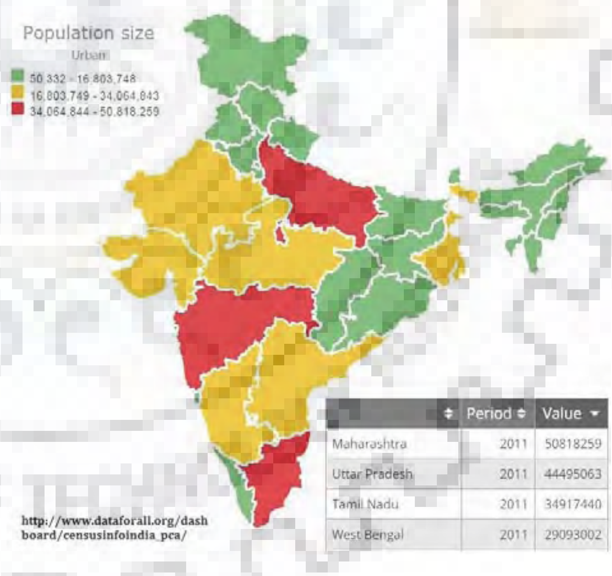


Figure 2-42 Distribution of urban population size across India Source: [100]

2.5.2. 73rd and 74th Constitution Amendment Act 1993

Through the 73rd and 74th Constitution Amendment Act 1993 the Constitution of India bestowed power to the people to plan for themselves and participate in the decision making process by making provisions for the establishment and operation of local self governments both in rural as well as urban settlements. Provisions in the 74th Constitution Amendment Act of 1993 entrust Local Self governments in various types of urban settlements (including Nagar Panchayats) with functions listed in the Twelfth Schedule [137].

Table 2-8 List of functions entrusted to ULB's as per XIIth Schedule Source: [137]

S.No.	18 Items of the 12th Schedule	S.No.	18 Items of the 12th Schedule
1	Urban planning including town planning	11	Urban poverty alleviation
2	Regulation of land use and construction of buildings	13	Promotion of cultural, educational and aesthetic aspects
3	Planning for economic and social development	12	Provision of urban amenities and facilities such as parks, gardens, playgrounds
4	Roads and bridges		
5	Water supply for domestic, industrial & commercial purposes	14	Burials and burial grounds; cremations, cremation grounds and electric crematoriums
6	Public health, sanitation conservancy & solid waste management		
7	Fire services	15	Cattle pounds; prevention of cruelty to animals
8	Urban forestry, protection of the environmentand promotion of ecological aspects	16	Vital statistics including registration of births and deaths
9	Safeguarding the interests of weaker sections of society, including the handicapped and mentally retarded	17	Public amenities including street lighting, parking lots, bus stops & public conveniences
10	Slum improvement and up-gradation	18	Regulation of slaughter houses and tanneries

2.5.2.1. XIIth Schedule

The various functions entrusted to local self-governments are listed in Table 2-8 and include the following items pertaining to the design, construction and maintenance of a sustainable urban built environment; (i) Regulation of land-use and construction and buildings, (ii) Urban forestry, protection of the environment and promotion of ecological aspects, and (iii) Provision of urban amenities and facilities such as parks, gardens, playgrounds.

2.5.3. Urban Development Plan

The ministry of urban development, Government of India has formulated the Urban and Regional Plan development formulation and implementation (URDPFI) guidelines to enable various urban local bodies to discharge their functions listed in XIIth Schedule [137].

Table 2-9 Structure of URDPFI guidelines Source: [137]

Volumes	Chapters	Key Contents
Volume I: Urban & Regional Planning Guidelines		
1	Introduction	Need for Revision of UDPFI Guidelines1996, Recommended planning system for India, overall guiding Sustainable Urban and Regional planning aspects of the guidelines
2	Plan Formulation	Planning Process, Contents of various level of plans
3	Resource Mobilisation	Land assembly, fiscal resource mobilisation, good governance, institutional set-up and key institutional reforms
4	Regional Planning Approach	Aspects of regional planning and classification of region in the Indian context, regional planning approach and its plan implementation
5	Urban Planning Approach	Guidelines for study on location and settlement setting, distribution of land use, city typology, planning for townships.
6	Sustainability Guidelines	Sustainability and aspects of urban development including impact of climate change, environment policies and statuary obligation, planning for disaster management
7	Simplified Planning Techniques	Comprehensively covering data collection techniques, types of survey, analytical techniques, projection techniques, base map & development plan preparation
8	Infrastructure Planning	Introduces the hierarchy of urban development and norms & standards for physical infrastructure, social infrastructure, safety management, commercial activity. Details for transportation planning and provisions for barrier free built environment
9	Simplified Development Promotion Regulations	Lists the simplified urban land use classification and zoning regulations, simplified development promotion regulations for specific land use zones, special requirements
10	General Recommendation	Recommendations to several Ministries, State Governments and Organisations

2.5.3.1. URDPFI

The structure of URDPFI guidelines is illustrated in Table 2-9. One hand the guidelines refer to climatic analysis for the purpose of implementing sustainability guidelines, infrastructure planning and simplified development promotion regulations; while on the other hand they prescribe use of detailed form based codes, involving zoning of the city into different transects based on land use intensity, density, building disposition, building configuration, building function, standards, mixed use and neighborhood.

The URDPFI guidelines specify the requirement of clearance from environmental agencies after verification of Environmental Impact Assessment of projects formulated under various development plans.

2.5.4. Environmental Impact Assessment

Depending on the extent of their impact on environment, industry, infrastructure and construction projects in regional plan area have been brought under the ambit of Environmental Clearance (EC)[93]. Prior EC is required for projects in 39 development sections including the few listed in Table 2-10 .

Table 2-10 List of selected ten out of thirty-nine sectors requiring prior environmental clearance Source: [93]

S.No.	Sector	S.No.	Sector
1	Mining	6	Asbestos
2	Mineral Beneficiation	7	Highways
3	Ports and Harbours	8	Coal Washery
4	Airports	9	Aerial Ropeways
5	(A) Building Construction (B) Townships	10	Nuclear: Power Plants, Fuel Processing Plants & Waste Management Plants

The guidance manual for performing Environmental Impact Assessment of 'Building, Construction, Townships and Area Development' refers the applicants to provisions related to energy conservation method in a section titled 'Alternative Technologies. The applicant is required to apply for GRIHA rating discussed in section 2.5.7.1 or show compliance with the ECBC discussed in section 2.5.6. Environmental clearance of projects in urban settlements with notified development plans is governed by their respective Development Control Regulations.

2.5.5. Building Codes and Standards

Regulations such as, Energy Conservation Building code[23][85]; National Building Code Part XI Approach to Sustainability [14] and GRIHA Certification [92] are already in place to cater the sustainability targets discussed in 2.4.1 i.e. to promote energy conservation in building industry.

2.5.5.1. National Building Code of India

National Building Code provides comprehensive guidelines for all building construction activities carried out across various climate zones of India shown in Figure 2-43. The code has been split into 10 Parts namely I - X. Climatic factors which generally help in deciding the responsive design strategies in buildings to get desirable benefits of lighting and ventilation inside the building are covered in Part VIII.

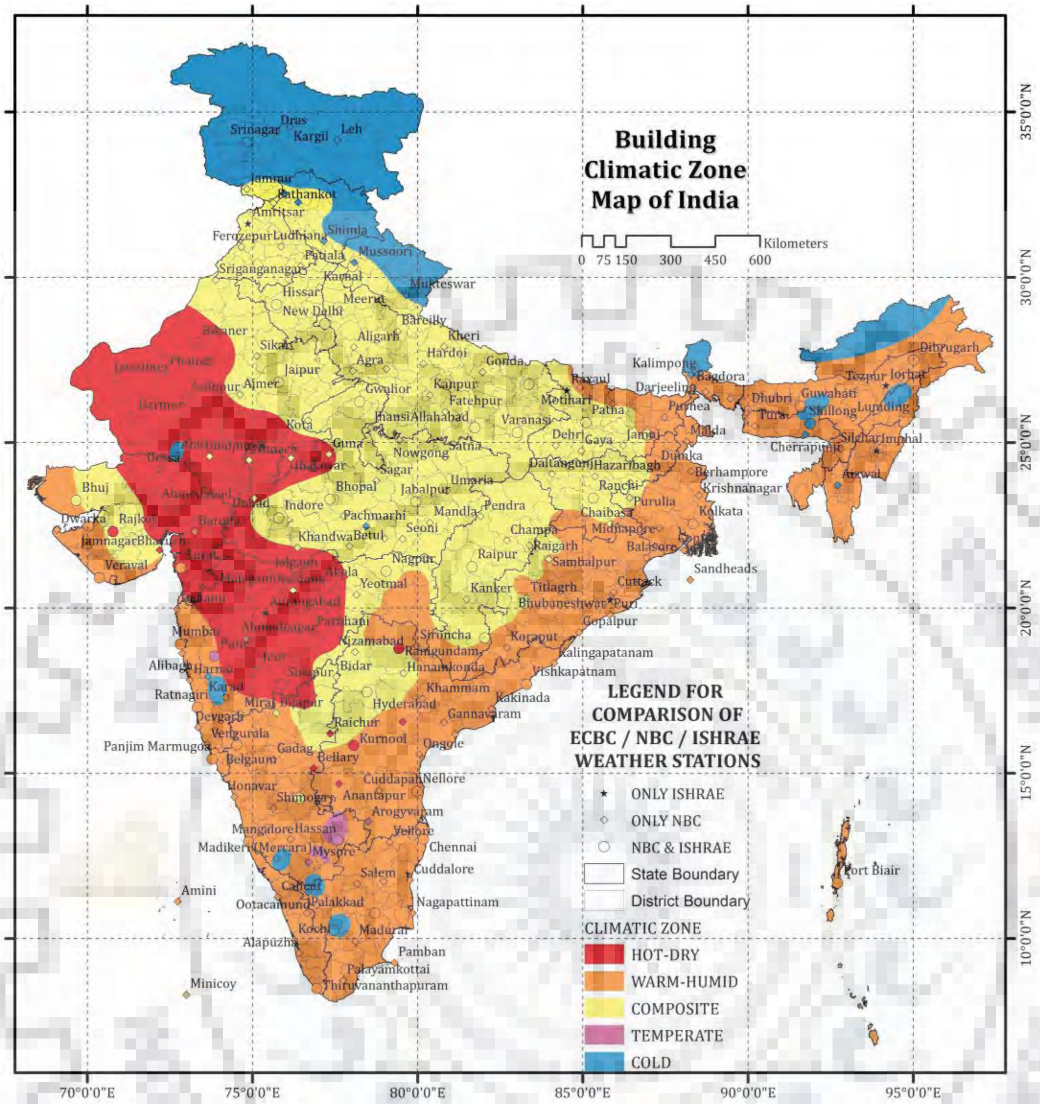


Figure 2-43 Building Climate Zone boundaries superimposed with classified weather stations
(based on: [76] [3])

2.5.5.2. Climate Classification for Building Codes

For specifying regional climate responsive best practices, these codes refer to the Climatic zones for building design developed at CBRI, based on heat flow computations, to communicate zone wise basic design features in buildings. While classifying Building Climate Zone Map of India Figure 2-43, monthly mean maximum air temperature and relative humidity values were compared with human thermal comfort range [3,24].

By analyzing 'mean monthly maximum temperature and relative humidity' data of 225 weather stations, Ali et al. [3] assigned one of the four seasons (viz., 'hot-dry', 'warm-humid', 'temperate' and 'cold') to individual month.

Each station was assigned to a Climate zone named after the season prevalent at that station for 6 or more months. Climate zone boundaries encompassing weather stations with similar climate types differentiate between regions experiencing predominance of a particular mode of heat dissipation and calls for certain specific features in building design. Greater part of India falls under 'Composite' climate type with dominant feature being change in seasons from hot-dry, warm-humid, cold and temperate for varying periods within a year. Ali et al. [3] posited that a building should go beyond its primary objective of sheltering its occupants from harsh weather conditions and the building envelop should be designed to make acceptable habitat. Accordingly they used thermal comfort range of human body compared with monthly mean maximum air temperature and relative humidity values (climate normals) recorded at a given station to classify each month into one of four season's vis. Hot-dry, Warm-humid, Temperate and Cold.

2.5.5.3. NBC Part XI: Approach to Sustainability

The approach to sustainability in Part XI of NBC has been prepared with the objective of using India's ancient wisdom and practices, building in harmony with nature through regional common knowledge, consuming as little as necessary, applying low cost technology innovations, using recycled materials, and recognizing performance (not intent) through easily measurable parameters [14]. The approach was to consolidate from various parts of NBC, the due considerations given to important dimensions of sustainability. Like in building planning, design and construction provisions for effective utilization of natural light and ventilation; in material selection including use of low gestation plantations and agriculture and industrial wastes; recyclability and reusability aspects; design approach; proper management practices; efficient building and plumbing services; energy conservation; rain water harvesting; etc. All these were duly interwoven throughout the Code for addressing both the issues of embodied energy and the operational energy [14].

While aspects of sustainable site planning have been touched upon briefly, NBC part XI refers to the same requirements for building envelope prescribed in ECBC. This code should have ideally recommended climate responsive building design specifications pertaining to the various climatic conditions found across India.

2.5.6. Energy Conservation Building Code

As provided for in the Energy Conservation Act (EC Act) of 2001, Government of India in consultation with the Bureau of Energy Efficiency (BEE) prescribed the Energy Conservation Building Code (ECBC) 2006, with intent to promote efficient use of energy and its conservation in buildings or building complexes [Section 14 (p) ,50]. While ECBC defines norms and standards of energy consumption in terms of per square meter of the area wherein energy is used and includes the location of the building [Section 2 (j) ,50]; the GOI or state government can amend these norms and standards for a particular region or location to suit the regional and local climatic conditions [Section 14(q) & 15(a) ,50].

Like those in the U.S. and Canada, commercial building energy code of India too is derived from the standards produced by the ASHRAE, although specific requirements in each country vary [76]. The ECBC stipulates compliance requirements for Building envelope, HVAC, Service water heating and pumping, Lighting and Electrical power including motors; and takes into account five climate zones of India specified by NBC. The criteria used for classifying Indian climate zones (discussed in section 2.5.5.2) varies significantly from the criteria used by ASHRAE for classifying IECC climate zones (discussed in section 3.2.1.1). It is important to understand how the prescriptive requirements specified under these codes have been regionalized with reference to their respective climate zones.

Apart from the mandatory requirements in each segment, compliance for some of the requirements can be achieved either by Prescriptive method (including envelope trade-off option) or Whole Building Simulation method. Kumar et. al. [76], provide a detailed discussion on the provisions of the Energy Conservation Building Code in the ECBC User Guide. Various compliance requirements pertaining to Building Envelope that were regionalized based on climatic zones have been discussed in the following.

2.5.6.1. Mandatory requirements

As part of mandatory requirements for building envelope, the data and procedure for determining U-factors of opaque construction has been prescribed. Calculation of U-factor and SHGC of glazing and maximum limit of air leakage has been prescribed for *fenestration systems* [76].

2.5.6.2. Prescriptive requirements for Building envelope

Unique requirements for building thermal comfort and architectural responses based on climate profile were compiled for the different climate zones for easy reference [76]. Based on these responses, the minimum specifications for four components of Building envelope including Roofs, Opaque walls, Vertical fenestration and Skylight, prescribed by ECBC have been regionalized for individual climatic zone [76], as described in the following.

2.5.6.2.1. Roof assembly and Opaque wall assembly

The prescribed U-factor and R-value requirements for roof assembly and opaque wall assembly are shown in Table 2-11 and Table 2-12 respectively. Separate values are prescribed for 24-Hour use and Daytime use buildings. For roof assembly in daytime use buildings same values of maximum U factor and minimum R values have been stipulated all climate zones. Whereas for roof assembly in 24 hour use buildings the values of maximum U factor and minimum R values stipulated for moderate climate zone are different from rest of the climate zones.

Table 2-11(4.1 of ECBC) Roof assembly requirements Source:[76]

Climate Zone	24-Hour use buildings Hospitals, Hotels, Call Centers etc.		Daytime use buildings Other Building Types	
	Maximum U-factor of the overall assembly (W/m² ·K)	Minimum R-value of insulation alone (m² ·K/W)	Maximum U-factor of the overall assembly (W/m² ·K)	Minimum R-value of insulation alone (m² ·K/W)
Composite	U-0.261	R-3.5	U-0.409	R-2.1
Hot and Dry	U-0.261	R-3.5	U-0.409	R-2.1
Warm and Humid	U-0.261	R-3.5	U-0.409	R-2.1
Moderate	U-0.409	R-2.1	U-0.409	R-2.1
Cold	U-0.261	R-3.5	U-0.409	R-2.1

Table 2-12 (4.2 of ECBC) Opaque Wall Assembly Requirements Source: [76]

Climate Zone	Hospitals, Hotels, Call Centers (24-Hour)		Other Building Types (Daytime)	
	Maximum U-factor of the overall assembly (W/m² ·K)	Minimum R-value of insulation alone (m² ·K/W)	Maximum U-factor of the overall assembly (W/m² ·K)	Minimum R-value of insulation alone (m² ·K/W)
Composite	U-0.440	R-2.10	U-0.440	R-2.10
Hot and Dry	U-0.440	R-2.10	U-0.440	R-2.10
Warm and Humid	U-0.440	R-2.10	U-0.440	R-2.10
Moderate	U-0.440	R-2.10	U-0.440	R-2.10
Cold	U-0.369	R-2.20	U-0.352	R-2.35

For wall assembly in daytime use as well as 24 hour use buildings respectively the values of maximum U factor and minimum R values stipulated for cold climate are different from the typical values stipulated for rest of the climate zones.

2.5.6.2.2. Vertical Fenestration

The prescribed U-factor and maximum SHGC requirements for vertical fenestration are shown in Table 2-13 with separate SHGC values prescribed for WWR ≤ 40% and 40% < WWR ≤ 60%. As can be observed only two classes of Wall Window Ratios have been acknowledged for all climatic zones irrespective of the need for air movement experienced in climatic zones with overheating stress (or protection from heat loss required in zones with under heating stress).

Table 2-13 (4.3 of ECBC) Vertical Fenestration requirements Source:[76]

		WWR≤40%	40% <WWR≤60%
Climate	Maximum U-factor	Maximum SHGC	Maximum SHGC
Composite	3.30	0.25	0.20
Hot and Dry	3.30	0.25	0.20
Warm and Humid	3.30	0.25	0.20
Moderate	6.90	0.40	0.30
Cold	3.30	0.51	0.51

The maximum U-factor value stipulated for vertical fenestration in Moderate Climate zone is less stringent than the typical value stipulated for rest of the climate zones. The typical maximum SHGC values stipulated for both categories of WWR in Cold climate are least stringent as compared to other climate zones. The maximum SHGC values stipulated for Moderate climates in case of the two WWR categories is less that the value stipulated for Cold Climate but more that the respective typical values stipulated of other three climate zones. The SHGC "M" factor adjustments that may be integrated with the fenestration U-factor in case of inclusion of overhangs and / or fins in design case are shown in Table 2-14. These adjustments have been customized with respect to orientation of the opening as well as location of the project to the North or South of 15° North latitude.

The minimum VLT values stipulated for various window wall ratios have also been prescribed in Table 2-15. As the WWR increases in four stages from 0.3 to 0.6 the stipulated minimum VLT value decreases from 0.27 to 0.13

'M' factor of ECBC 2007 is now refined and renamed in ECBC 2017 as 'Shading Efficiency Factor' SEF and needs to be calculated using the following equation:

$$SEF = (C_3 \times PF^3) + (C_2 \times PF^2) + (C_1 \times PF) + C_0$$

Where,

$0.25 \leq PF \geq 1.0$, and, C3, C2, C1 and C0 are the coefficients listed in Table 2-14

Table 2-14 Coefficients of Shading Equivalent Factors for Overhangs and Fins Source:[163]

for Latitudes greater than or equal to 15 °N

	Overhang + Fin				*Overhang*				*Fin**			
Coefficients	C3	C2	C1	C0	C3	C2	C1	C0	C3	C2	C1	C0
North	-0.03	-0.23	1.09	0.99	-0.02	-0.10	0.43	0.99	0.14	-0.39	0.62	0.99
East	4.49	-6.35	4.70	0.52	-0.05	0.42	0.66	1.02	0.12	-0.35	0.57	0.99
South	-4.09	8.14	-0.73	1.32	-1.01	1.91	0.24	1.12	0.53	-1.35	1.48	0.88
West	-1.21	3.92	-0.56	1.28	1.52	-2.51	2.30	0.76	0.02	-0.15	0.46	1.01
North-East	-0.95	1.50	0.84	1.18	2.19	-3.78	2.62	0.72	-1.64	3.07	-1.05	1.30
South-East	2.67	-4.99	5.68	0.32	-0.93	1.37	0.76	0.99	0.68	-1.47	1.35	0.88
South-West	-0.50	1.36	2.45	0.73	-3.23	5.61	-1.56	1.32	1.86	-3.81	2.71	0.69
North-West	-6.85	11.7	-3.92	1.89	-0.22	0.19	0.74	1.01	-2.02	2.63	-0.18	1.14

for Latitudes less than 15 °N

	Overhang + Fin				*Overhang*				*Fin**			
Coefficients	C3	C2	C1	C0	C3	C2	C1	C0	C3	C2	C1	C0
North	-0.09	-0.29	1.41	1.05	-0.05	-0.10	0.54	1.02	0.10	-0.40	0.77	1.01
East	-0.55	0.89	1.28	0.97	-0.62	0.88	0.51	1.02	0.15	-0.41	0.56	0.98
South	-4.09	6.98	-1.92	1.41	-2.49	4.89	-2.45	1.43	1.57	-3.35	2.62	0.59
West	-1.99	3.82	-0.19	1.18	-0.16	0.10	0.89	0.97	0.06	-0.22	0.48	0.99
North-East	-1.73	3.45	-0.02	1.23	0.10	-0.55	1.15	0.92	-0.26	0.30	0.48	1.02
South-East	-2.06	4.32	-0.96	1.41	-0.60	0.90	0.37	0.94	0.83	-1.42	1.22	0.92
South-West	-2.06	4.48	-1.13	1.40	-0.39	0.50	0.60	0.87	1.56	-3.17	2.41	0.73
North-West	-0.53	0.72	1.79	0.93	0.10	-0.38	0.96	0.96	0.24	-0.57	0.90	0.97

* Coefficients are for side fins on both sides of fenestration. For side fins on only one side, divide the coefficients mentioned in this table by 2.

Table 2-15 (4.5 of ECBC) Minimum VLT Requirements Source:[76]

Window Wall Ratio	Minimum VLT
0 - 0.3	0.27
0.31-0.4	0.20
0.41-0.5	0.16
0.51-0.6	0.13

2.5.6.2.3. Skylights

The maximum U-factor values and SHGC values prescribed for skylights in various climatic zones are shown in Table 2-16. Separate U-factor values have been prescribed for skylights with curb and without curb. Also separate SHGC values have been prescribed for with SRR between 0 -2 % and 2.1- 5%. Extreme climatic conditions exist where exposure to sky even to the extent of 5% may not be practicable; these conditions cannot be identified from the current climatic zone classification criteria. Distinct typical values of maximum U-factor have been stipulated in all climate zones for skylights with curb and without curb respectively.

Table 2-16 (4.6 of ECBC) Skylight U-Factor and SHGC Requirements Source:[76]

	Maximum U-factor		Maximum SHGC	
Climate	With Curb	w/o Curb	0-2% SRR	2.1-5% SRR
Composite	11.24	7.71	0.40	0.25
Hot and Dry	11.24	7.71	0.40	0.25
Warm and Humid	11.24	7.71	0.40	0.25
Moderate	11.24	7.71	0.61	0.4
Cold	11.24	7.71	0.61	0.4

2.5.6.3. Whole Building Simulation

Whole building simulation analysis is carried out by testing thermal response and estimated energy consumption, in case of selected envelope configuration called *Proposed design;* against those in case of implementing the *Standard design* prescribed as per ECBC requirements. One of the primary datasets for energy simulation in this analysis is the reference climate data file called 'Typical Weather file" for the location being tested or its prescribed equivalent [76].

2.5.6.3.1. Typical Weather File

Table 13.2 in Appendix E of 'ECBC user guide' lists the climate zones of 58 major Indian cites for which typical weather files have also been developed by ISHRAE [61]. Weather data from most of these cities were used in the climatic classification of India [3]. These classified weather station points have been superimposed on the Climatic zone map of India shown in Figure 2-43. For the purpose of regionalizing climate based prescriptions, the climatic zone map was digitized by ECBC [76] based on NBC [3,24]. As may be seen some of the station points (circles) classified to a particular zone are not encompassed within the polygon boundary corresponding to their zone. A list of weather stations with climatic zones assigned as per NBC and ECBC is presented in Table 2-17, mismatch in the zone assignment as per the two publications are highlighted. Identification of the climate zones applicable to cities not listed in the ECBC User Guide seems not only difficult but also error prone, due to subjectivity existing in the delineation of zone boundaries between classified weather stations.

Table 2-17 Issues in implementing ECBC recommendations as per Weather File and Climatic Zones (also compared with NBC)

Weather Station	Latitude °N	Longitude °E	Cliamtic Zone As / NBC	Cliamtic Zone As / ECBC
Abu	24.60	72.72	CO	CZNA
Ahmedabad	23.07	72.63	HD	HD
Akola	20.70	77.03	HD	CZNA
Allahabad	25.45	81.73	CM	CM
Amritsar	31.63	74.87	CZNA	CM
Aurangabad	19.85	75.40	CZNA	HD
Bangaluru	12.97	77.58	TM	TM
Barmer	25.75	71.38	HD	HD
Belgaum	15.85	74.53	WH	WH
Bhagalpur	25.23	86.95	CM	WH
Bhopal	23.28	77.35	CM	CM
Bhubaneshwar	20.25	85.83	CZNA	WH
Bhuj	23.25	69.67	CM	CZNA
Bikaner	28.00	73.30	HD	HD
Chennai	13.00	80.18	WH	WH
Chitradurga	14.23	76.43	CM	WH
Dehradun	30.32	78.03	CM	CM
Dibrugarh	27.48	95.02	WH	WH
Gorakhpur	26.75	83.37	CM	CM
Guwahati	26.10	91.58	WH	CO
Gwalior	26.23	78.25	CM	CM
Hissar	29.17	75.73	CM	CM
Hyderabad	17.45	78.47	CM	CM
Imphal	24.77	93.90	CZNA	WH
Indore	22.72	75.80	CM	CM
Jabalpur	23.20	79.95	CM	CM
Jagdalpur	19.08	82.03	CM	WH
Jaipur	26.82	75.80	CM	CM
Jaisalmer	26.90	70.92	HD	HD
Jamnagar	22.47	70.05	WH	WH
Jodhpur	26.30	73.02	HD	HD
Jorhat	26.73	94.17	CZNA	WH
Kodaikanal	10.23	77.47	CO	CZNA
Kolkata	22.53	88.33	WH	WH
Kota	25.15	75.85	HD	HD

Weather Station	Latitude °N	Longitude °E	Cliamtic Zone As / NBC	Cliamtic Zone As / ECBC
Kurnool	15.83	78.07	HD	WH
Lucknow	26.75	80.88	CM	CM
Mangalore	12.92	74.88	WH	WH
Mumbai	15.42	73.78	WH	WH
Nagpur	18.90	72.82	CM	CM
Nellore	21.10	79.05	WH	WH
New Delhi	14.45	79.98	CM	CM
Panjim Marmugo	28.58	77.20	WH	WH
Patna	25.60	85.10	CM	CM
Port Biair	11.67	92.72	WH	CZNA
Pune	18.53	73.85	TM	WH
Raipur	21.23	81.65	CM	CM
Rajkot	22.30	70.78	HD	CM
Ramgundam	18.77	79.43	HD	WH
Ranchi	23.32	85.32	CM	CM
Ratnagiri	16.98	73.33	WH	WH
Raxaul	26.58	84.52	CZNA	WH
Roorkee Saharanpu	29.85	77.88	CM	CM
Shillong	25.57	91.88	CO	WH
Solapur	17.67	75.90	HD	HD
Srinagar	34.08	74.83	CO	CZNA
SunderNagar	31.53	76.88	WFNA	CO
Surat	21.20	72.83	WH	HD
Tezpur	26.62	92.78	WH	WH
Thiruvananthapur	8.48	76.95	WH	WH
Tiruchirapalli	10.77	78.72	WH	WH
Tuticorin	8.76	78.13	WFNA	WH
Varanasi	25.30	83.02	CM	CZNA
Veraval	20.90	70.37	WH	WH
Vishkapatnam	17.68	83.30	WH	WH

Note:
CZNA - Climatic Zone Not Available
WFNA - Weather File Not Available
Issue Highlight
CO - Cold
HD - Hot and Dry
WH - Warm & Humid
TM - Temperate
CM - Composite

2.5.6.4. Status of implementation

Presently, ECBC is in voluntary phase of implementation. State governments have the flexibility to modify the code to suit local or regional needs and notify them. About 22 states are at various stages of mandating ECBC as shown in Table 2-18 [23]

Table 2-18 State wise status of activities for the implementation of ECBC Source: [23]

S.No.	Status of Activities	Name of States/UTs
1	Notification Issued	Rajasthan, Odisha, Uttrakhand, Punjab, Karnataka, Andhra Pradesh and UT of Puducherry
2	Amended ECBC to suit their local and regional climatic condition	Uttar Pradesh, Kerala, Chhattisgarh, Gujarat, Bihar, Tamil Nadu, Haryana, Maharashtra and West Bengal
3	In process of amendment	Himachal Pradesh, Assam, Tripura, Mizoram, Jharkhand, Goa and Madhya Pradesh

2.5.7. Green Rating Systems

Apart from the ECBC, various private and government organizations have initiated energy and environmental assessment and rating systems [75] [53] [92] [52].

Leadership in Energy and Environmental Design (LEED) managed in India by the Indian Green Building Council (IGBC) promotes a whole-building approach to sustainability by addressing performance in the following five areas: (1) sustainable site development, (2) water savings, (3) energy efficiency, (4) materials selection and (5) indoor environmental quality. The LEED rating system largely focuses on air-conditioned buildings.

2.5.7.1. GRIHA

Green Rating for Integrated Habitat Assessment (GRIHA) was developed by The Energy and Resources Institute (TERI) for assessing non-air-conditioned, new commercial, institutional and residential buildings. This rating System contains 34 evaluation criteria with 100 points. These criteria have been categorized into following groups:

(i) Site Planning includes conservation and efficient utilization of resources, health and wellbeing during building planning and construction stage.

(ii) Water Conservation

(iii) Energy Efficiency includes embodied & construction energy and renewable energy

(iv) Waste Management including waste minimization, segregation, storage, disposal and recovery of energy from waste and

(v) Environment for good health and wellbeing.

Additional criteria for innovative developments such as alternative transportation, environmental education, enhanced accessibility for physically / mentally challenged are also awarded points.

GRIHA consisting of some core points, which are mandatory to be met while the rest are optional point that can be earned by complying with the commitment of the criterion for which the point is allocated. Different levels of rating (one star to five stars) are awarded based on the number of points earned. The minimum points required for rating is 50. Buildings scoring 50 - 60 points, 61 – 70 points, 71 - 80 and 81 –

90 points will get one star, two stars, three stars, and four stars, respectively. A building scoring 91 - 100 points will receive the maximum rating, which are five stars.

To achieve any GRIHA rating it is mandatory to fulfill a criteria requiring optimization of building design to reduce conventional energy demand which can earn maximum 6 points. Whereas additionally up to 12 optional points can be earned for optimizing energy performance of building within specified comfort [92].

While GRIHA is applicable to buildings / projects with built-up area more than 2500 sq.m.; SVAGRIHA is a guidance-cum-rating system developed for small stand alone buildings with a cumulative built-up area of 2500 sq.m. or less. Residences, commercial offices, motels, dispensaries, schools etc. may be assessed under SVAGRIHA [53].

GRIHA LD is a framework created to assess the environmental performance of larger developments, with total site area greater than or equal to 50 hectares that form the singular units which together make up cities – neighborhood/townships [52].

Urban local bodies have started conscious effort towards promoting sustainable development and wise use of natural resources by adopting GRIHA as part of their development control regulations [114].

2.5.8. Development Control Regulations

Development Control Regulations also known as Building Bye-Laws are legal tools used to regulate various aspects of buildings so as to achieve orderly development of an area. They serve to protect buildings against fire, earthquake, noise, structural failures and other hazards by regulating their coverage, height, building bulk, and architectural design and construction. The Town and Country Planning Organization (TCPO) had prepared "Model Building Bye-Laws- 2004" for the guidance of the State Governments, Urban Local Bodies, Urban Development Authorities, etc., where the regulatory mechanism is absent [139].

2.5.8.1. Model Building Bye-Laws by TCPO

Model Building Bye-Laws were revised and updated in view of emerging issues, including resilience to climate change [140]. Environmental clearance has been integrated into the

Model Building Bye-laws with various provisions being made mandatory depending upon the category of project listed in Table 2-19 .

Table 2-19 Categories of buildings for environmental clearance

SN.	Conditions for	Built-up Area
1)	Category 'A' Buildings	5000 sqmt – 20000 sqmt
2)	Category 'B' Buildings	20000 sqmt – 50000 sqmt
3)	Category 'C' Buildings	50000 sqmt – 150000 sqmt

As per provisions of model building bye-laws buildings under category 'C' need to satisfy the following conditions related to energy efficiency for procuring environmental clearance [140]:

Use the concept of passive solar design of buildings. Architectural design approach should be to minimize energy consumption in buildings by integrating passive design elements, such as building orientation, landscaping, efficient building envelope, appropriate fenestration, increased day lighting design and thermal mass with the conventional energy-efficient devices, such as mechanical and electric pumps, fans, lighting fixtures and other equipment.

The concept of passive solar design is deeply rooted in the use of natural resources for achieving thermal comfort in buildings. This signifies the necessity to regionalize building bye-laws as per the various geographical regions where existence of natural resources varies, resulting in various climates and thermal stresses.

2.5.8.2. Standardized DCR for Municipal Councils in Maharashtra State

Though there is an emphasis on regionalized building byelaws at National level, recently standardized development control regulations (SDCR) were adopted at State level in Maharashtra [150][151]. This disparity in emphasis may be attributed to inadequate understanding about the significant variation in climatic stresses across the state or its warranting variation in responsive design strategies.

The 254 urban local bodies of Maharashtra (230 covered under SDCR) are assigned to one of four climatic zones (see Figure 2-43) but as compared with Figure 2-44 the assigned climatic zones do not share any resemblance to the administrative divisions of Maharashtra which are based on geographic regions (see Figure 1-1).

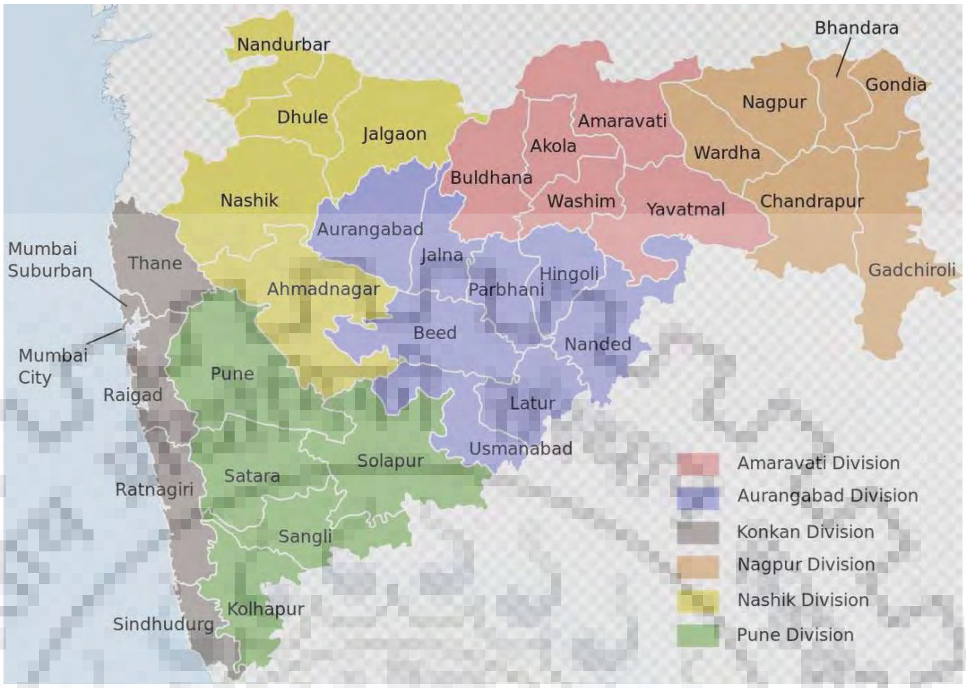


Figure 2-44 Maharashtra administrative divisions **Source:**[51]

2.6. Summary

Different kinds of climatic data are required in the climatic analyses for planning various human activities ranging from agriculture to architectural design. Climate data is continuously collected at several meteorological stations across India. Individual cities for which climatic data is unavailable generally use data from nearby city where it is available. At present the population of India is growing in small and large urban agglomerations located sporadically across various geographical regions. Environmental stresses in these cities are bound to increase due to urbanization, unless formulation of building legislation in each city is informed by appropriate passive design strategies identified based on prevailing climatic stresses.

As discussed in section 2.4.4.3 passive design strategies need to be identified based on regional climatic conditions, to inform building legislation, especially Development Control & Promotion Regulations (DC&PR) for implementation by Local self-governments concurrently with the state governments [111]. Municipal corporations can notify and modify the DC&PR applicable in their jurisdiction in consultation with Town and Country Planning Organization and state government, based on recommended climate responsive design specifications [138]. Similarly state governments can notify new or modification in existing Standardised DCPRs of smaller towns and regional plan areas for incorporating such recommendations [148][149].

The building legislations rely upon the Building Climate Zone Map of India [3,24] for regionalizing the energy conservation measures applicable in each zone. Few gaps have been identified in the existing Climatic Classification for Building Design in India [113].

1. The Climate Zone Map does not help in arriving at climate responsive design recommendations.
2. The map does not benefit from the best available interpolated climatic datasets. Implementation of appropriate energy conservation measures depends on the identification of correct climate zones and the availability of appropriate weather file.
3. The map needs to be redrawn considering 'adaptive comfort range' which varies with residents at various geographical regions acclimatized to various annual mean temperatures, as shown by Bedford [10,40,62].
4. Delineation of simplified zone boundaries between the few classified weather stations seems to be based on intuitive knowledge of macro level geographical regions. Incorrect identified climate zone leads to implementation of incorrect energy conservation measure; while use of inappropriate weather files lead to incorrect estimation of energy consumption.

The map does inform building codes and standards about the type and duration of prevailing thermal stress but does not expressly help architects in selection of thermal comfort design strategies. Variations are observed within the delineated building climate zones due to geographical peculiarities [129] [34].

Interpolated climate data like the one used for development of Agro-ecological zones may be useful for developing climate zones based on building design criteria. The background literature reviewed in this chapter helps in establishing the inter relation between various domains and developing the reasoning for selecting components of the analytical framework discussed in Chapter Four. The component parts namely, modeling approaches, tools and techniques for climatic data analyses for building design available from literature will be discussed in Chapter Three.

CHAPTER 3. MODELING : APPROACH AND TECHNIQUES

3.1. General

This chapter starts with a discussion on various climatic classification criteria for building design prevalent in different countries. It then deals with state of the art in climate modeling, and explores multi-level strategies of interpolation based on physical basis of climate variation. Methodologies pertaining to application of climatography to urban design and sustainable built environment have been reviewed in detail. Several case studies relevant to selection of an appropriate approach to climate study for responsive built-environment are dealt in this chapter, along with their inherent techniques. A later section in this chapter is dedicated to an important tool called geographical information system which has been used extensively for climatic data collection, collation & analysis.

3.2. Climate Classification for Architecture

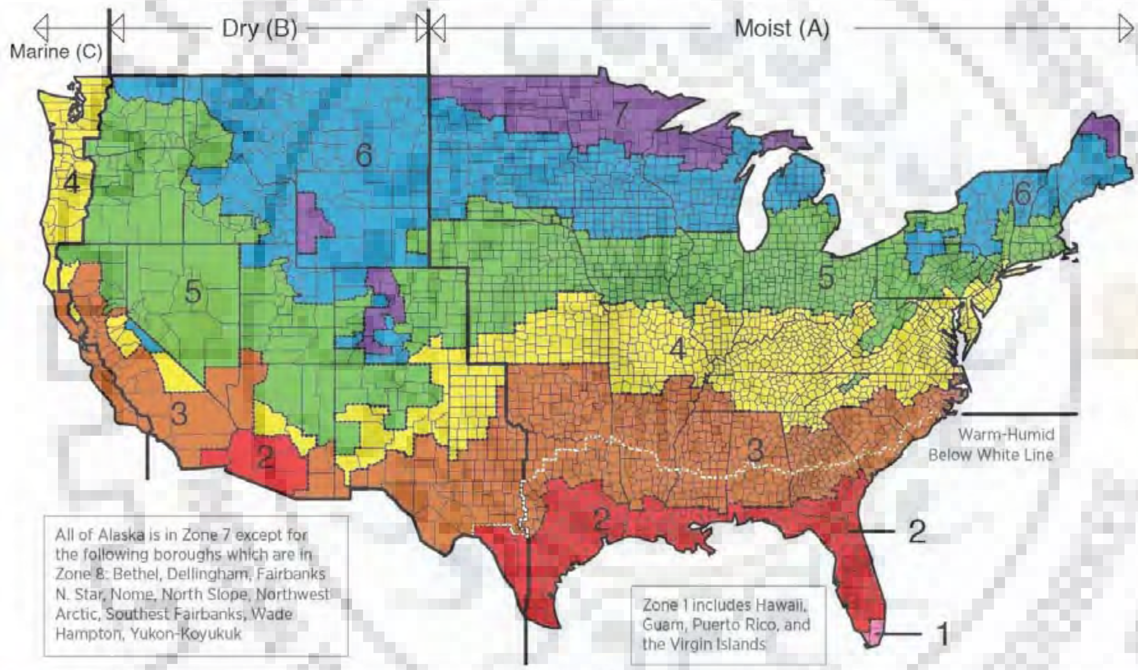
Activities involved in the design process are classified by various model proponents in different ways. One may accept the broad categorization of these activities into three types namely analysis, synthesis and evaluation. Analytical work which precedes the formulation of a design solution (analysis phase) is described as forward analysis; as opposed to the analytical work applied to a design hypothesis (evaluation phase) is described as backward analysis. As discussed in section 2.4.4.3 the type of climate class assigned to a location may inform design decisions at two stages namely: forward analysis and backward analysis. The criteria for climatic classification for building design used worldwide are based on either of these stages of analysis.

3.2.1. Backward Analysis Criteria

In the backward analysis stage the proposed design solution (hypothesis) is suitably represented as a model and its performance is evaluated (tested) against relevant criteria. In case the design under performs in certain aspects the need for design modification pertaining to that aspect is identified. As described in section 2.5.6 the Energy Conservation Building Code of India stipulates energy conservation requirements of various components of the building envelope with reference to the climatic classification discussed in section 2.5.5.2. This criterion does not directly relate to performance of the building like the backward analysis criteria discussed in the following.

3.2.1.1. Building energy climate classification in America

The climatic region map of USA has been classified into 8 zones for supporting implementation of energy conservation codes and standards based on the criteria of heating degree days and cooling degree days [17]. As seen from Figure 3-1 some of the 8 climate zones have been divided into sub-types namely marine, dry or moist based on listed climatic criteria. Energy conservation requirements for each zone have been specified for various building element listed in Table 3-1. The list includes specifications for heat loss coefficients for fenestration & skylight; heat gain coefficient for glazed fenestration; and thermal resistance of ceiling, various types of walls and floors.



Climate Zone	Name (sub-type)	Thermal Criteria
= 1	Very Hot-Humid (1A) Very Hot-Dry (1B)	5000 < CDD10°C
= 2	Hot-Humid (2A) Hot-Dry (2B)	3500 < CDD10°C ≤ 5000
= 3	Warm-Humid (3A) Warm-Dry (3B)	2500 < CDD10°C < 3500
= 3	Warm-Marine (3C)	CDD10°C ≤ 2500 & HDD18°C ≤ 2000
= 4	Mixed-Humid (4A) Mixed-Dry (4B)	CDD10°C ≤ 2500 & HDD18°C ≤ 3000
= 4	Mixed-Marine (4C)	2000 < HDD18°C ≤ 3000
= 5	Cool-Humid (5A) Cool-Dry (5B) Cool-Marine (5C)	3000 < HDD18°C ≤ 4000
= 6	Cold-Humid (6A) Cold-HDry (6B)	4000 < HDD18°C ≤ 5000
= 7	Very Cold	5000 < HDD18°C ≤ 7000
= 8	Subarctic	7000 < HDD18°C

Marine (C) definition –
Locations meeting all 4 criteria below:
1. Mean temperature of coldest month between -3°C and 18°C
2. Warmest month mean < 22°C
3. At least four months with mean temperatures over 10°C
4. Dry season in summer. The month with the heaviest precipitation in the cold season has at least three times as much precipitation as the month with the least precipitation in the rest of the year. *The cold season is October through March in the Northern Hemisphere and April through September in the Southern Hemisphere.*

Dry (B) definition –
Locations meeting the following criteria:
Not Marine and $P < 2.0 \times (T + 7)$

Where: P = annual precipitation in inches (cm)
and T = annual mean temperature in °C.

Moist (A) definition –
Locations that are **not marine** and **not dry**.

Figure 3-1 International Energy Conservation Code (IECC) climate regions Source: [17]

Table 3-1 Insulation and fenestration requirements by component [a] in IECC climate zones Source: [116]

CLIMATE ZONE	FENESTRATION U-FACTOR[b]	SKYLIGHT[b] U-FACTOR	GLAZED FENESTRATION[b,e] SHGC	CEILING R-VALUE	WOOD FRAME WALL R-VALUE	MASS WALL R-VALUE[i]	FLOOR R-VALUE	BASEMENT[c] WALL R-VALUE	SLAB[d] R-VALUE & DEPTH	CRAWL SPACE[c] WALL R-VALUE
1	1.20	0.75	0.30	30	13	3 / 4	13	0	0	0
2	0.65[j]	0.75	0.30	30	13	4 / 6	13	0	0	0
3	0.50[j]	0.65	0.30	30	13	5 / 8	19	5 / 13[f]	0	5 / 13
4 except Marine	0.35	0.60	NR	38	13	5 / 10	19	10 / 13	10, 2ft	10 / 13
5 and Marine 4	0.35	0.60	NR	38	20 or 13+5[h]	13 / 17	30[g]	10 / 13	10, 2 ft	10 / 13
6	0.35	0.60	NR	49	20 or 13+5[h]	15 / 19	30[g]	15 / 19	10, 4 ft	10 / 13
7 and 8	0.35	0.60	NR	49	21	19 / 21	38[g]	15 / 19	10, 4 ft	10 / 13

a. R-values are minimums, U-factors and SHGC are maximums, R-19 batts compressed into a nominal 2 x 6 framing cavity such that the R-value is reduced by R-1 or more shall be marked with the compressed batt R-value in addition to the full thickness R-value.

b. The fenestration U-factor column excludes skylights. The SHGC column applies to all glazed fenestration.

c. "15/19" means R-15 continuous insulated sheathing on the interior or exterior of the home or R-19 cavity insulation at the interior of the basement wall. "15/19" shall be permitted to be met with R-13 cavity insulation on the interior of the basement wall plus R-5 continuous insulated sheathing on the interior or exterior of the home. "10/13" means R-10 continuous insulated sheathing on the interior or exterior of the home or R-13 cavity insulation at the interior of the basement wall.

d. R-5 shall be added to the required slab edge R-values for heated slabs. Insulation depth shall be the depth of the footing or 2 feet, whichever is less in Zones 1 through 3 for heated slabs.

e. There are no SHGC requirements in the Marine Zone.

f. Basement wall insulation is not required in warm-humid locations as defined by Figure 301.1 [116] and Table 301.1 of [116].

g. Or insulation sufficient to fill the framing cavity, R-19 minimum.

h. "13+5" means R-13 cavity insulation plus R-5 insulated sheathing. If structural sheathing covers 25 percent or less of the exterior, insulating sheathing is not required where structural sheathing is used. If structural sheathing covers more than 25 percent of exterior, structural sheathing shall be supplemented with insulated sheathing of at least R-2.

i. The second R-value applies when more than half the insulation is on the interior of the mass wall.

j. For impact rated fenestration complying with Section R301.2.1.2 of the IRC or Section 1608.1.2 of the IBC, maximum U-factor shall be 0.75 in Zone 2 and 0.65 in Zone 3.

For SI: 1 foot = 304.8 mm | U-value measured in (Btu/h·ft^2·°F) | R-factor measured in (h·ft^2·°F/Btu)

This table specifies values for building thermal envelope elements of air conditioned residential buildings. Thermal transmittance value specified for fenestration and skylight goes on increasing from warm (3) to hot (2) and very hot (1) climate zones, whereas it is on the lower side and constant in rest of the (4-8) climate zones. Similarly Solar Heat Gain Coefficient of 0.3 is specified only in the warm, hot and very hot zones. On the contrary the specification for thermal resistance goes on increasing from warmer climates to cooler climates. The most variable specification of thermal resistance is for Mass wall.

Data from one weather station representing each administrative unit called county has been used in the classification and the whole county is classified under one climate zone. This method was too general for areas with high climatic variability like California State.

3.2.1.2. California Climate Zones

California has the most diverse set of climatic conditions of any state in the U.S., and perhaps of any other administrative region of its size anywhere [58]. The long Pacific coast line experiences a variety of weather conditions due in part to the differences between areas with coastal plains and areas where mountain ranges drop right to the beach. Along these coastal plains the marine influence diminishes as the distance from the ocean and the elevation increase. Portions of the vast interior valley are strongly influenced by marine air, while other portions and other interior valleys are isolated from such tempering influences. The state's many ranges of mountains not only separate climatic regions but form, themselves, another climate [58].

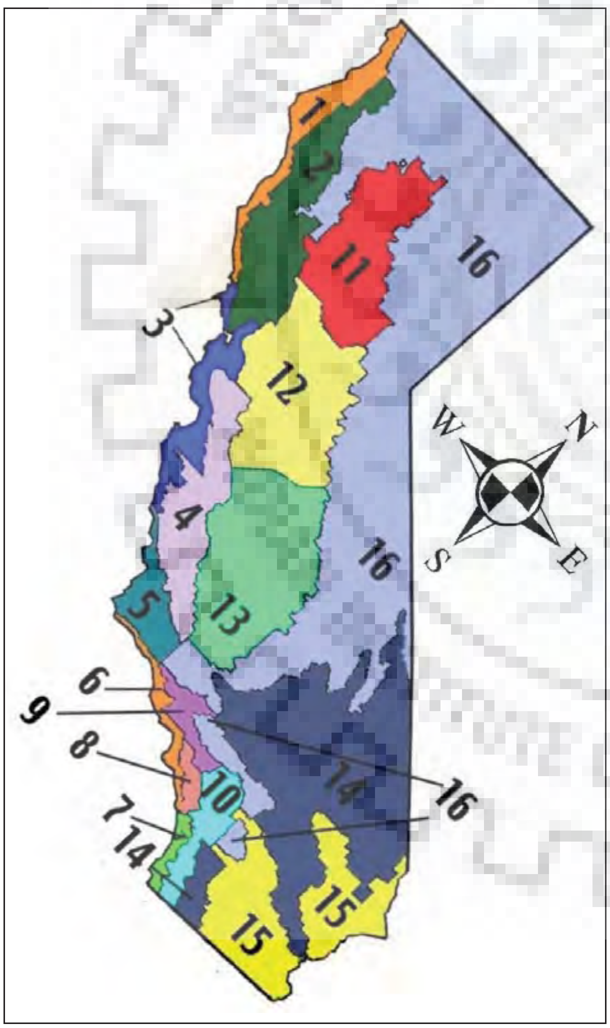


Figure 3-2 California Climate Zones Source: [109]

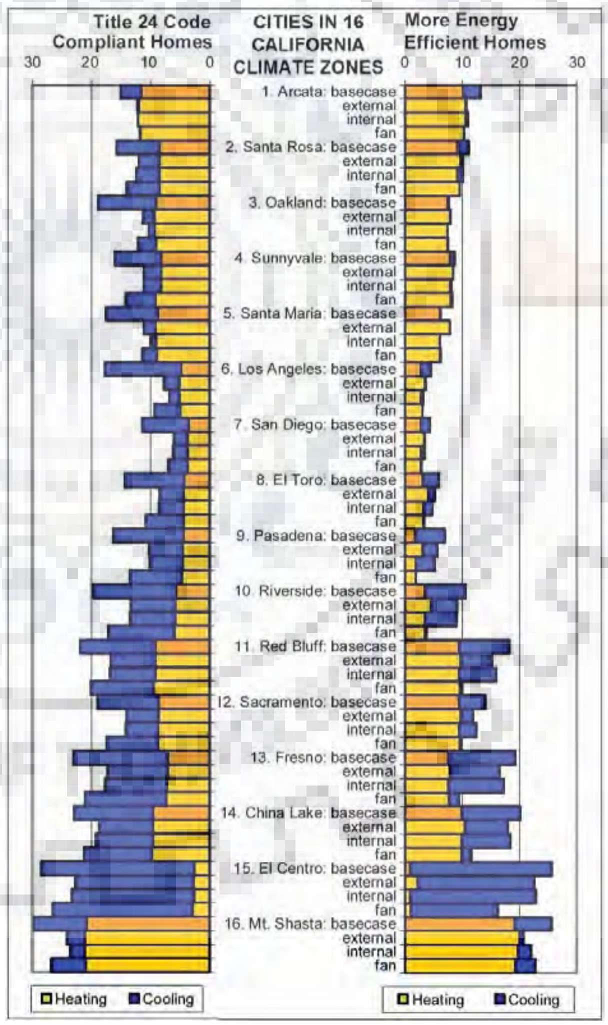


Figure 3-3 Heating and Cooling Loads for a 2000 sq.ft. Homes designed specifically for 16 California Climate Zones (kBTU/sq.ft.year) Source: [90]

California energy commission developed weather data files corresponding to 16 climate zones in the state as shown in Figure 3-2 to support diverse energy performance criteria specified in 'Title 24 building permit ordinance' [25] [109]. Energy consumption resulting from heating load and cooling load estimated in "Title 24 Compliant" and "More Energy Efficient homes" designed specifically for 16 California Climate Zones, has been compared in Figure 3-3. The bars representing heating was well as cooling load are shorter on right hand side as compared to corresponding bars on the left hand side, which proves the effectiveness of additional strategies implemented in "More Energy Efficient" homes [90]. Such detailed investigation can be used to inform the code compliance criteria in each zone. Distinct weather files need to be compiled for each climate zone.

3.2.1.2.1. Weather Files

Different countries have used different methods of compiling weather files from long term meteorological record to represent the most probabilistic climatic conditions at a station[36]. A comparison between different methods used in weather file compilation helps in listing the implications as shown in Table 3-2. When weather files generated for location 'A' are used for simulating performance of buildings at location 'B', the estimated energy usage or hours of overheating etc. may be unrealistic. Appropriate method available for compilation of more realistic weather files has been discussed in 3.3.3.

Table 3-2 Implications of using representative weather files for building simulation **Source:** [36]

Description	Pros	Cons
Only one or two files used (e.g. TRY and DSY)	Simple, allows easy comparison with other buildings.	Can give unrealistic values for energy usage and overheating etc.
Based on previous observations of weather at a location.	Data is realistic, as it has already happened.	Limited data available to create representative files. The files are out of date; files like the DSY no longer represent a near extreme warm year.
Files are compiled from several years of weather.	Files like the TRY are representative of the average weather and climate.	Average files like the TRY ignore natural variation in the weather, no information about the range of variation.
Only a few locations available	Easy to choose which file to use.	Weather at file location is unrepresentative of where building is located.

3.2.2. Forward Analysis Criteria

In the forward analysis stage data are collected, sorted and processed, in order to accumulate and present all the information necessary for the synthesis of a formal solution. Mahoney Tables is one of the methods in forward analysis using which one can prioritize between climate responsive design strategies even in case of conflicting thermal stress across the year. In this method thermal stresses are analyzed separately for day time and night time as well considering significant variation in clothing and activity levels [41]. Three ranges of annual mean temperature and four groups of monthly average humidity are used in this analysis.

Data on thermal stresses and original climatic information define six bioclimatic design indicators namely, Air movement essential, air movement desirable, rain protection necessary, thermal capacity necessary, outdoor sleeping desirable, protection from cold, which help in the selection of elemental design recommendations from outdoor space, building form through to roofs, walls and openings [68] [134] [41].

As will be demonstrated in the next section, following advantages of Mahoney Tables signify its appropriateness for developing bio-climatic zones: Clarity, Speed, Simple Input, Output for design and Elemental recommendations.

Legend		Remedial actions (number of months of the year)					
		H1	H2	H3	A1	A2	A3
Coastal Zone	e(1)	11 - 12	0 - 1	3 - 12	0 - 1	0	0
Forest Zone	e(2)	10	0 - 1	0	2	0	0
Transitional Zone (a)	e(3)	3 - 9	0 - 1	1-2	3 - 5	0	0
Transitional Zone (b)	e(4)	3 - 9	0 - 1	3 - 12	3 - 5	0	0
Highland Zone	e(5)	3 - 9	0 - 1	3 - 12	3 - 5	0	0
Savannah Zone (a)	e(6)	3 - 9	0 - 1	3 - 12	6 - 10	1 - 12	0
Savannah Zone (b)	e(7)	1	2 - 12	3 - 12	6 - 10	0	0
Semi-Desert Zone (a)	e(8)	1	0 - 1	1-2	11 - 12	1 - 12	0
Semi-Desert Zone (b)	e(9)	2	0 - 1	1-2	6 - 10	1 - 12	0

Figure 3-4 Climatic zones for architectural design in Nigeria Source: [102]

3.2.2.1. Architectural climatic zones in Nigeria

Nine 'Architectural climatic zones' were identified in Nigeria based on unique combination of environmental stresses [102]. As seen from Figure 3-4 thirty weather stations located across Nigeria were classified into their respective climate zone based on varying duration of remedial actions warranted by the environmental conditions existing at these stations.

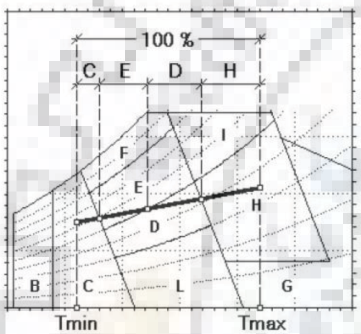
Set Theory was applied to identify the various combinations of architectural responses for each zone based on environmental conditions as shown in Table 3-3. While using such a climate classification, it is difficult to ascertain applicability of identified architectural responses to other cities due to lack of information related to spatial variation in climate between the classified cities.

Table 3-3 Sets of Architecture responses corresponding to environmental circumstances Source: [102]

Possible Architectural Responses			Response to Conditions e(1) to e(9)								
			r(1)	r(2)	r(3)	r(4)	r(5)	r(6)	r(7)	r(8)	r(9)
Layout	A1	Buildings oriented on East-West axis.	●	●	●	●	●	●			●
	A2	Compact courtyard planning.							●	●	
Spacing	B1	Open spacing for breeze penetration	●								
	B2	Open spacing, protect from hot and cold winds.		●	●	●	●	●			
	B3	Compact planning.							●	●	●
Air movement	C1	Rooms single banked, permanent provison for air movement.	●	●	●	●	●	●			
	C2	Double-banked rooms with temporary provision for air movement.							●	●	●
	C3	No air movement required.									
Size of Openings	D1	Large, 40 - 80% of North and South walls.	●								
	D2	Medium, 25 - 40 % of wall area.		●	●	●					
	D3	Composite, 20 - 35% of wall area.					●	●	●		●
	D4	Small, 15 - 25 of wall area.								●	
Positions of Openings	E1	Openings in North and South walls at body height on windward side.	●	●	●	●	●	●			
	E2	Openings in North and South walls at body height on windward side and on internal walls.							●	●	●
	E3	Has no climate-related value.									
Protection of openings	F1	No special protection necessary.									
	F2	Exclude direct sunlight.		●	●		●			●	
	F3	Protect from rain and direct sunlight.	●			●		●	●		●
	F4	Provide protection from rain.									
Walls and floors	G1	Light: low heat capacity.	●	●							
	G2	Heavy: over 8 hours time lag.			●	●	●	●	●	●	●
Roofs	H1	Light: reflective surface and cavity	●	●							
	H2	Light and well insulated.			●	●					
	H3	Heavy: over 8 hours time lag.					●	●	●	●	●
Outdoor sleeping	I1	No space for outdoor sleeping required.	●	●	●	●			●		●
	I2	Space for outdoor sleeping required.					●	●		●	
Rains protection	J1	Adequate drainage for rain water.			●		●			●	
	J2	Protection from heavy rain needed.	●			●		●			●
	J3	No protection from heavy rain needed.		●					●		

3.2.2.2. Brazilian Climate zone map

Roriz et al [125] resolved the problem of climatic information between weather stations by applying grid interpolation technique. They used gridded climatic data of Brazil to delineate 8 bioclimatic zones, based on Givoni and Mahoney tables' criteria as shown in Figure 3-5 [125]. Maxima and minima of monthly climatic parameters were plotted on the adapted bioclimatic chart as shown in Figure 2-27, to determine percentage duration of applicable (adapted) bioclimatic strategies of each zone [125]. However the duration of bioclimatic strategies applicable in each climatic zone do not help to explicitly determine recommended architectural responses.



Zone → / Strategies	Z1	Z2	Z3	Z4	Z5	Z6	Z7	Z8
A	Required	Required						
B			Required	Required				
C					Required	Required		
D			Forbidden		Forbidden			Forbidden
H			Forbidden		Forbidden		Required	
I	Forbidden							
J	Forbidden							
Coverage	_00.8%	_06.4%	_06.5%	_02.0%	_05.6%	_12.6%	_12.6%	_53.7%
City Count	**12**	**33**	**62**	**17**	**30**	**38**	**39**	**99**

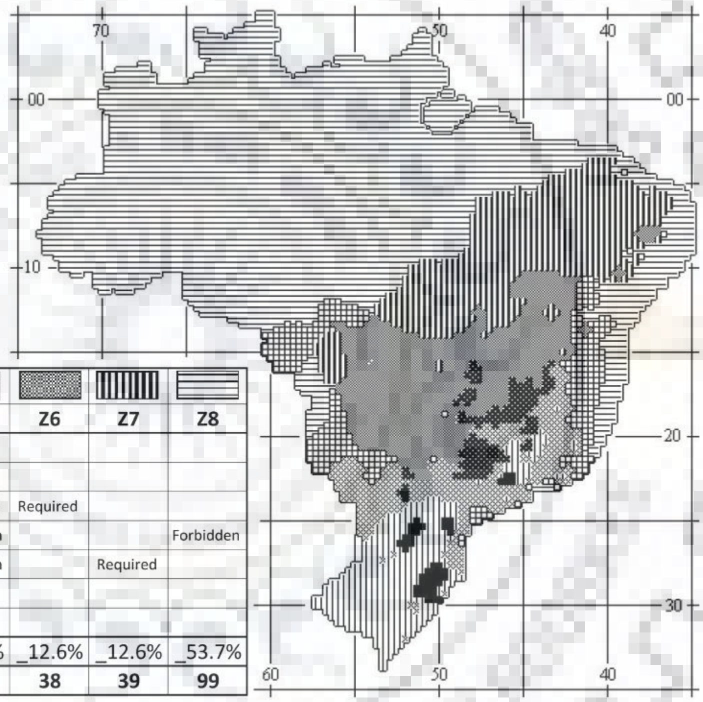


Figure 3-5 Brazilian Bioclimatic Zoning

From above case studies were instrumental in the identification of scope for delineating climate zones explicitly related to building design recommendations, by combining the approach of using gridded climate data, with the approach of identifying extents of thermal stresses warranting unique combinations of architectural responses.

Availability of spatially and temporally interpolated climatic data is crucial for forward and backward analyses instrumental in the development of climate classification criteria for building design, hence state of the art in climatic data modeling will be discussed in the following section.

3.3. Climatic Data Modeling

As discussed in section 2.2.1 using Figure 2-1 The Climate Cube, climate studies may be trifurcated into three levels each from the domains of 'time', 'space' and 'perception'. Most studies in climate data modeling deal with only one level of detail in space, time and perception [87]. Studies initiated to assess climates over the entire land surface of the world (space) spatially interpolate historic climatic normals synthesized (perception) from 30 years of weather station data (time) collected in a Global Climate Network [59] [115]. Studies initiated to assess thermal stresses in urban environments (perception) cover entire neighborhoods (scale) and predict thermal stresses in afternoon of the hottest season (time) [43][88].

Few studies though have modeled climatic data across two levels of time/perception while maintaining the level of detail in the domain of space. Algorithms have been developed to estimate hourly (time/perception 1) temperature and humidity values for any location of the earth (space) based on monthly means climatic normals synthesized from 30 years of data (time/perception 2) [124]. Recently a model has been developed for predicting heat wave formation (time/perception 1) through the summer months (time/perception 2) across various land use types of an urban agglomeration (space) [123]. For discussion the aforementioned case studies have been framed on the basis of spatial and temporal interpolation in the following.

3.3.1. Spatial Interpolation of Data

Spatially interpolated climate data on grids, generally referred to as 'climate surfaces', are used in many applications, particularly in environmental, agricultural and biological sciences [125][115]. The spatial resolution of the climate surfaces used in a particular study depends on the needs for that application and on the data available. For many applications, data at a fine ($\leq$1 km^2) spatial resolution are necessary to capture environmental variability that can be partly lost at lower resolutions, particularly in mountainous and other areas with steep climate gradients [59]. For this purpose climatic normal parameters were interpolated over a spatial grid of 30 arc s covering the entire land surface using a high resolution digital elevation model. Long-term data (at least 10 years from the period 1950–2000) of precipitation, mean temperature and maximum or minimum temperature, of weather stations across the world as shown in Figure 3-6 were collated from large number of global, regional, national, and local sources[59].

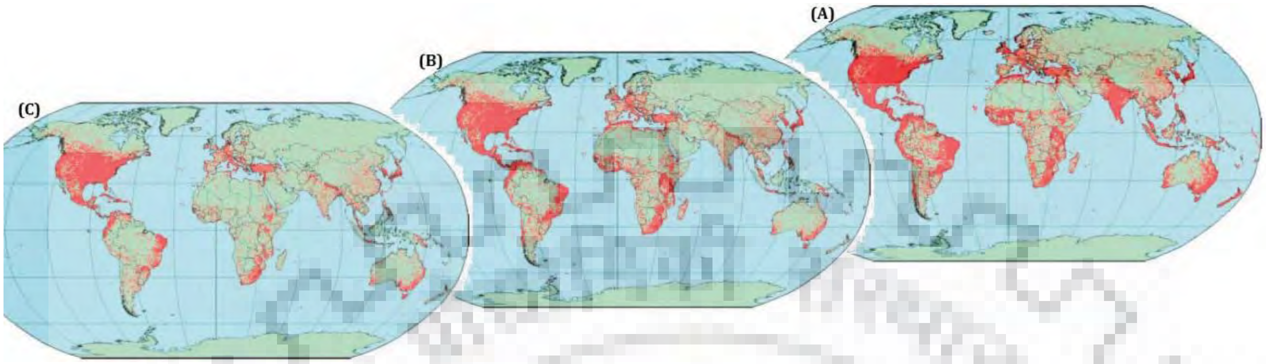


Figure 3-6 Distribution of weather stations used in interpolation of parameter (A) precipitation (47,554 stations); (B) mean temperature (24,542 stations); (C) maximum or minimum temperature (14,930 stations) Source: [59]

The world map of Köppen classification system based on a complex classification criteria described in Table 2-2 was updated as shown in Figure 3-7, by applying raster analysis on such an interpolated grid in GIS platform [115].

The air temperature and precipitation data listed in Table 2-5 is available from aforementioned dataset. Monthly and annual average relative humidity GIS data at one-degree resolution of the World is also available from NASA [133].

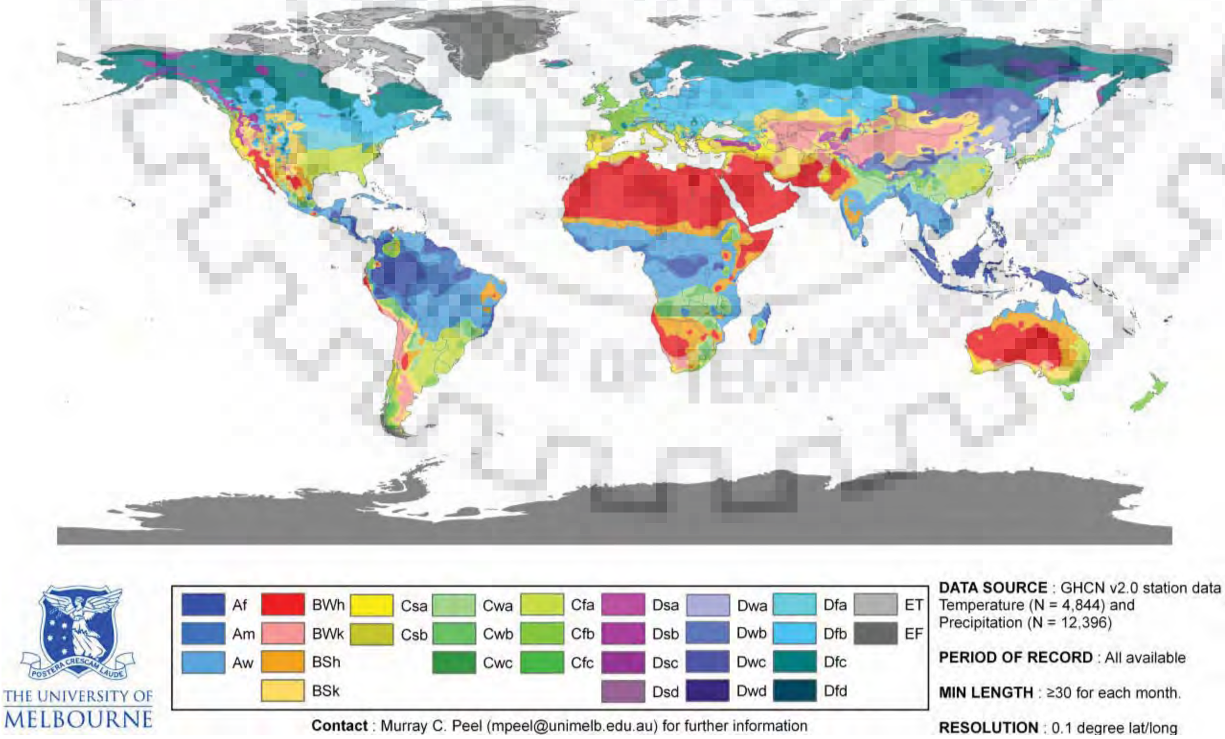


Figure 3-7 World map of Köppen-Geiger climate classification Source:[115]

3.3.2. Basis of Urban Climate Variation

In an attempt to establish physical basis of urban climate variation, some studies have succeeded in quantifying urban greenery proportionate to areal units using various indices [56,155]. However various studies have been able to substantiated the extent of variation with in an urban agglomeartion [88,132] with the help of physical classification system called Local Climate Zone discussed in section 2.2.2.3.

3.3.2.1. Field survey and numerical modeling

A mobile field survey was conducted across Vancouver, along a 48 km long traverse through varying elevation and LCZ locations, to quantify temperatures [132]. The nocturnal temperature profile (shown in Figure 3-8) for 4 November 1999, a night with clear skies and low wind speeds, shows strong thermal patterns. In LCZ 1, temperatures are 5–7 K higher than LCZ D, giving rise to a heat island ($T_{LCZ\ 1-D}$) of about 6K. As the traverse moves from LCZ1 (city centre) to A (forested park), temperatures drop by 4K; and when it moves from LCZ6 (residential zone) to D (cropped fields) temperature drops by another 5K.

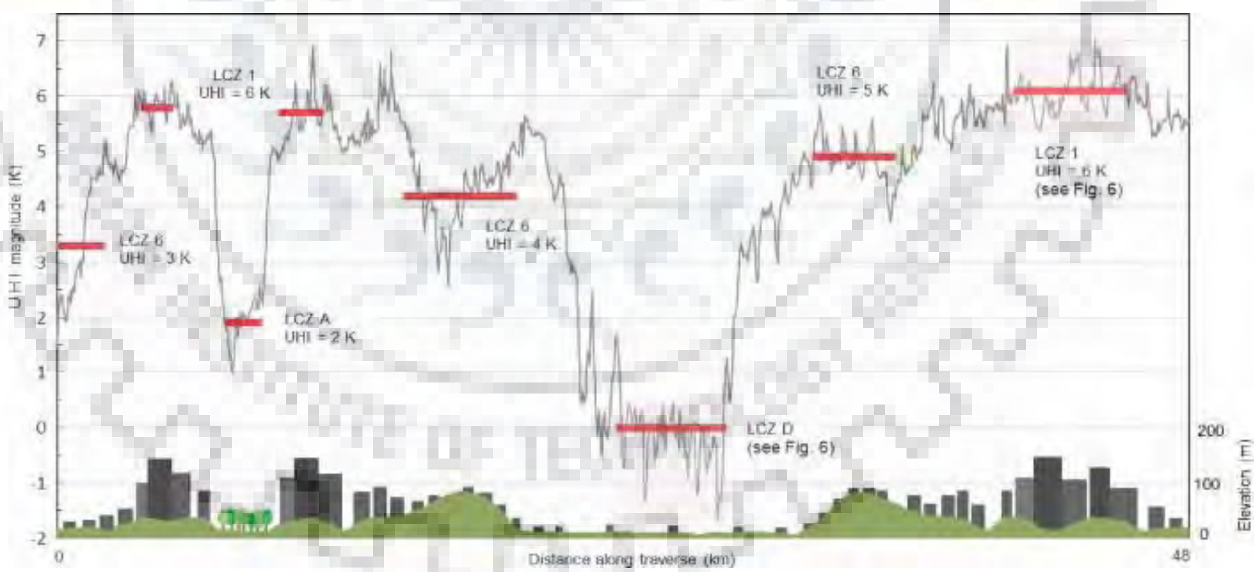


Figure 3-8 Heat island magnitudes ($T_{LCZ\ X-D}$) for Vancouver during a nighttime traverse in calm, clear weather

Thick horizontal lines indicate the distance travelled through, and the average temperature in, the LCZs of Vancouver. Surface relief and building height/density are shown along bottom axis. Source: [132]

Data from the aforementioned field survey from Vancouver and similar ones in Nagano, and Uppsala were used in comparison with data from numerical simulations described in the following to substantiate signature thermal behaviour of individual LCZ class.

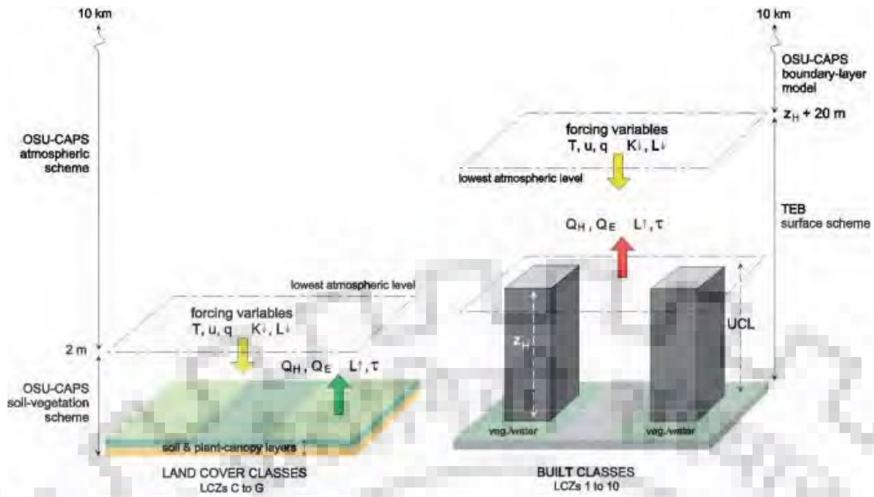


Figure 3-9 LCZ Schematic representation of OSU-CAPS and TEB Source: [132]

Temperatures for all classes in the 'built' series (LCZs 1–10) were modeled with the atmospheric portion of the Oregon State University Coupled Atmosphere-Plant-Soil (OSU-CAPS) scheme coupled to the Town Energy Balance (TEB) urban surface scheme as show in Figure 3-9; to obtain a simple but complete representation of heat, moisture, momentum, and radiation exchange between the surface and atmosphere above each LCZ class [132].

Hourly LCZ temperature differences between the observed and modeled datasets cannot be compared because; hourly model temperatures are not comparable among LCZ classes due to the divergence of LCZ thermal states after appropriate spin-up time in a (1D) column model. Hence diurnal temperature range (DTR) is used to express LCZ thermal differences, and to aid comparability of the modeled and observed data.

For the observed data, DTR is defined as the difference between the daily maxima and minima, and for the modeled data, as the average temperature range over the final two diurnal cycles of a simulation (i.e. two heating periods and two cooling periods). The same baseline class (LCZ D: low plants) is used to aid comparison with the observational data in Vancouver, Nagano, and Uppsala as shown in Table 3-4. The DTR for each class is therefore presented as a departure from the DTR for LCZ D_d. As seen from Table 3-4 modeled DTR values for several LCZ classes show general agreement with observed values from other cities and datasets. It is notable in this comparison that modeled DTR values are consistently lower than observed values for LCZs having an open form, a point that suggests TEB is less appropriate for these zones.

Table 3-4 Comparison of modelled and observed diurnal temperature range (DTR) in selected locations and local climate zones (LCZ) **Source:** [132]

Local climate zone	DTR modelled (K)	DTR observed (K)	Location	Data source
LCZ 1: compact high-rise	6	5–8	Vancouver, Canada	McClean (1993)
		6–9	Tokyo, Japan	Japan Meteorological Agency: http://data.jma.go.jp
LCZ 2: compact mid-rise	6	8–10	Goteborg, Sweden	Eliasson 1994
		11–15	Basel, Switzerland	Basel Urban Boundary Layer Experiment (BUBBLE): http://www.geog.ubc.ca/~achristn/research/BUBBLE
LCZ 3: compact low-rise	8	7–9	Kugahara, Japan	Kanda *et al*. 2005
LCZ 5: open mid-rise	8	10–12	Goteborg, Sweden	Eliasson 1994
		10–14	Uppsala, Sweden	Figure 9
LCZ 6: open low-rise	9	11–16	Uppsala, Sweden	Figure 9
		12–15	Vancouver, Canada	Environmental Prediction in Canadian Cities (EPiCC) Network: http://www.epicc.ca
LCZ 7: lightweight low-rise	11	10–14	Sao Paulo, Brazil	Silva and Ribeiro 2006
LCZ C: bush, scrub	20	17–23	Mohave, USA	Arizona Meteorological Network: http://ag.arizona.edu/azmet
LCZ D: low plants	17	10–15	Vancouver, Canada	McClean 1993
		15–18	Uppsala, Sweden	Figure 9
LCZ F: bare soil or sand	19	14–18	Basel, Switzerland	Basel Urban Boundary Layer Experiment (BUBBLE): http://www.geog.ubc.ca/~achristn/research/BUBBLE

[a]DTRs are representative of summer and/or dry season days with light winds and clear or partly cloudy skies.

Despite these discrepancies between and within the observed and modelled datasets, the most important finding in this study is that all LCZ classes are thermally unique, and all classes exhibit temperature contrasts that are largest at night, over dry surfaces, and in calm, clear weather. From the above discussion it is clear that LCZ classification is useful for assessing desirable urban built form between the various existing LCZs. In order to enable urban canopy modeling based on the LCZ classification for multiple cities across the world [29] a standardized protocol called WUDAPT has recently been developed [9].

3.3.2.1.1. WUDAPT – World Urban Database and Access Portal Tools

The World Urban Database and Access Portal Tools (WUDAPT) was developed as an international effort to assimilate information – that describes aspects of the form and function of cities at a detailed spatial resolution – useful for the progress of climate science[9]. Various community-based modeling systems for climate, weather and air quality are dependent upon data inputs including initial boundary conditions and emissions and static information such as land use classes, terrain and vegetation. WUDAPT enables local experts to implement supervised classification of remotely sensed databases (Google Earth and Landsat), based on the broad ranges of canopy parameters

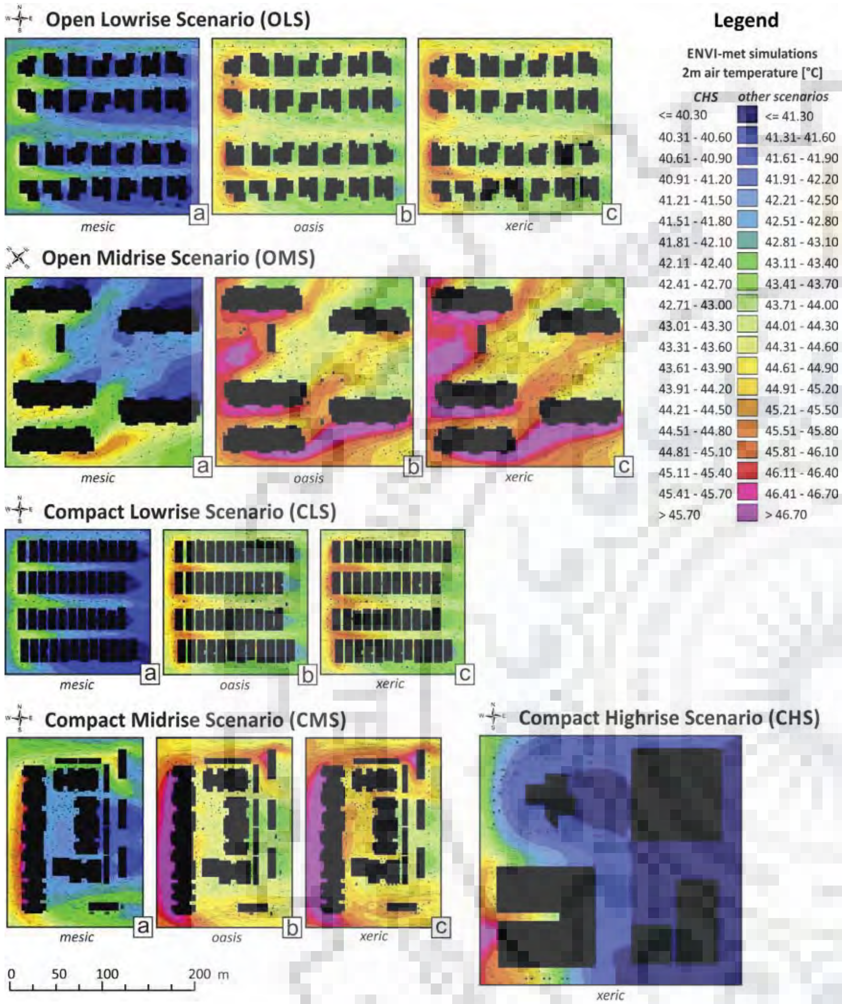


Figure 3-11 Air temperature distribution at 2m AGL at 1400 hrs across CAP LTER North Desert village experiment model in ENVI MET

Source: [88]

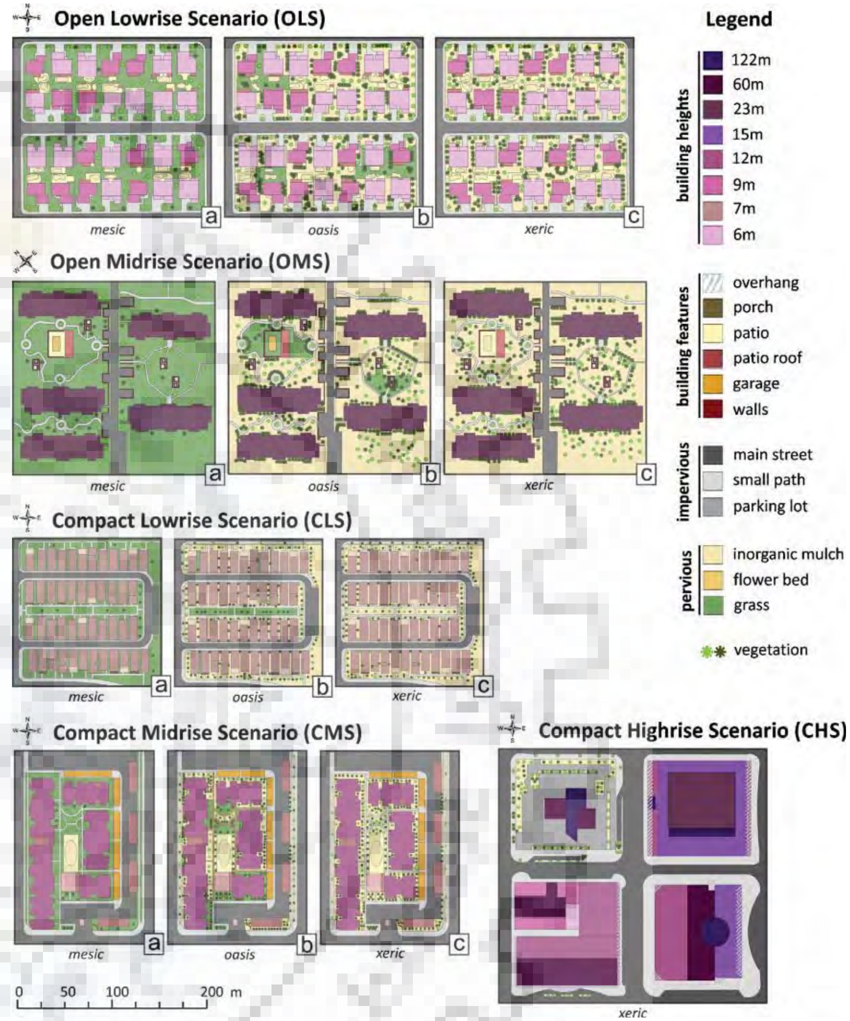


Figure 3-10 LCZ and landscape scenarios of CAP LTER North Desert village experiment modeled in ENVI MET

Source: [88]

in LCZ for use in urban climate modeling[29]. WUDAPT has been developed to satisfy the three considerations or urban climate modeling namely; 1) regard for spatial complexity of underlying surfaces & emission details for air quality modeling, 2) Resolution of the spatial grid must be flexible enough to fit the highly complex gradients of both inputs and output fields in urban areas, 3) specialized data requirements including comprehensive information on buildings and structural materials, as well as population density[29].

3.3.2.2. 3D CFD Based Modeling

A 3D Computational Fluid Dynamics (CFD) based surface-plant-air interaction model named ENVI-met, that can predict spatial and temporal variation in temperature, humidity and wind speed across the modeled urban neighborhood has been developed by Bruse et al [21]. This model was used to simulate spatial distribution of air temperatures in 5 types of LCZ combined with three landscape scenarios[88]. The simulation experiment was validated using true scale prototype courtyards in the ***CAP LTER North Desert village*** landscaped with the three scenarios. The combinations of LCZ and landscape scenarios namely, xeric, oasis and mesic modeled in ENVI MET are shown in Figure 3-10. The estimated air temperature at 2m AGL around 1400 hours in all the modeled scenarios are shown in Figure 3-11.

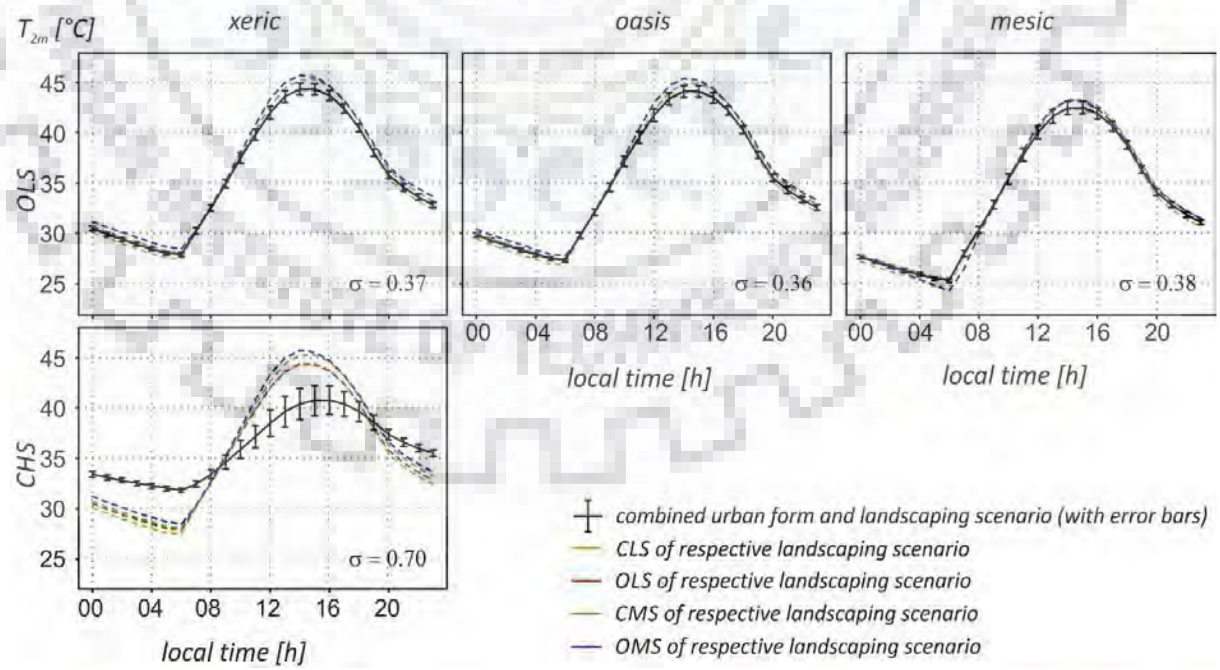


Figure 3-12 Diurnal 2-m air temperature curve for each combined urban form and landscaping scenario spatially averaged with error bars and averaged standard deviation Source: [88]

As can be seen from Figure 3-12 the maximum standard deviation in diurnal air temperature is found in scenario CHS xeric while the minimum standard deviation is found in scenario OLS mesic. This means that air temperature varies most in CHS xeric neighborhood while it varies the least in OLS mesic neighborhood. From Figure 3-13 it can be seen that the extreme temperatures may exist in various neighborhoods in varying extents, and it is difficult to assume that the variation is high enough to cause great variation in thermal stresses.

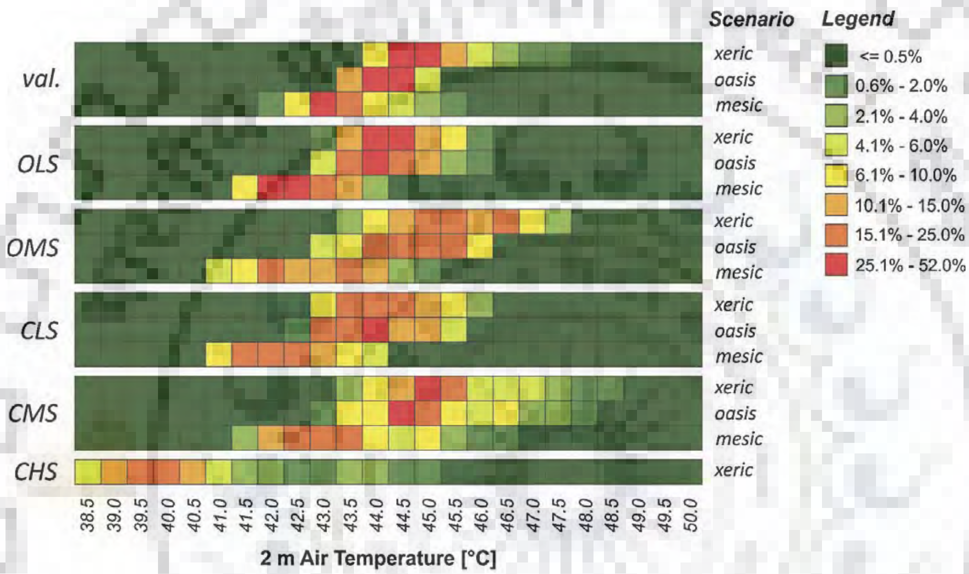


Figure 3-13 Histogram for 2-m air temperature distribution

For each scenario (rows), the occurrence of temperatures (rounded to 0.5 ◦C) in percent (columns) is mapped (val. = validation run) Source: [88]

The level of detail information required in ENVI-met model will be unavailable for many Indian cities; hence it would be difficult to assess the most desirable urban built form in these cities using ENVI-met. A model capable of simulating atmospheric parameters based on sparser LCZ information would be more suitable for Indian cities.

3.3.2.3. Energy Flux Modeling

Recently a faster energy flux based model called Urb-Clim has been developed for predicting temperatures across various land use types across an urban agglomeration [123]. Urb-Clim uses land cover types and vegetation cover fraction scheme shown in Figure 3-14. The percentage urban land cover is obtained from Urban Soil Sealing raster data files at 250m resolution distributed by the European Environment Agency and vegetation cover fraction Normalized Difference Vegetation Index (NDVI) acquired by the MODIS instrument on-board the TERRA satellite [123].

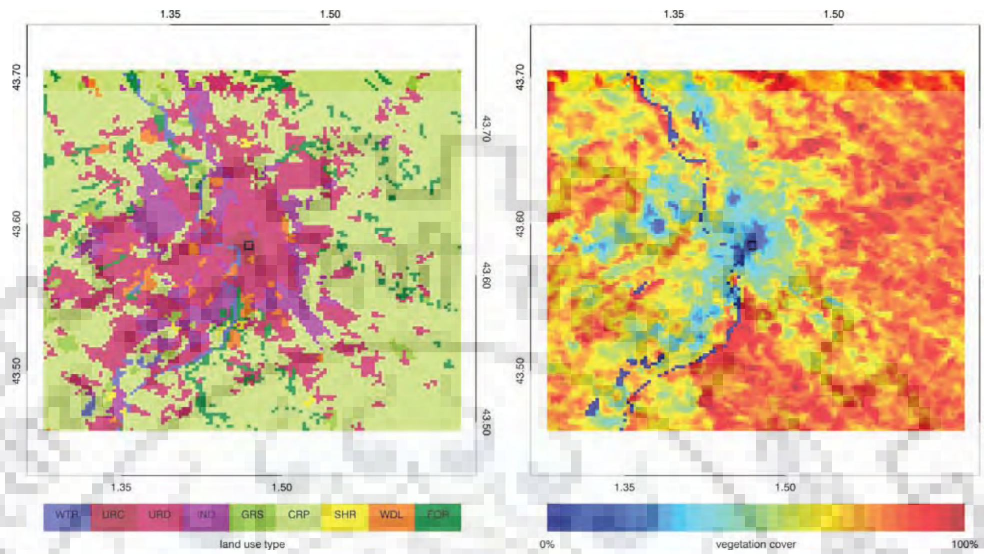


Figure 3-14 UrbClim Input parameters LU type and Vegetation Cover at Toulouse Source: [123]

Micro-meteorological measurements from core city and rural areas are used to validate the distribution of day time and night time heat flux obtained by simulating Urb Clim coupled with forcing data from European Centre for Medium Range Weather Forecasting (ECMWF) as shown in Figure 3-15.

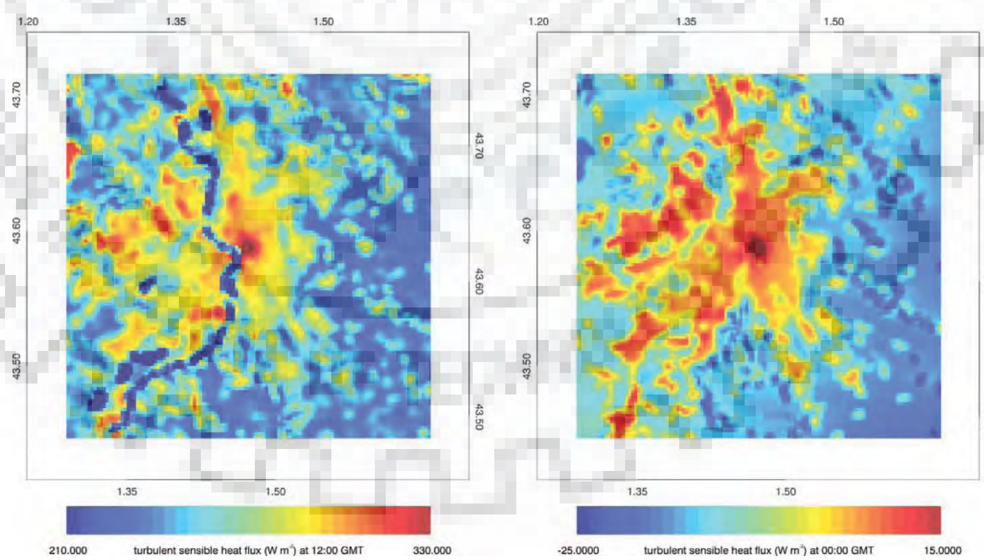


Figure 3-15 UrbClim Output simulated Heat flux at Toulouse 1200 and 0000 UT Source: [123]

LCZ classification of selected city using WUDAPT workflow can also be utilized in UrbClim model, to estimate monthly mean minimum and maximum temperature and relative humidity values required in local climate level analysis [122].

3.3.3. Temporal Interpolation of Data

Hourly values of climatic parameters throughout the year are required for detailed analyses of thermal and energy performance of buildings (see 2.5.6.3). Currently typical weather files are available for limited number of locations. Nevertheless these files can be generated for other locations for which monthly climate normals are available, by performing temporal interpolation. Roriz [124] developed algorithms to estimate typical hourly values of temperature and humidity as a function of climatological normal tables for each place irrespective of latitude and times of the year. The research paper originally published in Portuguese language has been translated by this author and attached herewith as APPENDIX 3.

3.4. Climate Modulation Strategies

Traditionally, exposition of methods of achieving comfort conditions inside buildings through natural means used to be categorized – on the basis of thermodynamic principles – into heating, cooling, combined heating and cooling, humidity control and day lighting methods [6,20]. Several architects also contributed to the establishment of climate as basic paradigm of architectural design [30,71,106]. A scientific process had also been developed for designing constituent elements of building and built environment in a sequential but cyclic manner, considering climate as a basic parameter in decision support [72]. It is relatively easy to arrive at climate responsive design recommendations if the analysis of normal climatic pattern reveals a hot-dry or warm-humid climate type [47]. However when contradictory performance requirements emerge from the analysis of composite climate type, it becomes necessary to use a weighting system like Mahoney Tables [82] to assess the relative importance of conflicting requirements [68].

3.4.1. Design Matrix

A design matrix provided by Krishan et. al. [72], lists various optional strategies available for each building element and uses a shaded color code (see Table 3-5) to indicate the most desirable & least desirable options appropriate in case of various thermal stress conditions. A mixed color gradient had been used to indicate strategies appropriate for cases of multiple thermal stress conditions.

Table 3-5 Color Codes for indicating most and least desirable strategy in specific stress condition

Stress Conditions / Color Code for:	Most Desirable option	Least Desirable option
Over heated condition	Dark Yellow	Light Yellow
Under heated condition	Dark Blue	Light Blue
Over heated humid condition	Dark Green	Light Green
Day lighting	Dark Pink	Light Pink

The climatic factor/s determining the choices of design options as well as those possibly affected by the choice of appropriate design option were both listed in columns besides every design element. The design matrix can be used effectively for choice of design options; when the climate of a place leads to any one predominant stress condition. Design options suitable for various stress conditions for individual constituent element listed in the design matrix have been discussed in sections 3.4.3 through 3.4.5. Krishan, Jain, Rajgopalan, et al. [73] used Mahoney Tables analysis as an illustration while discussing the responsive design strategies relevant to case study cities representative of each climatic zone of India. The criteria for selection of each building element, provided in Mahoney Tables have been discussed alongside respective options discussed in sections 3.4.3 through 3.4.5.

3.4.2. Mahoney Tables

More often than not the climatic conditions lead to more than one stress conditions becoming dominant during different seasons. In such cases the designer has to rely on extraneous decision support for choice of design option (see section 2.4.4.3) such as that available in the form of Mahoney Tables. For prioritizing between conflicting stress conditions Mahoney Tables [69] provide decision support criteria based on three humidity and three aridity indicators derived from various primitive, combined and derived climatic parameters listed in Table 3-6. Annual rainfall is a primitive climatic parameter, while monthly mean relative humidity is a combined parameter. Monthly mean temperature range and humidity group are examples of derived parameter. The monthly humidity group is determined using the ranges given in legend below Table 3-6. The concept of adaptive comfort limits discussed in section 2.4.4.2 is applied in the determination of monthly daytime and nighttime stresses. The identified humidity group and monthly stresses form criteria for ascertaining applicability of 4 climatic indicators out of 6. Following section deals with detailed assessment of how climatic indicators provided in Mahoney tables [69] may be refined to determine appropriate strategies from gamut of strategies presented in design matrix [72].

Table 3-6 Climatic Indicators as per Mahoney Tables Source: Koenigsberger et al. [69]

Climatic Parameters	Humidity & Aridity Indicator/s							
	H1		H2	H3	A1	A2		A3
Annual Rainfall in mm				>200				
Monthly Mean Temperature Range (degC)		<10°			>10°		>10°	
Monthly Relative Humidity Group	4	2, 3	4		1, 2, 3	1, 2	1, 2	
Monthly Stress Nighttime						H	O	
Monthly Stress Daytime	H	H	O				H	C

Indicator description	
H1	Air movement essential
H2	Air movement desirable
H3	Rain protection necessary
A1	Thermal capacity necessary
A2	Out door sleeping desirable
A3	Protection from cold

LEGEND

if mean R.H.=x; **Humidity Group:** **1** = x<30%; **2** = 30%<x<50%; **3** = 50%<x<70%; **4** = x>70%

Monthly **Nighttime / Daytime Stress:** **H** = Hot; **O** = Comfortable; **C** = Cold

3.4.3. Specifications for built form

Aspects such as Building layout, Orientation, spacing between buildings and configuration of exterior spaces; may be considered as constituents of a climate responsive built form.

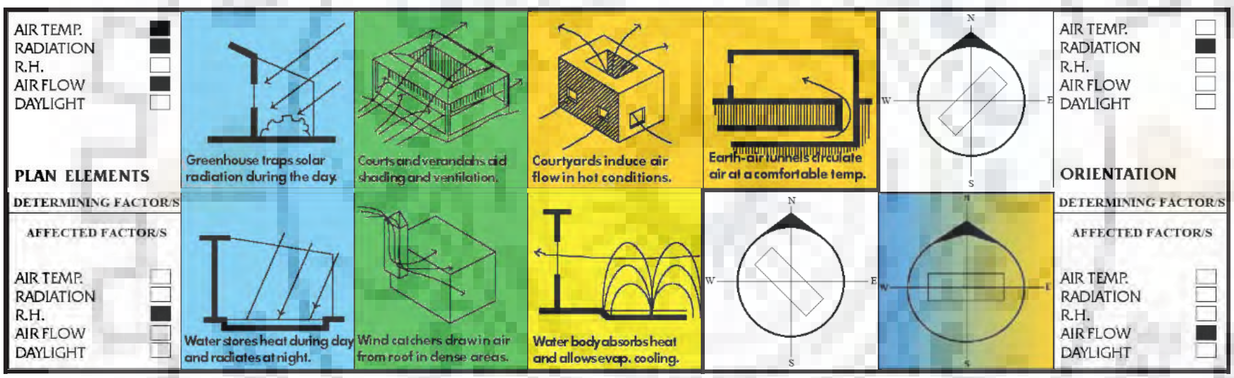


Figure 3-16 Design options for building layout and orientation Based on: Krishan et. al. [72]

3.4.3.1. Specification options for building layout and orientation

The plan elements most desirable in predominant stress conditions are shown in Figure 3-16. The selection from these plan elements may be done based on feasibility of incorporating building layout recommended as per Table 3-6 and Table 3-7.

Compact courtyard planning is a must where the monthly mean temperature range is above 10 degC for more than 10 months and there is monthly daytime cold stress for up to 4 months. On the other hand N-S orientation is recommended for all other conditions, however courtyards with or without verandah have also been recommended for climate modulation in overheated or humid overheated conditions respectively. Figure 3-16 also lists most desirable street orientation in case of both overheated and under heated conditions.

Table 3-7 Climatic criteria for building orientation and layout Source: Koenigsberger et al. [69]

	↓ Design Option | Indicator month count →	A1	A3
a1	Orientation N&S	0-10	
		11,12	5-12
a2	Compact Courtyard Planning	11,12	0-4

3.4.3.2. Specification options for spacing between buildings

Spacing between buildings is determined by, street widths and orientation. Along with desirable configurations of open spaces, the most desirable streets widths for particular stress conditions are listed in Figure 3-17.

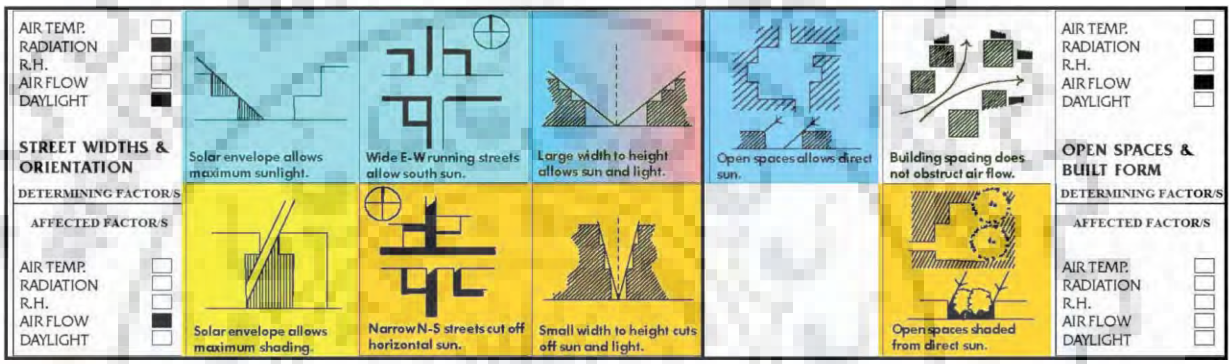


Figure 3-17 Design options for spacing between buildings Based on: Krishan et. al. [72]

The criteria for selecting appropriate spacing between buildings are shown in Table 3-8 with reference to H1 climatic indicator shown in Table 3-6. Compact layout of estates is recommended where air movement is essential (H1) for up to 1 month. Open spacing for breeze penetration is recommended for rest of the conditions. However protection from hot or cold winds is recommended when air movement is essential from 2 to 10 months.

Table 3-8 Climatic criteria for spacing between buildings Source: Koenigsberger et al. [69]

	↓ Design Option | Indicator month count →	H1
b1	Open spacing for breeze penetration	11,12
b2	Open spacing for breeze penetration, protect from H&C wind	2-10
b3	Compact Layout of Estates	0,1

3.4.3.3. Specification options for exterior spaces

The selection from options of ground cover and texture and colors for exterior finishes shown in Figure 3-18, design options for building exterior spaces should be determined considering the overall radiation budget and air temperature respectively. The selection from these options may affect the daylight available in the surrounding buildings.

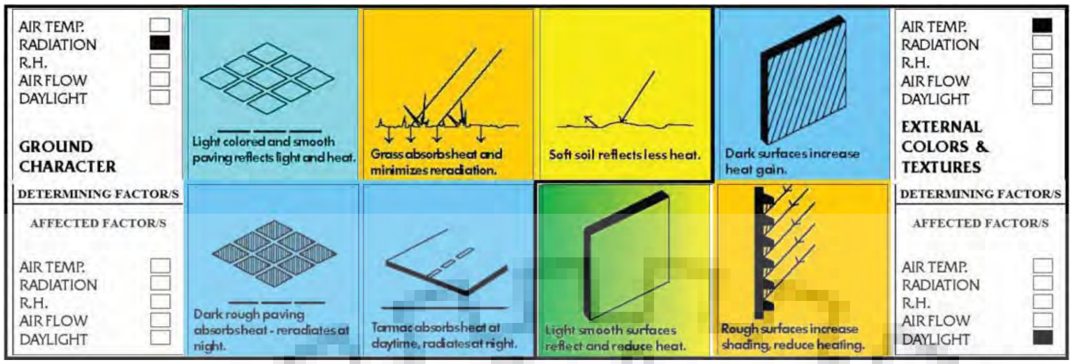


Figure 3-18 Design options for building exterior spaces Based on: Krishan et. al. [72]

The criteria available in Mahoney tables for exterior spaces are shown in Table 3-9; these recommend provisions of outdoor sleeping space and rain protection. No criteria are available for selection of ground cover or wall finishes.

Table 3-9 Climatic criteria for building exterior spaces   Source: Koenigsberger et al. [69]

↓ Design Option | Indicator month count →		H3	A2
i1	No space for out-door sleeping		0
i2	Space for out-door sleeping		1-12
j1	Protection form heavy rain needed	2-12	
j2	No Protection form heavy rain needed	0,1	

Most decisions in the subsequent levels will be determined to a certain extent based on the selected / possible options from built form specifications.

3.4.4. Specifications for building envelope

Roofs, walls and floors passively participate in climate modulation as they constitute the building envelope.

3.4.4.1. Specification options for roof design

As shown in Figure 3-19 two aspects roof design, namely roof form and roof materials need to be considered in response to the prevalent thermal stresses. While airflow and daylight have been identified as factors determining choice of roof form; the selected roof form will in turn determine the amount of exposure to solar radiation. The choice of thermal capacity and u-value of selected roof material is determined by the amount of incident solar radiation that needs to be reflected, absorbed, retained and (re)radiated to the inside/outside.

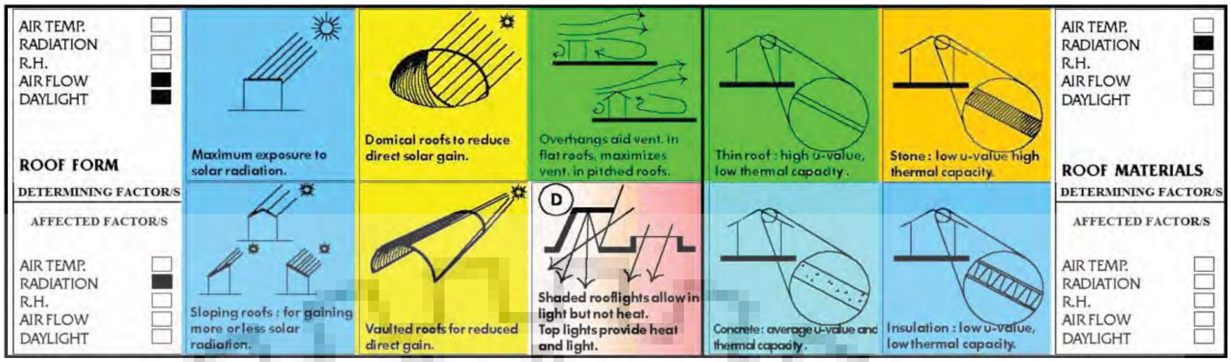


Figure 3-19 Design options for roof design Based on: Krishan et. al. [72]

While the roof design options suitable for predominant thermal stress have been indicated using color and shade codes, the criteria for assessing suitable option in case of conflicting stresses is has been shown in Table 3-10.

Table 3-10 Climatic criteria for roof design **Source: Koenigsberger et al.** [69]

	↓ Design Option | Indicator month count →	H1	A1
h1	Roof Light, reflective surface, cavity	10-12	0-2
h2	Light well insulated roofs	10-12	3-12
		0-9	0-5
h3	Heavy roofs, over 8 h time-lag	0-9	6-12

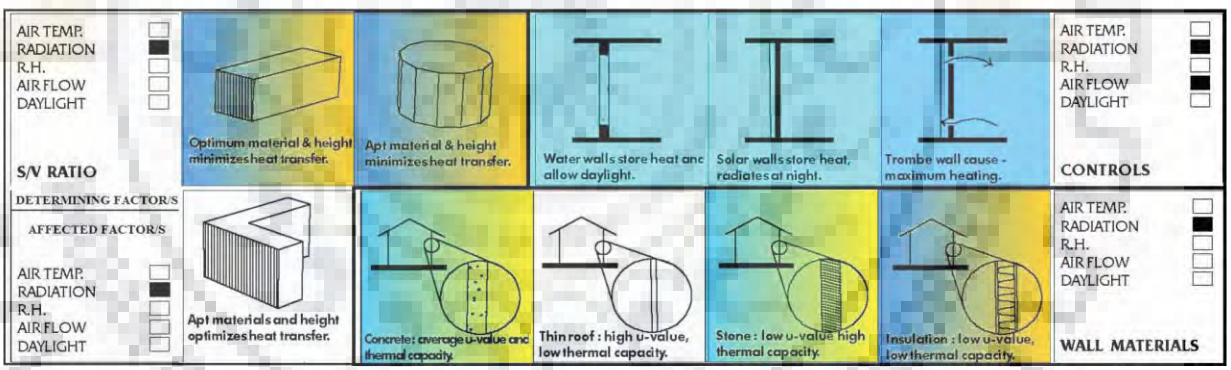


Figure 3-20 Design options for walls and floors Based on: Krishan et. al. [72]

3.4.4.2. Specification options for walls and floors

As shown in Figure 3-20 three aspects of wall and floor design, namely 'surface area to volume ratio', wall materials and additional controls need to be considered in response to the prevalent thermal stresses.

While solar radiation has been identified as factors determining choice of surface area to volume ratio; the selected S/V ratio will in turn determine the amount of exposure to solar radiation. The wall material can then be selected in response to radiation budget. Some additional controls have been listed for selection in response to under heating stress conditions while avoiding air flow. Climatic criteria for selecting appropriate wall and floor design are listed in Table 3-11.

Table 3-11 Climatic criteria for design of walls and floors **Source: Koenigsberger et al.** [69]

↓ Design Option | Indicator month count →		A1
g1	Light walls, short time-lag	0-2
g2	Heavy external & internal walls, over 8 hour time-lag	3-12

3.4.5. Specifications for opening design

Openings in walls provide light and ventilation to the interior spaces, but in appropriate positioning, sizing and lack of protection may lead to undesirable speed and amount of air movement, heat gain / loss. Various design options are available for each component.

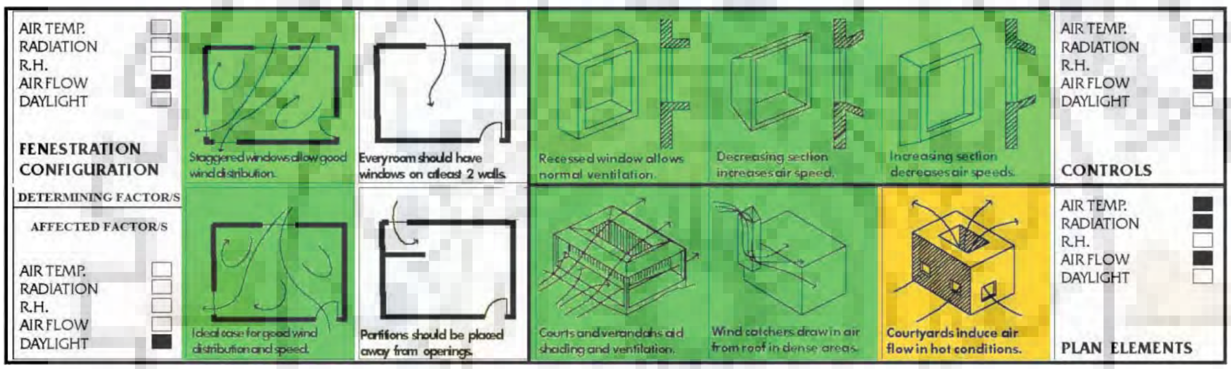


Figure 3-21 Design options for opening position and air movement Based on: Krishan et. al. [72]

3.4.5.1. Specification options for opening position & air movement

The speed and quantity of air movement may be controlling as per prevailing stress conditions using options of fenestration configuration, structural controls and other plan elements as shown Figure 3-21.

The criteria for establishing the requirement of air movement either throughout the year, during particular season of the year or never during the year are shown in Table 3-12.

Table 3-12 Climatic criteria for design of opening position & air movement **Source: Koenigsberger et al.** [69]

↓ Design Option | Indicator month count →		H1	H2	A1
c1 & e1	Single banked Rooms, permanent provision for air movement & Openings in N&S walls at body height on windward side	3-12		
		1,2		0-5
c2 & e2	Double banked Rooms with temporary provision for air movement & Openings in N&S walls at body height on windward side,openings also in internal walls	1,2		6-12
		0	2-12	
c3 & e3	No air movement required & Has no climate related value	0	0,1	

3.4.5.2. Specification options for opening size

Radiation budget, airflow requirement and daylight requirement are the factors determining the fenestration orientation and pattern. As shown in Figure 3-22 the selection of various options will help to determine the size of opening to achieve the desirable quality of daylight.

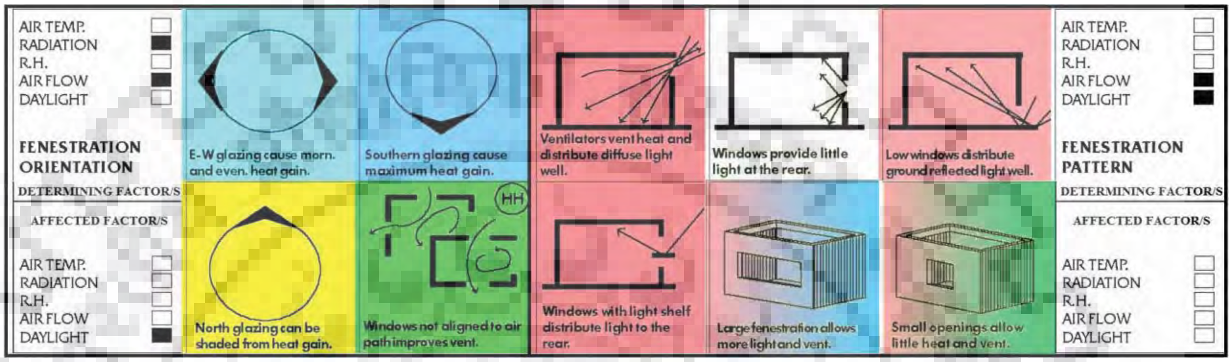


Figure 3-22 Design options for opening size Based on: Krishan et. al. [72]

The opening size as percentage of wall area can be selected based on the duration of requirement of thermal storage balanced with the duration of access to solar exposure required to counter cold season problem Table 3-13

Table 3-13 Climatic criteria for design of opening size Source: Koenigsberger et al. [69]

↓ Design Option | Indicator month count →		A1	A3
d1	Large openings, 40-80% of wall area	0,1	0
d2	Medim Openings, 25-40% of wall area	0,1	1-12
		2-5	
d3	Composite Openings, 20-35% of wall area	11,12	4-12
d4	Small openings, 15-25% of wall area	6-10	
d5	Very small openings, 10-20% of wall area	11,12	0-3

3.4.5.3. Specification options for opening protection

Various components shown in Figure 3-23 may be selected to provide opening protection.

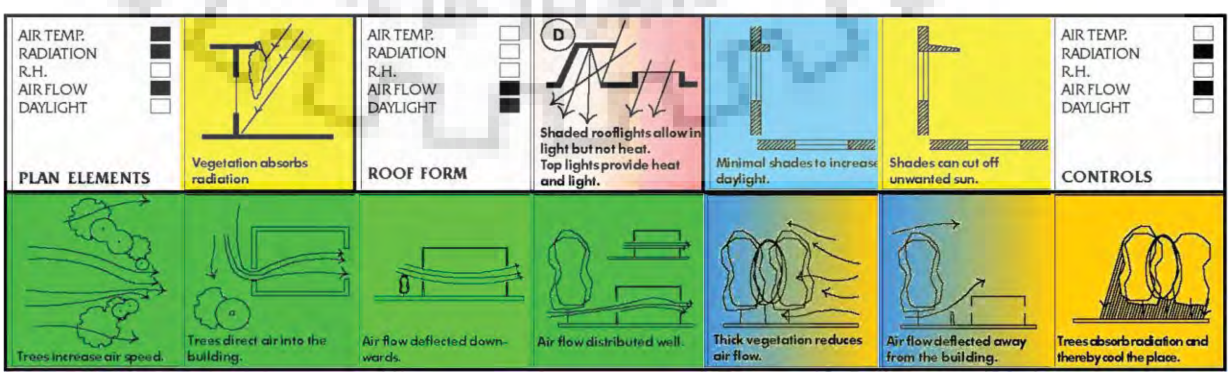


Figure 3-23 Design options for opening protection Based on: Krishan et. al. [72]

The choice will depend upon the conditions of air temperature, radiation and airflow. The necessity of the type of protection required is determined with reference to duration of rainfall and cold season as shown in Table 3-14.

Table 3-14 Climatic criteria for design of opening protection **Source: Koenigsberger et al.** [69]

↓ Design Option | Indicator month count →		H3	A3
f1	No special protection necessary	0,1	3-12
f2	Exclude direct sunlight		0-2
f3	Protection from rain & direct sunlight	2-12	0-2
f4	Provide protection from rain	2-12	

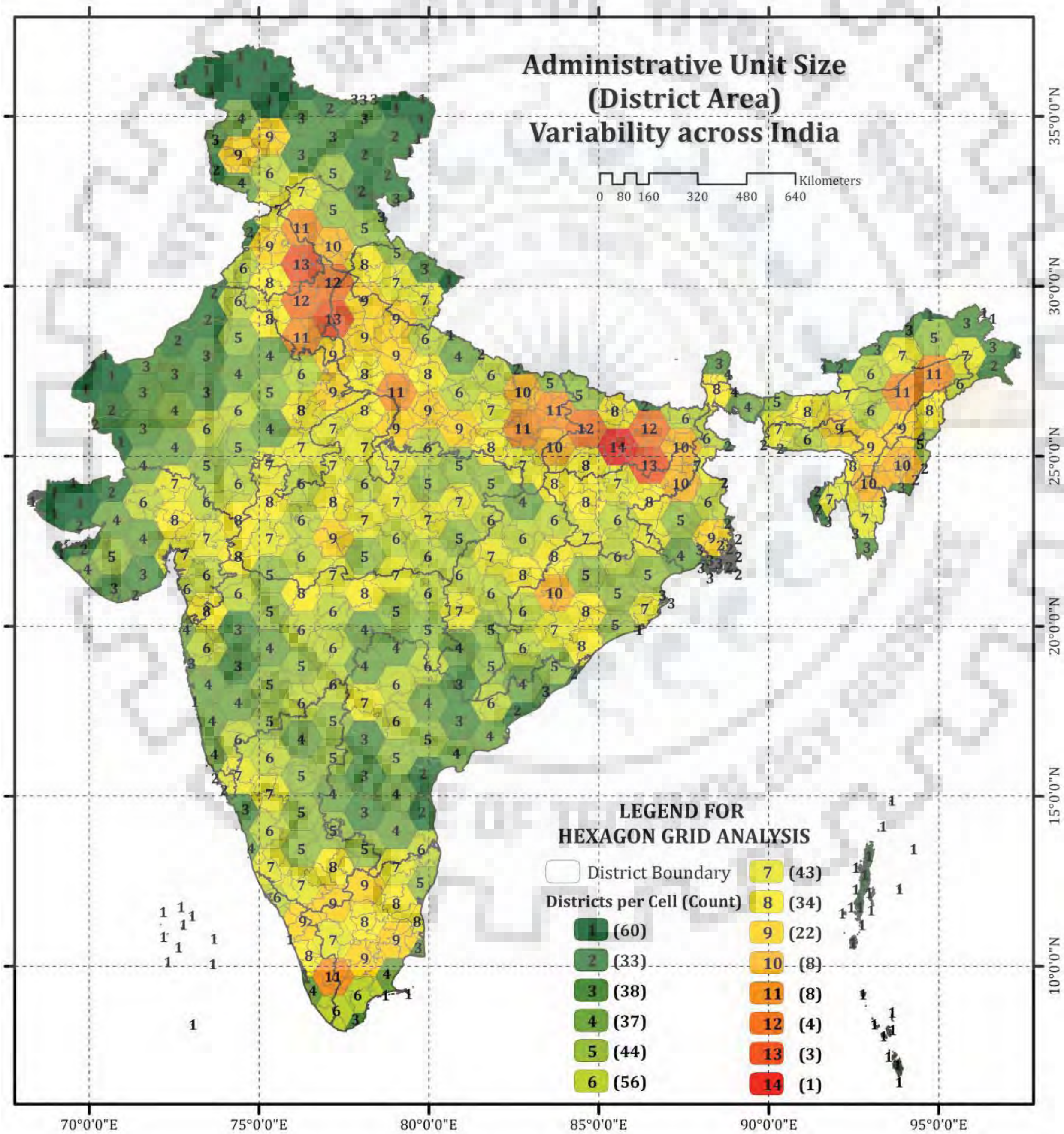


Figure 3-24 Variability of administrative unit size across India Based on: [60]

3.5. Geographical Information System

Geographical Information System (GIS) offers a practical and relevant working environment for the integration, analysis visualization and management of spatial data from the field of climatological and meteorological together with other spatial data sources [35]. A commercial GIS application named Arc Map was used for spatial analysis aspects of this research. Constituent aspects of GIS pertaining to this research are discussed in the following. As the name suggests GIS consist of three major aspects namely, 'Geography' dealing with the location of phenomenon on earth. 'Information' dealing with measurements of various physical and environmental parameters at the particular location on earth and a 'System' dealing with the various software and hardware components required to put the geographical information together for human understanding.

3.5.1. Geography

Climatological and meteorological data has a strong relationship with the physical space, the natural and human aspects of which fall under the purview of geography. For instance, air temperature is clearly correlated with the height above mean sea level, distance from water bodies, slope, aspect, longitude and latitude.

3.5.1.1. Physical

Geophysical data such as elevation (with slope and exposure of the area), land cover (with parameters dependent on and independent of the season of the year), hydrography and soils is not only useful for visualization but also for analysis including various kinds of spatial interpolation and modeling.

3.5.1.2. Human

Not only do human settlements exist at geographically advantageous locations, but also administrative extents often result from some geo-political homogeneity. Spatial data analysis with reference to these human aspects of geography is often necessary while drawing inferences from various climatological and meteorological analyses. Overlay analysis using hexagonal grid (uniform in shape and size) is a form of regional analysis widely used in environmental studies[13]. Various types of landscape / ecology related regional analysis can be performed in Arc Map using a plug-in called Patch Analyst [120].

The area of an administrative unit depends on its geo-political complexity. It may be governed either by geographical isolation or population size. To assess the variability in area of administrative units across India, the district boundary shape files [60] were superimposed with uniform hexagonal grid with cells admeasuring approximately 10,590 sq. km. (when calculated in comparison with district Kota Rajasthan falling across 25°N Latitude). Due to their non-uniform shape and size, the count of district boundaries found coinciding with each hexagonal cell varied from 1 to 14 across India.

As seen from Figure 3-24 very high number of (11-14) administrative unit boundaries coincide with a single cell around the districts of Nalanda, Jamui, Saharsa and Saran in Bihar; district Hamirpur in Himachal Pradesh, district Fatehgarh Sahib in Punjab; districts Sonepat, Yamuna Nagar and Jind in Haryana; Bhagpat, Etawah, Jaunpur and Deoria in Uttar Pradesh; districts Dibrugarh and Lakimpur in Assam; and district Idikki in Kerala.

As many as 60 hexagonal grid cells (mostly incomplete) along the northern and western edge of India encompass only one district, signifying that these border areas are inaccessible and as such sparsely populated. Most number of hexagonal grid cells 56, 44 and 43 encompass 6, 5 and 7 districts respectively. This analysis helps in understanding the distribution of population across India.

3.5.2. Information

The large amount of climatological and meteorological information produced by many countries during the last decades facilitated the creation of a huge and varied database. Meteorological agencies spread all over the world yield lots of information about atmospheric conditions and their interactions with oceanic and continental surfaces. The different types of data produced by numerical models, satellites, telemetric stations and others present different formats and bring information which reproduces the weather conditions in different areas and in different temporal and spatial resolutions [35].

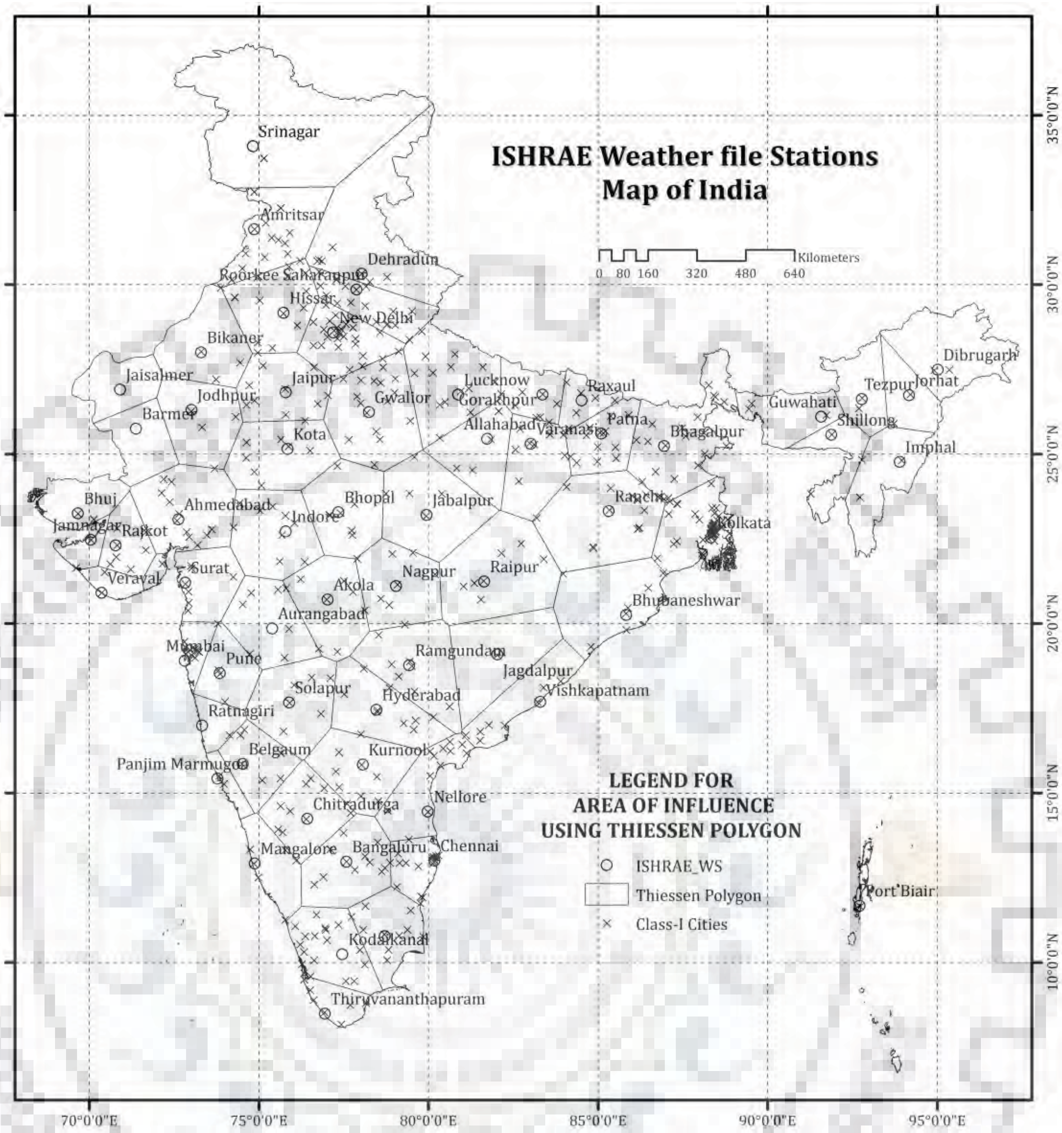


Figure 3-25 Area of influence around each ISHRAE weather file station Based on:[61]

3.5.2.1. Continuous data

The information produced by numerical models and also by satellite displays values in fields which can be represented by vectors (isolines) or grid points (pixels). Thus, they represent variables whose main characteristic is their spatial continuity.

3.5.2.2. Discrete data

Variables measured by telemetric stations display punctual values, but for limited number of locations. As seen in section 3.2.1.1 reference climate data is available for representative locations and for analyzing buildings in other cities a prescribed equivalent climate data is to be used [76]. In many countries for compliance purposes weather file from the geographically closest weather station needs to be used for thermal modeling. To demarcate area of influence for individual weather station, often *Thiessen Polygons* are drawn around each station [36].

As shown in Figure 3-25 *Thiessen Polygons* drawn around ISHRAE weather file stations [61] are varied in shape and area. The number of major cities encompassed within the neighborhood (*Thiessen Polygon)* of individual weather file station is listed in Table 5-7. This number varies from a high of 56 cities in the neighborhood of Kolkata weather file station to a low of only one or two cities in the weather file station neighborhoods of Bhuj, Dibrugarh, Jagdalpur, Jamnagar, Jorhat, Panjim Marmugoa, Port Blair, Ratnagiri, Srinagar, Tezpur and Veraval. Most weather file stations have 8 cities encompassed in its neighborhood.

3.5.3. System

The word "system" is used in different contexts to mean different things. Generally speaking, all systems, whether they are physical or conceptual, have the following characteristics [81]:

1. They are formed or constructed to achieve certain basic objectives or functions.
2. Their continuing existence depends on the ability to satisfy the intended objectives – if this ability fails/ starts to decline, the systems concerned must be upgraded/replaced.
3. An individual system is composed of many interrelated parts, which may be operational systems themselves.
4. These parts operate individually and interact with one another according to certain rules of conduct, such as procedures, laws, contractual agreements, and accepted behavior.

3.5.3.1. Information system

Information systems are a special class of systems that can be understood with respect to above general characteristics together with Figure 3-26 [81]. From the functional aspect, and information system is setup to achieve the specific objectives of collecting, storing, analyzing, and presenting information in a systematic manner. Interrelated components including data combined with technical and human resources form the structural aspects of information system. It can also be perceived as being made up of input, processing and output subsystems, all working according to a well-defined set of operational procedures. Lastly, individual information systems can be operated independently, and at the same time linked with other information systems through standard communications protocols to form an information systems network.

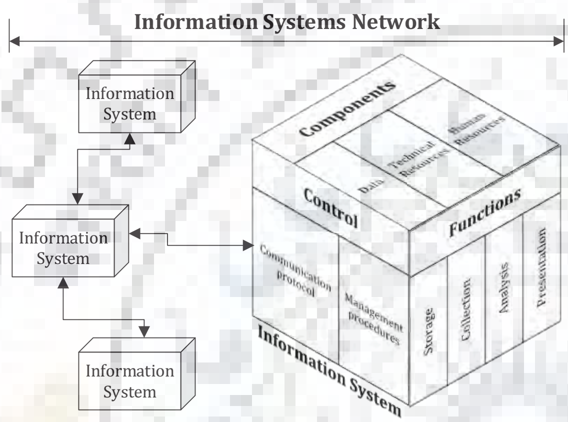


Figure 3-26 Different aspects of Information System
Source: [81]

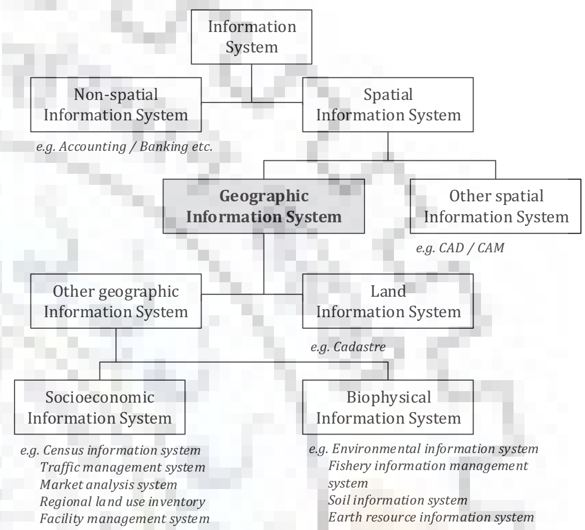


Figure 3-27 Typology of information systems
Source: [81]

3.5.3.2. Geographically referenced data

Use of geographically referenced data distinguishes GIS from other spatial information systems as shown in Figure 3-27 [81] and it too consists of various subsystems. The interdisciplinary subsystems relevant for this research are discussed in the following.

3.5.3.3. Positioning systems

Data use in this research was generally available in / converted to WGS 84 geographical coordinate system, and then projected to UTM coordinate system where required. The areas and distances between places get distorted when the spherical surface of the earth is represented as a flat map using projected coordinate system.

Spatial information related to field surveys was collected using GIS enabled instruments. Total Station was found suitable for collecting planer data while Handheld GPS was found suitable for collecting point and linear data.

3.5.3.4. Storage and retrieval system

Data needs to be stored in packages of manageable size, considering its bulk and convenience of transfer over internet. The data storage and retrieval system can be best described using example of data used during this research. The datasets were purchased / downloaded from variety of sources described in the following.

Climatic data in the form of bioclimatic variables was available free of cost from internet [157]. Three tiles of each bio climatic variable corresponding to the area of interest were downloaded. High resolution Multispectral and Pan-chromatic satellite imagery is available on order from National Remote Sensing Center's UOPS at a cost [98] . Medium to low resolution true-colour composite imagery is freely available from ISRO [11], some thematic layers are also available there as web map service [12] . Low resolution multi-spectral and thermal imagery freely available from USGS [152] was also useful in local climate studies.

3.5.3.5. Manipulation System

ESRI's Arc GIS 10.3.1 was used in this research and various aspects of this system have been discussed at length in an published article [113] attached as appendix PAPER1.

3.6. Summary

Detailed descriptive analysis of climatic classification of USA, Nigeria and Brazil was useful in developing various aspects of the proposed climatic classification system namely; selection of appropriate climatic parameters, derived from climatic data representative of appropriate geographical unit and selection of appropriate building design stages to be regulated.

Climatic classification is implemented world over to inform the building design process at two different stages namely forward analysis and backward analysis. The approach to climatic data analysis differs from stage to stage. As part of forward analysis the approach is to identify most appropriate passive design options for all building elements in various regions of India. As part of backward analysis the approach is to identify physical factors (aspects of existing built form) causing variation in local climate at that scale; whereas at the micro scale the approach is to use data collated during forward analysis for generating a typical weather file most suitable for more realistic building performance evaluation.

Various types and forms of datasets have been identified for use in workflows developed using analytical tools like GIS, Spreadsheets and climate models. Meteorological measurements collected using portable instruments are useful for explaining the variation in local climate. Those retrieved from climatological records are useful for forward analysis automated in spreadsheets. Climatic data available from websites in the form of interpolated raster grids is useful for delineating the spatial variation in climate. Land use land cover information for the whole city is available at sparse resolution from remotely sensed satellite imagery. This information can also be collected at higher resolution by conducting physical surveys. Geographical Information System helps in the collation of different kinds of information required in the climatic analysis for building design.

The review of state of the art in climate classification for building design, climate modeling, climate modulation strategies and geographical information system presented in the present chapter lays the foundation for the approach developed further in the next chapter 'Analytical Framework'.

CHAPTER 4. ANALYTICAL FRAMEWORK

4.1. General

This chapter deals with the data theory including a description of what has been done. An analytical framework has been articulated (see Figure 4-1) to deliberate upon the multi level context of work done. As suggested in an updated practical guide to architectural research [55], a set of hierarchal frames represent the 'strategies' (approach) and 'tactics' (techniques) nested within the 'school of thought'. The structure and functions of the hierarchal frames have been discussed at length in section 1.4.

4.2. Multi level analytical framework

This thesis is aligned to a school of thought that considers; climatology, responsive built environment and building legislation as the three intertwined domains / facets responsible for enabling a sustainable urban built environment.

4.2.1. Domain of Climatology

Overall scales of study in the domain of Climatology have been discussed at length in Section 2.2. However in the context of the proposed analytical framework it has been trifurcated into strategies at three levels namely Local Climate, Regional Climate and Typical Climate. The distinction has been made in correspondence with the various approaches and techniques identified in literature.

Regional Climate level is named after the regional approach used in geography for understanding the whole through its parts[130]; as it is devised to inform Building Legislations operational across the country including National Building Code, Building Byelaws and Energy Conservation Building Code.

Local Climate level is named after the local climate zone approach used in urban climate studies [131]; as it devised for generating Local Climatic Data using Energy Flux Modeling [123].

Typical Climate level is named after the approach adopted by building physicist for discussing climate data used in energy simulation [32] for optimizing building components and systems; and it is devised to enable compilation of Typical Weather files required in growing number urban centers across India.

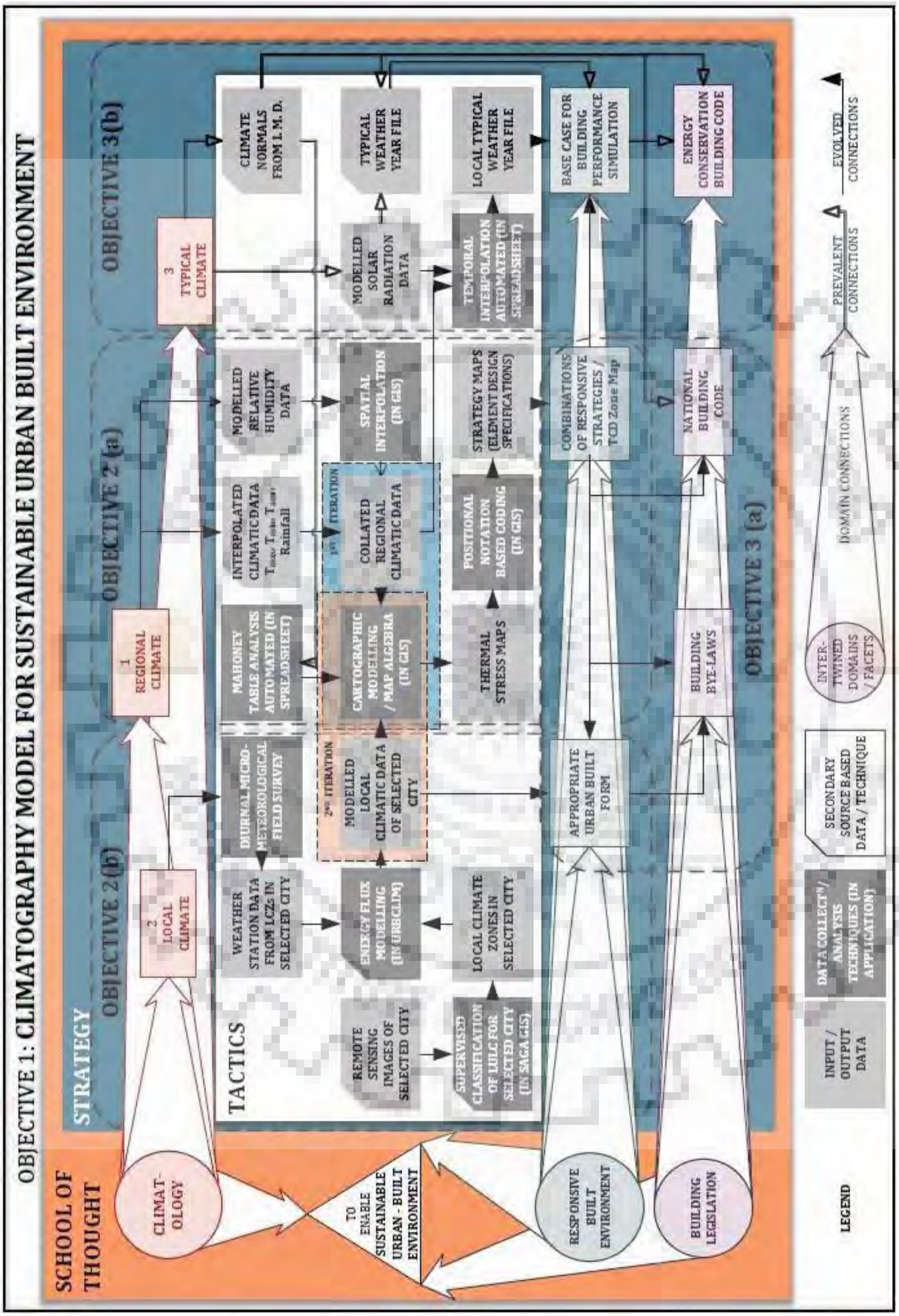


Figure 4-1Analytical Framework

4.2.2. Domain of Responsive Built Environment

The domain of responsive built environment has been trifurcated into strategies of Desirable Urban Built Form, Combination of Responsive Building Elements and Building Performance Simulation.

Combinations of Responsive Strategies assessed using Regional Climate data and Local Climate data for that city need to be compared in order to identify Desirable Built Form. If some settlement level modulation (amelioration / deterioration) (see Section 3.4.3) has been effected by particular Desirable Built Form/s; use of these Built Forms needs to be promoted / discouraged according by amending Building Byelaws of that city.

Thermal Comfort Design Zone (TCDZ) map is generated by overlaying the Strategy Maps delineated resulting from Regional Climate Analyses. As per the proposed framework, the TCD Zones need to be used for distinguishing passive building design specifications recommended in the National Building Code (see Section 2.4.4.4).

Compliance with Energy Conservation Building Code (ECBC) can be achieved by performing Whole Building Performance Simulation, to ascertain that the proposed case performs better than the base case. As per the proposed framework, base case or standard case needs to be assembled using Combination of Responsive Strategies and analyzed using Local Typical Weather file.

4.2.3. Domain of Building Legislation

The domain of Building Legislation needs to be trifurcated into strategies at three levels viz., Building Bye Laws, National Building Code and Energy Conservation Building Code to implement location specific recommendations / data made available by analyses in the other two domains as shown above.

Details of various analyses conducted – for enabling sustainable urban built environment synthesizing interaction between the domains of climatology, responsive built environment and building legislation – have been discussed at length in the following.

4.3. Regional Climate level analyses

Functioning at the broadest level regional climate analyses are based on use of gridded climatic parameters for implementing forward design analysis prescribed in Mahoney

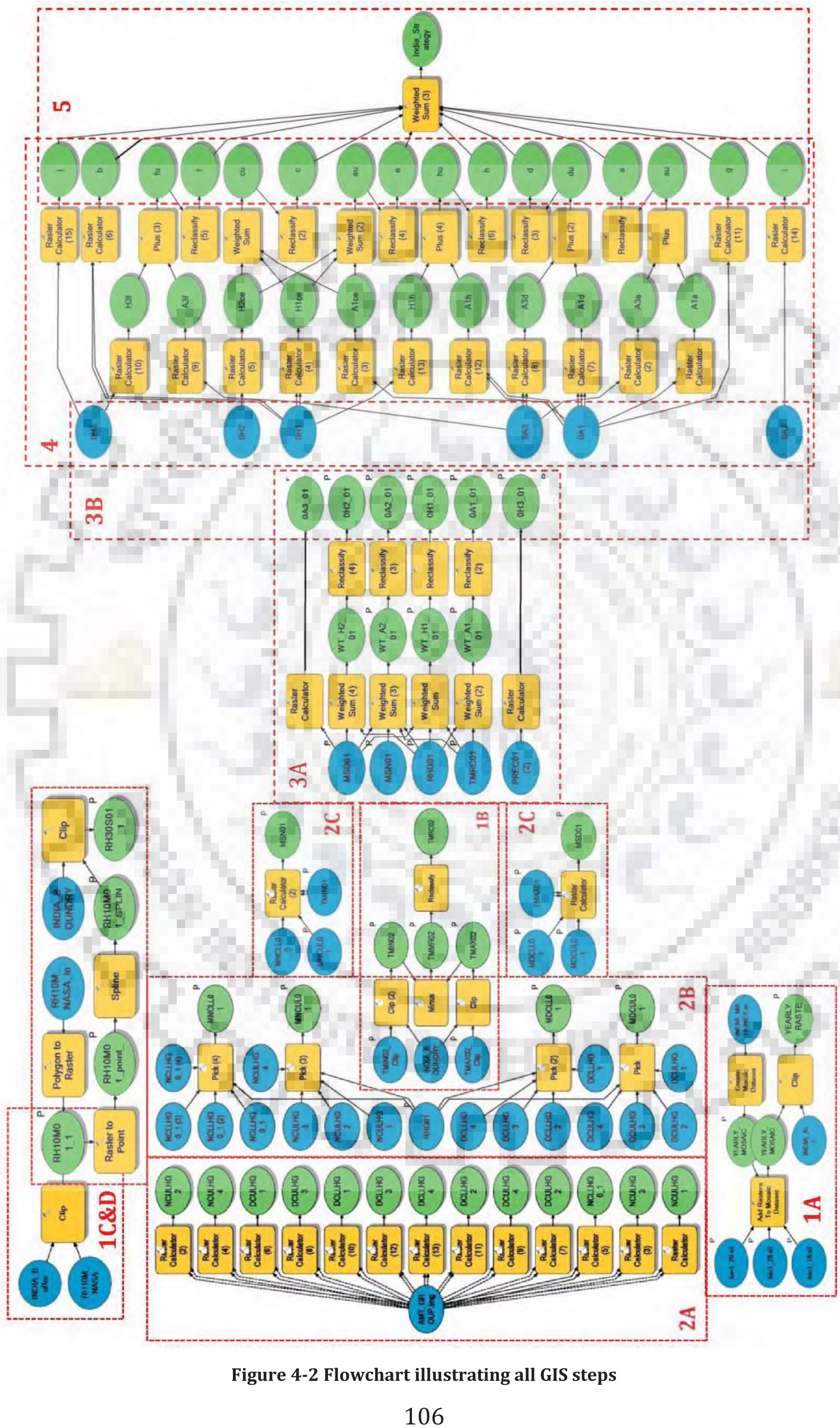


Figure 4-2 Flowchart illustrating all GIS steps

tables [68]; and are useful for delineating extents of recommended design specifications across India (Strategy Maps).

Interpolated climatic data having resolution 1km X 1 km [59] subset for India is used in the development of Thermal Comfort Design Zones based on Mahoney table analysis in Arc GIS for whole of India.

4.3.1. Methodology for delineation of Thermal Comfort Design Zones

TCD zone delineation has been achieved by adopting the method of understanding the whole through its parts as illustrated by Singh et al [130]. The detailed GIS procedure for delineating these zones has been published in peer reviewed journal article [113] attached in appendix as PAPER 1. To give a broad overview of the methodology, the 5 steps (some of them combined and some are iterative) involved in the raster based spatial analyses implemented in GIS have been illustrated together in Figure 4-2.

Steps 1A, 1B, 1C and 1D were performed to collate the climatic parameters required in Mahoney table analysis as shown in Table 2-5. Steps 2A, 2B and 2C were performed to analyze thermal stress based on adaptive comfort limits shown in Figure 2-32. Steps 3A and 3B were performed for ascertaining applicability and duration of climatic indicators across India based on criteria shown in Table 3-6. Step 4 was performed for ascertaining elemental design recommendations under 8 (+2 combined) strategy groups on the map of India based on respective criteria shown in Table 3-7 through Table 3-14. Maps output from Step 4 were superimposed in step 5 for identifying zones with unique combinations of recommendations for component design. Results of regional climate level analysis are discussed in section 5.2.

4.3.2. Strategy identification interface

The resulting thermal comfort design zone map of India has 62 significant zones. Unique combination of elemental design recommendations for a particular zone can be read from Tabulation of Zone wise recommended strategies APPENDIX 1. As shown in Figure 5-1 the TCD Zone of any location in India can be accessed using Google Earth App.

Building legislation is a state level subject. A comparison between administrative units of a particular state and the delineated TCD Zones therein is necessary to assess the usefulness and enable designation of TCD Zones as a basis for regionalization of building legislation. A comparative assessment was carried out across the extents of administrative units of India and across ULBs in Maharashtra state.

4.3.3. TCD Zone as a basis for Regionalization of building legislation

As shown in section 1.1.1.1, Maharashtra being the most urbanized state of India is a suitable candidate for the assessing the efficacy for TCD Zones in regionalizing the building legislation. For maximum coverage, recommendations have been formulated for regional rules pertaining to climate responsive design, enforced through the recently standardized development control and promotion regulations.

4.3.3.1. Classification of identified ULBs

As seen in section 2.5.2.1 urban local bodies are responsible for the enforcement of regulations pertaining to building design and construction as well as upkeep of the urban environment. Various types of urban local bodies are constituted from time to time for governing various types of urban settlements listed in Table 2-7 as and when they fulfill the specified criteria. The Urban Development Department - Government of Maharashtra issued two separate notifications for enforcing standardized development control and promotion regulations (DC&PR) for municipal councils, nagar panchayats and urban areas under regional plan [148,149]. The notification enlists 228 ULBs belonging to six different administrative classes namely A- Class, B- Class and C- Class Municipal Councils, Non Municipal councils, nagar panchayats and zilla praishad. Apart from these DC&PRs for 24 Municipal Corporations are notified separately.

4.4. Local Climate level analyses

Functioning at the intermediate level local climate analyses are to be based on local climate zones delineated within the selected city [9] and measurement of diurnal micro-meteorological data simultaneously at various locations across seasons [122]; and will be useful for identify the desirable urban built-form existing in the selected city. Before arriving at the methodology suitable for local climate analysis at city scale, field-study and satellite image-analysis based work flows were implemented for various study areas at neighborhood scale in stages as discussed below.

4.4.1. Micro meteorological field survey

Two modes of micro meteorological field surveys namely, mobile survey and diurnal survey were implemented for I. I. T. Roorkee campus. The details of instrumentation and methodology of conducting the surveys have been discussed in published articles [161] attached as appendix PAPER 3 and [160] attached as appendix PAPER 2 respectively.

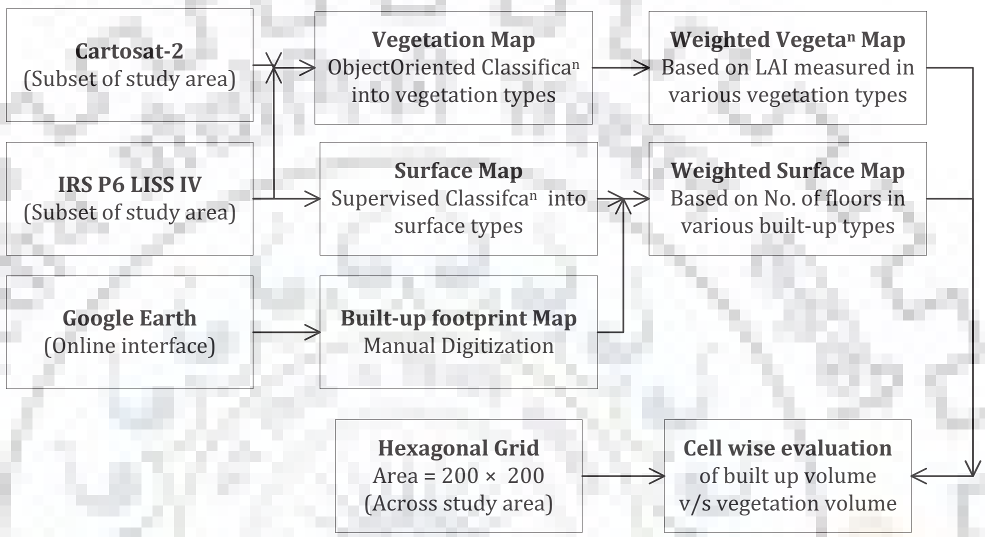


Figure 4-3 Workflow for surface classification used in Local climate analysis

4.4.2. Urban surface Classification & Built-up to vegetation ratios

Urban surface classification is the first step in calculating built-up to vegetation ratio, required for establishing the physical basis of climate variation at local level [132]. Physical land cover survey implemented at I. I. T. Roorkee is discussed in published article [160] attached as appendix PAPER 2. The method provides classification at a high resolution; however it was found to be cumbersome and is prone to errors due to dependence on subjective classification by surveyors.

Satellite imagery based classification was identified as a more objective and quick method for urban surface classification. State of the art methodology has been implemented using supervised classification of 'land cover' for calculating constituent parameters. The resulting "Urban Neighbourhood Greenery Index" map [56] has been analyzed on the basis of sector wise 'land use' designated by NOIDA as described in published article [162] see appendix PAPER 4. The method provides quick classification of urban surfaces but it was found to have a low resolution that may not be suitable for identifying three dimensional composition of vegetation required for estimating local climate variation.

To overcome the limitations of the two methods of urban surface classification discussed above, a method has been devised as shown in Figure 4-3. The method uses manual photo interpretation of urban surfaces at high resolution and object oriented analysis of multispectral imagery for three dimensional classification of urban vegetation. Paper discussing the method is in communication.

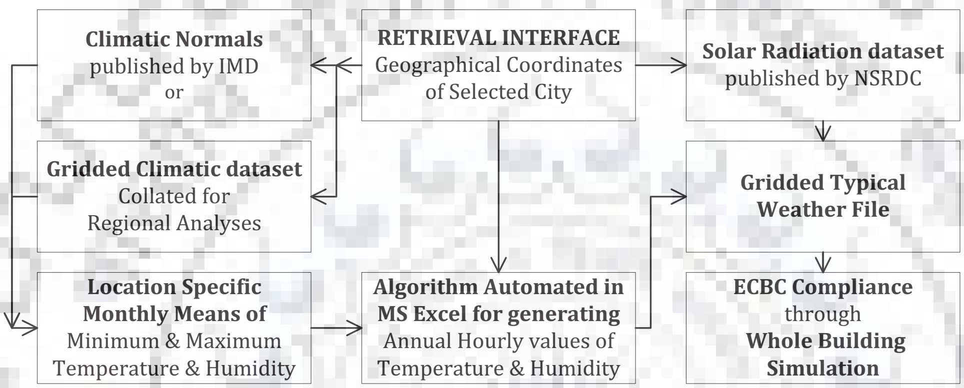


Figure 4-4 Workflow for Typical Climate Analyses

4.5. Typical Climate level analyses

Functioning at detailed level, typical climate analyses are formulated to deal with the issues arising from use of hourly climatic data published for representative cities. A methodology has been developed to generate typical weather files for any city where performance evaluation of buildings is intended as per whole building compliance method stipulated by ECBC.

4.5.1. Generation of Regionalized Typical Weather Files

The workflow has been developed for generating Local Typical Weather Files as shown in Figure 4-4. The workflow is based on temporal interpolation of climate variables introduced in section 3.3.3 [124] (translation from Portuguese attached as APPENDIX 3). The algorithms for estimation of hourly temperature and humidity values have been automated using MS excel. Maxima and Minima of monthly temperature and humidity can be input from climatic normals while the solar angle information has been completed using a published automated spreadsheet [49].

Gridded data collated during Regional Climate analysis can be used to retrieve monthly extremes of temperature and humidity based on the geographical coordinates of any location. This data can be used as input for the algorithm in the absence of published climatic normals for a particular city, Modeled hourly solar radiation data [128] in grid format has recently been published and is available for collation with other climatic variables.

4.6. Application of research tools

The various tools required to carry out the research may be categorized into tools for data collection, analysis, illustration, documentation and reference management. Geographical Information System is an integrated research tool which performs various categories of research activities and hence has been discussed in the following at length.

4.6.1. Analysis and Illustration tools

While Arc GIS is a versatile tool that performs analysis and illustration using vector and raster data, support from other applications was necessary. Many analyses involved attribute data from Arc GIS exported to MS Excel for utilizing features like pivot table, custom sorting and filtering, gradient fill using conditional formatting, etc. At few instances the data analyzed in Excel had to be imported in GIS for illustration.

Though it was possible to achieve most of the diagramming of process flows during their formulation in 'Model Builder' module of Arc GIS; few methodology flow charts were also created using vector graphics in MS Visio.

4.6.2. Documentation and Illustration tools

While Microsoft office applications namely, Word and PowerPoint are primarily used as a word processor and a presentation application respectively, they many times doubled up as illustration tools for assembling graphical support to literary discussion. The Snipping tool available as part of Windows accessories is especially useful for converting any graphic displayed on screen into a figure used in documentation. Microsoft Paint comes handy for cropping, annotating and touching up scanned or snipped figures.

4.6.3. Reference management tools

Backward searches and forward searches collectively called 'Snowball search' are an integral part of rigorous literature review [18]. The process has now been automated to a considerable extent due to the use of advanced research repositories like Scopus from Science Direct, JStore, Google Scholar, Research gate etc., where researchers themselves are sharing their publications online. The task of reference / citation management has also become streamlined due to integration of all these repositories with software like Mendeley and through it with the word processor.

4.7. Summary

Workflows have been established at the three levels of climatic analyses identified in the analytical framework; using the state of the art materials and methods, tools and techniques dealt with in literature review.

At the Regional Climate level, unique combination of climate responsive design specifications recommended for any location across India can be ascertained by using the developed Google Earth app. Thermal Comfort Design Zones developed at this level form the basis for regionalization of development control and promotion regulations.

At the Local Climate level, ratio between the densities of built form and vegetation was identified as the indicator for assessing variation in local climate. A workflow was developed to overcome the deficiencies in two separate methods available for mapping built form and vegetation density.

At the Typical climate level, location specific local typical weather file can be generated using mean monthly extremes available from published climate normals or collated gridded climatic data [59] for selected city obtained from retrieval interface.

The workflows were implemented and results were published or are in the process of publication. The following chapter deals with results obtained from the established workflows.

CHAPTER 5. ASSESSMENT AND DISCUSSION

5.1. General

This chapter deals with assessment of result found after implementation of workflows identified in analytical framework. Furthermore development of the focal theory is also discussed. The beginning section deals with variation in recommendations for individual element design and resulting TCD Zones across India. The next section deals with regionalization of development control regulations across Maharashtra and variation in ECBC specifications for building components and design conditions in response to TCD Zones. The later sections deal with results of local climate & typical climate assessment.

5.2. Extents of Thermal Comfort Design Zones across India

As the culmination of Regional Climate level analyses (section 4.2.2), a Google Earth App has been developed to access the TCD Zones delineated across India (Figure 5-1.).

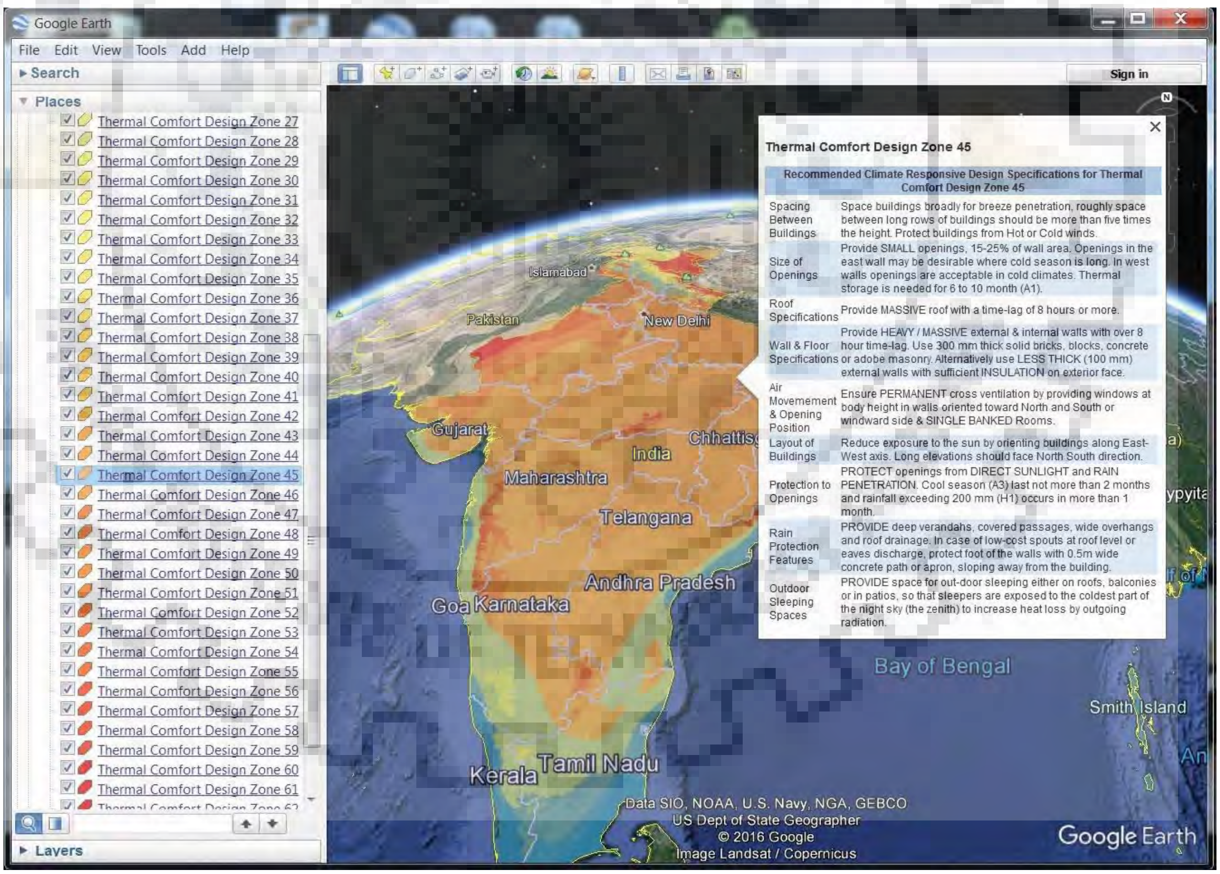


Figure 5-1 Google Earth App to access extents of TCD Zones and corresponding specifications

On selecting a particular location a popup displaying its TCDZ SR & description appears. The zone description lists the unique combination of passive design specifications recommended in response to the thermal stresses arising out of that location's prevalent climatic conditions. Nine strategy maps – delineating extents of design specifications recommended for various components based on Mahoney Tables selection criteria – used in overlay analysis for creation of TCD Zones are described in the following. The discussion of extents of recommended specifications is trifurcated into sections namely built form design, building envelope design and opening design as per the sequence followed in section 3.4 while dealing with *Climate Modulation Strategies*.

5.2.1. Regions based on recommendations for built form

Four maps delineating extents of recommended specifications for 'building layout and orientation', 'spacing between buildings', 'outdoor sleeping spaces' and 'rain protection' are discussed in this section.

5.2.1.1. Regional recommendations for building layout & orientation

Two regions namely a1 and a2 (see Figure 5-2), have been delineated based on climatic criteria described in Table 3-7, to identify distinct specifications for **building layout & orientation** recommended as per Mahoney Tables [69].

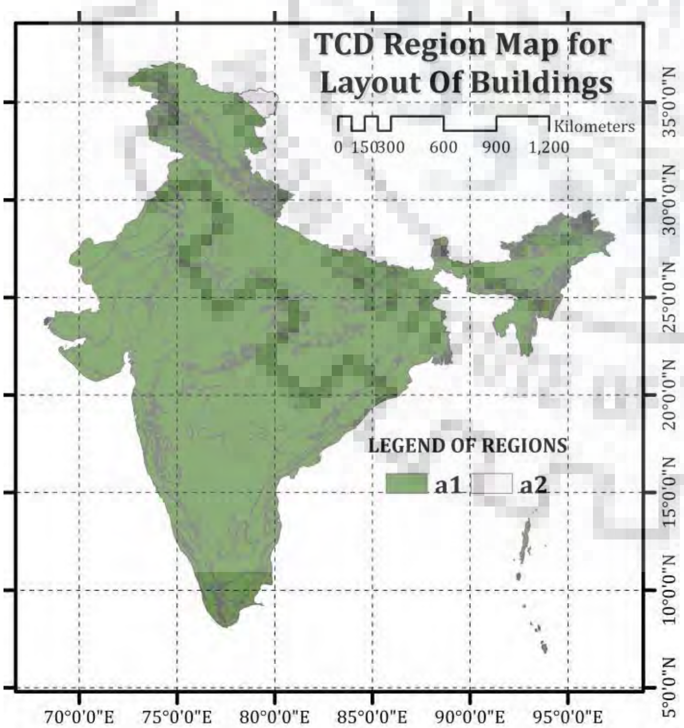


Figure 5-2 TCD Region Map of recommended Layout of Buildings

Region a2 is located in the state of J&K to the northeast of Karakorum Range, rest of India falls under region a1. In region a1, "*either thermal storage (A1) is required for up to ten months or if there is requirement of thermal storage for eleven or twelve months along with winter (A3) season of more than four months. Here as far as possible buildings should be oriented on an east-west axis with the long elevations facing north and south to reduce exposure to the sun. The buildings may be turned slightly so as* *to catch the breeze prevailing in the vicinity of site or to allow limited solar heating during the cold season (A3)”* [69].

In region a2, on the other hand “*cold season (A3) exists for less than five months, but thermal storage (A1) is required for eleven or twelve months and hence it is necessary to plan the buildings around small courtyards”* [69].

5.2.1.2. Regional recommendations for spacing between buildings

As shown in Figure 5-3 three regions, namely b1, b2 & b3 have been delineated based on climatic criteria described in Table 3-8, for identifying distinct specifications pertaining to **spacing between buildings** recommended as per Mahoney Tables [69].

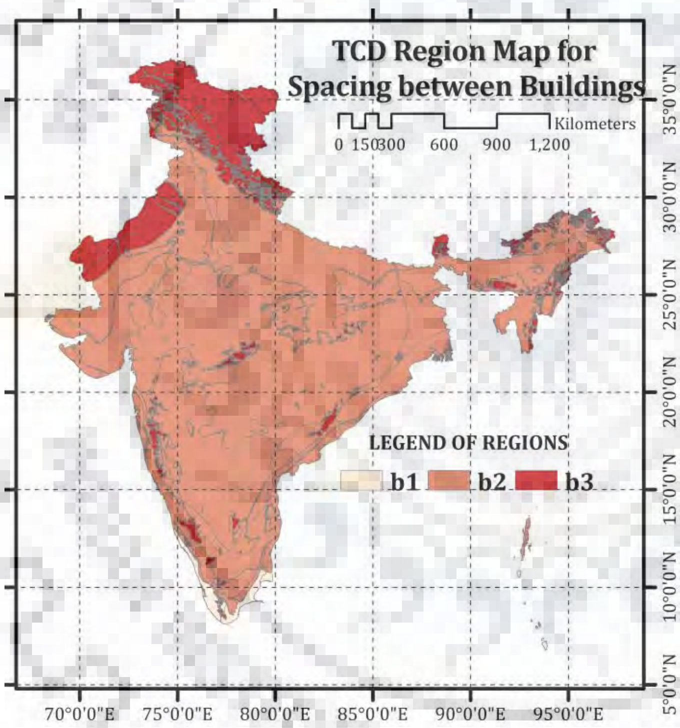


Figure 5-3 TCD Region Map of recommended Spacing between Buildings

Region b1 is found to be located in a narrow strip along the Malabar and Coromandel coast to the south of latitude 13° N; while region b3 is found to be scattered in diverse locations, mainly located in various states encompassing the Himalayan range and its highlands, and in Thar Desert of Rajasthan. It is also to be found scattered in Western Ghats of Maharashtra, Karnataka, Kerala and Tamil Nadu, Eastern Ghats of Andhra Pradesh and Orissa, Satpura Range in Madhya Pradesh.

The rest of India falls under region b2. In region b1, “*air movement (H1) is essential for eleven to twelve months, hence the space between long parallels rows of buildings should be roughly five times the height of buildings or more, to allow for breeze penetration*. In region b2, *air movement (H1) is need for two to ten months of the year, hence spacing for breeze penetration is still needed, but buildings and planting should also be planned to give protection against dusty hot or cold winds coming from prevalent directions at prevalent* *speeds"* [69]. On the other hand "*air movement (H1) is need for not more than two months, hence compact planning is essential"* [69] in region b3.

5.2.1.3. Regional recommendations for outdoor sleeping spaces

As shown in Figure 5-4, two regions, namely i1 & i2, have been delineated, based on climatic criteria described in Table 3-9, for identifying distinct specifications for **provision of space for outdoor sleeping** recommended as per Mahoney Tables [69]. Region i1 is found to be located in various states encompassing the Himalayan range and its highlands, seven northeastern states, Sikkim, parts of Bihar and West Bengal as well as in the Northern Circars, Coromandel Coast, Malabar Coast, parts of Konkan and Kathiawar peninsula. Rest of Indian Territory in found under region i2.

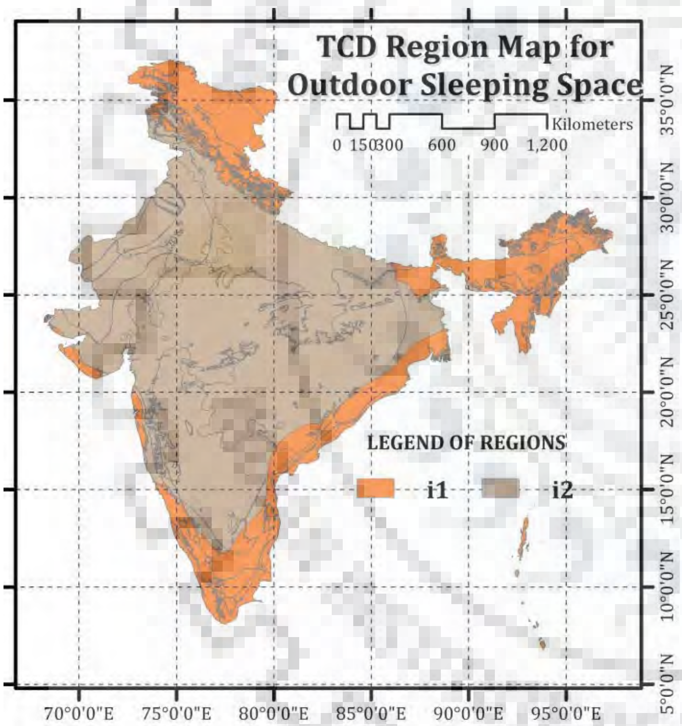


Figure 5-4 TCD Region Map of recommended provision of space for Outdoor Sleeping

In region i2 "*for more than one month, either night temperature is high (night time stress = H) and the humidity is low (HG = 1 or 2) or nights are comfortable outdoors but hot indoor as a result of heavy thermal storage (diurnal range is above 10 degC). Here sleeping spaces should be provided on the roofs or balconies or in patios and should be exposed to the coldest part of the night sky (the zenith) to permit heat loss by out-going radiation. Such an outdoor sleeping space may never be used"* [69] in region i1.

5.2.1.4. Regional recommendations for rain protection

Based on climatic criteria described in Table 3-9, two regions, namely j1 & j2, have been delineated as shown in Figure 5-5, for identifying distinct specification pertaining to rain protection recommended as per Mahoney Tables [69].

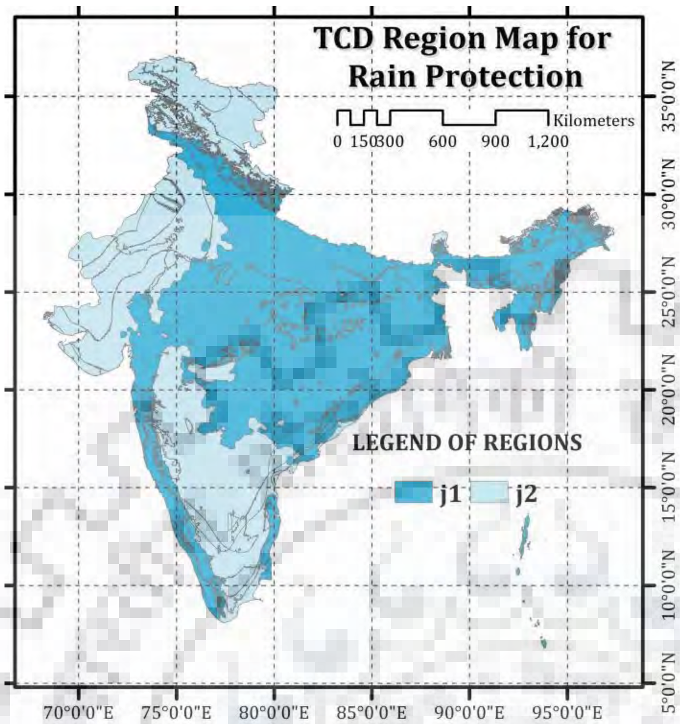


Figure 5-5 TCD Region Map of recommended Rain Protection

Region j1 is found all along the west coast on the windward side of Western Ghats; extending northward into parts of Gujarat, Malwa Plateau, Indo Gangetic Plain; eastward into Chhota Nagpur Plateau, Chhattisgarh Plains, Northern Circars and parts of Coromandel Coast; and seven states of north east India. The rest of Indian Territory falls under region j2. In region j1, *"rainfall exceeds 200 mm per month hence problems of rain penetration will be inevitable. Hence special protective measures like deep verandahs, wide overhangs and covered passages are recommended. Such measures are* not *necessary"* [69] in region j2.

5.2.2. Regions based on recommendations for building envelope

Two maps delineating extents of recommended specifications for 'roof design' and 'wall and floor design' are discussed in this section.

5.2.2.1. Regional recommendations for roof design

As shown in Figure 5-6 three regions, namely h1-h3 have been delineated based on climatic criteria described in Table 3-10, to identify distinct specifications pertaining to **roof design** recommend as per Mahoney Tables [69]. Region h1 is found to be located in a narrow strip along the Malabar and Coromandel coast to the south of latitude 13° N; while region h2 is found along a narrow strip on the coast of Kathiawar Peninsula, extending along the Konkan Coast, crossing the Western Ghats near the Coromandel Coast, then extending along Circars and into the plains of West Bengal and into the seven north eastern states. It is also found in the Western Himalayas and parts of Jammu and Kashmir. Rest of the Indian Territory is found under region h3.

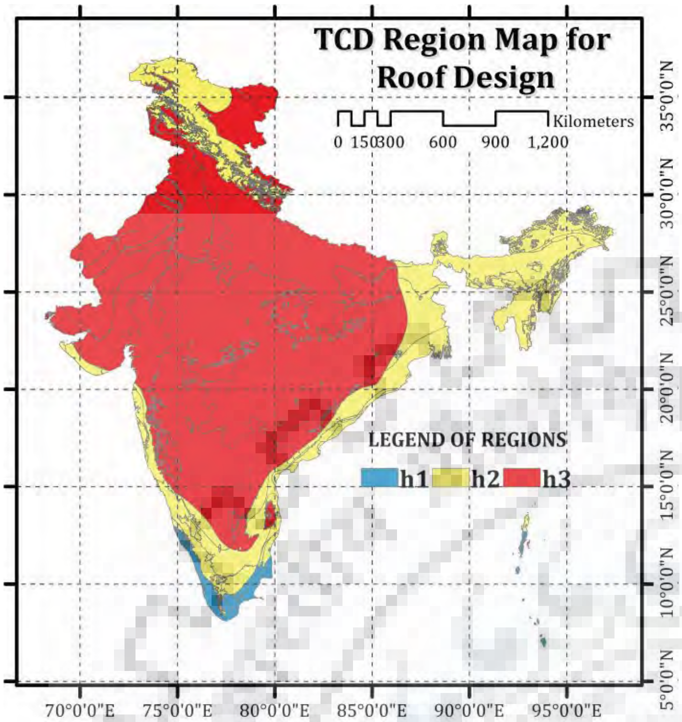


Figure 5-6 TCD Region Map of recommended Roof Design

In region h1, "*air movement is needed for more than nine months (H1 = 10 to 12) and thermal storage is required for not more than three months (A1 = 0 to 2), hence a light but well insulated roof should be used. The outer surfaces should have a light color or a shiny metal surface to reflect solar radiation. The roof should incorporate a cavity and insulation to ensure that only a small percentage of the solar radiation is transmitted through the structure*" [69].

Where as in region h2, "*air movement is needed for less than nine months (H1 = 0 to 9) and thermal storage is needed for less than six months (A1 = 0 to 5), hence a lightweight and especially well insulated roof should be used. The extra insulation is required to prevent the underside of the roof heating up incase ventilation is reduced during the months when thermal storage is needed. A well-insulated lightweight roof may consist of a thin light-colored or shiny metal skin, a cavity and a ceiling which incorporates some insulating material such as fiber board, expanded polystyrene and a reflective surface such as aluminum foil*" [69]. Glare control may be required incase shiny metal skin is used. On the other hand in region h3, "*the requirements of air movement and thermal storage as other than those mentioned above, hence a heavy roof should be used.*

It should provide a time lag of about eight hours. The density and thickness of homogenous materials which achieve an eight hour time lag can be found from Figure 5-7. The time lag is increased if lightweight insulation is added to the outside of heavy weight construction" [69].

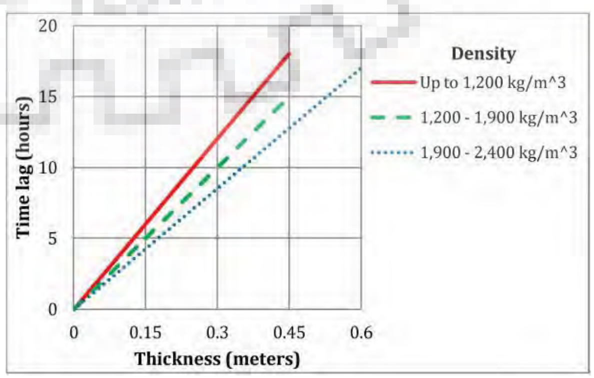


Figure 5-7 Time lag chart Source:[144]

The same time lag can be obtained by using a thinner structure with outside insulation. Where the roof is used for outdoor sleeping, a heavy terrace construction is justified.

5.2.2.2. Regional recommendations for wall and floor design

Two regions, namely g1 & g2 (see Figure 5-8), have been delineated based on climatic criteria described in Table 3-11, for identifying distinct specifications pertaining to wall and floor design, recommended as per Mahoney Tables [69]. Region g1 is found to be located in isolated narrow patches along the Konkan Coast, Malabar Coast, Coromandel Coast, Northern Circars; and isolated patches in Khasi hills and Dafla range in Eastern Himalayas; and in a contiguous stretch in Western Himalayas. The rest of Indian Territory is found under region g2.

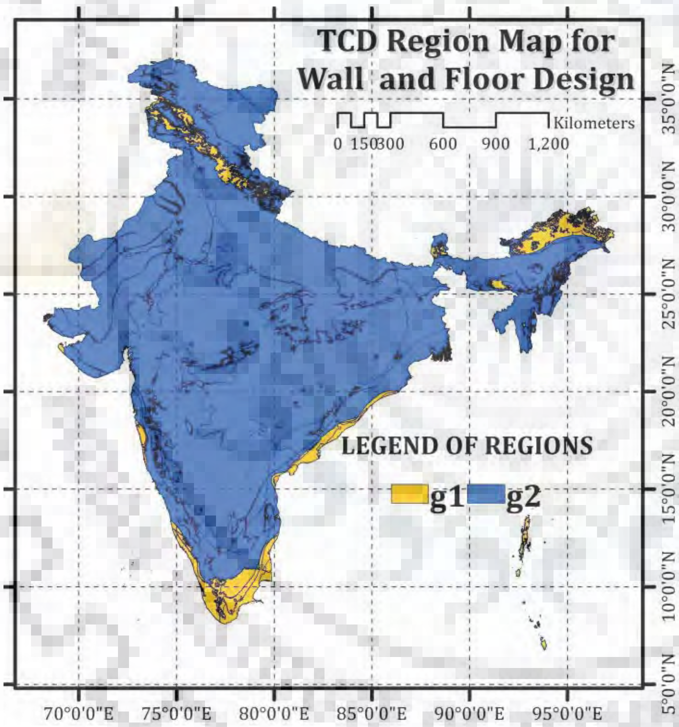


Figure 5-8 TCD Region Map of recommended Wall and Floor Designs

In region g1, "*thermal storage (A1) is needed for less than three months, hence light external walls should be used. The reduce thermal storage in the wall, hollow concrete blocks or bricks with a minimum void of 40 per cent can be used. A wall using two light materials and a cavity will give acceptable thermal properties, but the cavity might be a problem as it can harbor insects and vermin. A thin solid wall (e.g., 2 inches of dense concrete) is acceptable if precautions are taken to prevent rain penetration and condensation.*

To reduce the heating effect of solar radiation, the wall should have a light-colored surface, for instance, white, yellow or cream" [69].

In region g2, "*thermal storage (A1) is needed for more than two months, hence heavy, high-heat capacity walls should be used. Once again, light-colored surfaces are needed, but the very light colors may cause glare when reflecting bright sunlight. In many desert settlements* *a very light brown surface treatment is common. A solid or cement block wall 300 millimeters thick would have the required heat storage capacity. A slightly thinner wall can be used if a dense concrete block is used. Walls down to 100 millimeters are acceptable if they are insulated on the outside. An appropriate wall thickness can be found by using Figure 5-7"* [69].

5.2.3. Regions based on recommendations for opening design

Three maps delineating extents of recommended specifications for 'opening position and air movement', 'opening size' and 'opening protection' are discussed in this section.

5.2.3.1. Regional recommendations for opening position and air movement

In Figure 5-9 three regions, namely c1-c3, have been delineated, based on climatic criteria described in Table 3-12, for identifying distinct specifications pertaining to **air movement**, recommended as per Mahoney Tables [69]. Since climatic criteria e1-e2-e3 for recommending distinct specifications of **opening position** correspond with those of c1-c2-c3 respectively, regional recommendations for both elements are concurrently discussed. Region c2 is found to be located at sporadic locations in the Western Ghats, Satpura Range, Eastern Ghats, Khasi Hills, Mizo Hills, parts of Sikkim and Arunachal Pradesh; contiguous stretches in Western Himalayas; and a large contiguous area from the Rann of Kutch, running along Thar Desert to Doaba region of Punjab. Whereas region c3 is found in higher Himalayas and interior of Thar Desert bordering Pakistan. The rest of Indian Territory is found under region c1. Regions pertaining to opening position match exactly with those of air movement. In region c1, "*either air movement is essential (H1) for more than two months, or air movement is needed for one or two months and thermal storage (A1) is required for zero to five months"* [69].

Here, *"rooms should be single banked with windows in the north and south walls should be placed in order to direct breeze across the room at body level. In places where it is customary to sit or recline on the floor, window sills on the inlet side should not be higher than 200 millimeters. The outlet position has less effect on the flow pattern, but the size of the outlet does affect the speed of the wind. For optimum air speeds within the room, the outlet should be slightly larger than the inlet. Large windows make it necessary to take* *precautions against sky glare by the use of overhangs and sunshades. The view out of the window should be directed towards the ground and vegetation"* [69].

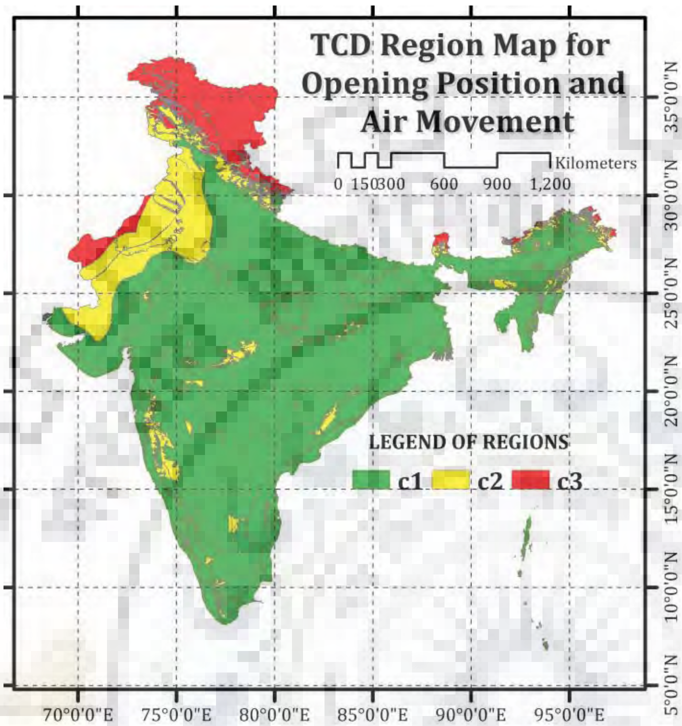


Figure 5-9 TCD Region Map of recommended Opening Positions and Air Movement

Whereas in region c2, *"either air movement is needed for not more than one or two months (H1 = 1 or 2) and thermal storage is needed for more than five months (A1 = 6 to 12); or air flow is not essential but desirable for more than two months (H2 = 2 to 12)"* [69]. Here, *"double banked rooms may be planned with internal openings* for instance *interconnecting doors / ventilators carefully designed to enable temporary cross-ventilation combined with visual privacy. If the prevailing wind is unreliable or if site limitations restrict planning for air movement, ceiling fans should be considered at the sketch design stage as it implies minimum room heights of not less than 2.75 meters.* On the other hand in region c3, *either air movement is never required (H1 = 0) to achieve comfort or it is required to maintain comfort for one month or less (H2 = 0 to 1)"* [69]. Here, *"rooms should be double banked, but though there is no requirement for air movement special provisions for ventilation are essential. Ventilation openings serve three purposes; (a) Replacement of stale air; (b) Removal of heat generated inside a room by people (classrooms or conference rooms) or machines (kitchens or workshops), and (c) Cooling down of the building fabric at night. This applies for instance when days are hot and nights are cool and thermal storage is used to improve the day time indoor climate. Effective ventilation needs openings on opposite side of a room, preferably a low-level air inlet and a high-level outlet. Ventilation openings need not be windows. Ventilation shafts, openings to ducts, wind scoops or light wells can be satisfactory"* [69].

5.2.3.2. Regional recommendations for opening size

As shown in Figure 5-10 five regions, namely d1-d5 have been delineated based on climatic criteria described in Table 3-13, to identify distinct specifications pertaining to opening size, recommended as per Mahoney Tables [69]. Region d1 is found to be located in isolated narrow patches along the Konkan Coast, Malabar Coast, Coromandel Coast, and Northern Circars to the south of latitude 18° N; while region d2 is found along a narrow strip on the coast of Kathiawar Peninsula, extending along the Konkan Coast, crossing the Western Ghats near the Coromandel Coast, then extending along Northern Circars and into the plains of West Bengal and into the seven north eastern states. It is also found in the Western Himalayas and parts of Jammu and Kashmir. Regions d3 and d5 are found in isolated patches in and interior of Thar Desert bordering Pakistan and northeast of Karakorum Range. Rest of the Indian Territory is found under region d4.

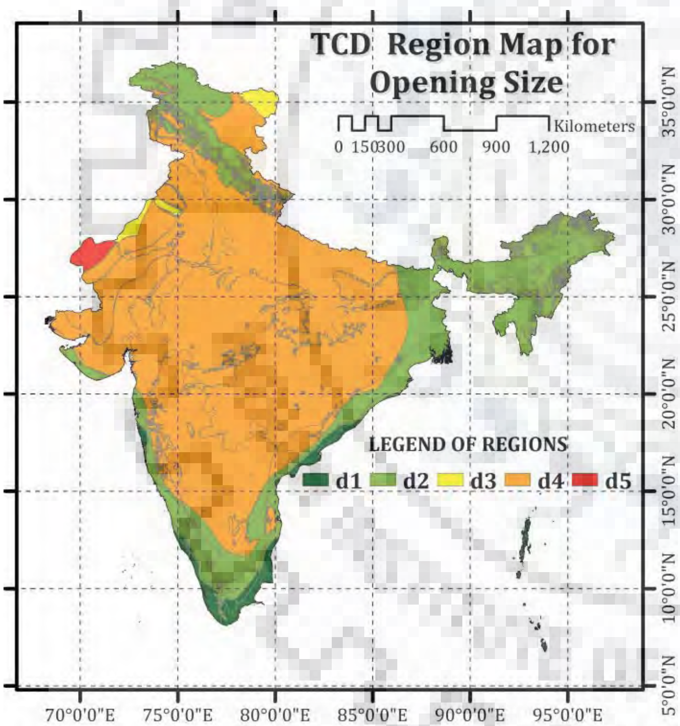


Figure 5-10 TCD Region Map of recommended Opening Sizes

In region d1,*"either thermal storage is never required, or even if it is required for only one month (A1 = 0 or 1); there is no cold season (A2 = 0)"* [69]. Here *"large openings between 40 to 80 per cent of wall area should be used and so planned as to direct the breeze across the room at body level"* [69]. In region d2, *"thermal storage is needed for less than two months (A1 = 0 or 1) and there is a cold season (A3 = 1 to 12)"* [69]. Here *"medium openings between 25 to 40 per cent of wall area should be used and may be designed to allow sun to penetrated during the winter months"* [69]. In region d4, *"thermal storage is needed between six and ten months (A1 = 6 or 10).* Here *small openings between 15 to 25 percent of wall area should be used. The increase in area of solid wall is needed for thermal storage".*

In region d5, *"thermal storage is needed for more than ten months (A1 = 11 or 12) and cold season is less than four months (A2 = 0 to 3)"* [69]. Here *"very small openings between 10 to*

20 per cent of wall area should be sufficient. Special provision should be taken to prevent sun penetration to the interior during the long hot season" [69]. In region d3, *"thermal storage is needed for more than ten months (A1 = 11 or 12)"* like d4, "but *cold season is longer (A2 = 4 to 12)"* [69]. Here *"composite openings between 20 to 35 per cent of wall area should be used and may be designed to allow the sun to penetrate during the cool months"* [69].

5.2.3.3. Regional recommendations for opening protection

Four regions, namely f1-f4 (see Figure 5-11), have been delineated based on climatic criteria described in Table 3-14, to identify distinct specifications pertaining to **opening protection**, recommended as per Mahoney Tables [69]. By comparing Table 3-14 and Table 3-9 one may be able to decipher that these regions are subsets of region j1 (f3 & f4) and j2 (f1,f2) corresponding to distinct specifications for rain protection. The bifurcation is based on the need for protecting openings from sun penetration during summers.

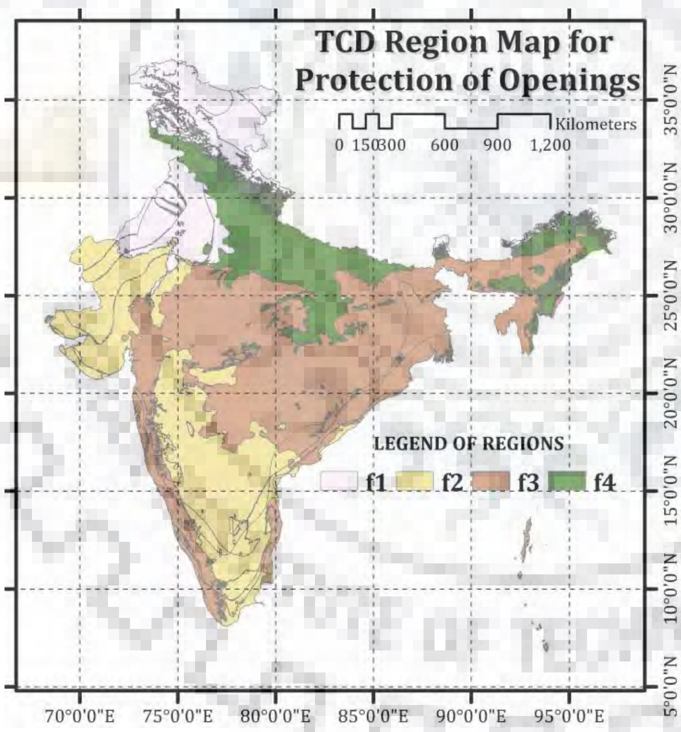


Figure 5-11 TCD Region Map of recommended Opening Protection

In region f1, "*cool or cold season lasts more than two months (A3 = 3 to 12), hence one might allow the sun to come in during winter months and exclude it for the rest of the year, by using overhanging eaves or special shading devices. The design of sun shades should be based on determination of critical dates, such as the beginning and end of the shading period, and estimation of hourly temperatures from the maxima & minima"* [69] [144; annex I].

In region f2, "*cool or cold season lasts for less than three months (A3 = 0 to 2), hence direct entry of the Sun into the interior of the house should be excluded"* [69]. Though cool season in region f3 is as short as in region f2, "*it receives more than 200 millimeters rainfall in at least one month; hence apart from exclusion of direct sunlight, effective rain protection will also be needed in this region. Heavy* *rain is often accompanied by strong wind that forces droplets through openings, even if they are protected by overhangs or louvers. Air temperature may drop slightly during tropical rainstorms, but the humidity remains high and air movement would be desirable for comfort"* [69]. Unless a louvered screen that allows breeze to enter but keeps rain out is installed [144], tightly closing windows is the only way of keeping rain out. Rainfall in region f4 is similar to region f3, and cool or cold season is similar to region f1, hence *only rain protection will be needed in this region.*

Region f1 is first subset of j2 and is found in two patches; one in parts of Thar Desert, Rajasthan and Haryana, extending up Doaba region of Punjab and the other to the north of Western Himalayas; while region f2 is also found in two patches; one in the Kathiawar Peninsula extending into the Rann of Kutch, and the other on the leeward side of Western Ghats covering most of Deccan Plateau and extending southwards in to parts of Coromandel Coast. Region f3 is found all along the west coast on the windward side of Western Ghats; extending northward into parts of Gujarat, Malwa Plateau; eastward into Chhota Nagpur Plateau, Chhattisgarh Plains, Northern Circars and parts of Coromandel Coast; and parts of seven states of north east India; while f4 is found in Indo Gangetic Plain and hilly areas of north eastern states.

Table 5-1 Zones merged during generalization

Strategies	TCDZ		SR →	1	2	4	6	8	9	10	14	15	16	17	19	20	21	22	23	24	26	27	30	31	32	34	35	36	42	43	44	45	46	47	48	49	50	51	53	54	55	56	57	58	60
22223119	4	A	44																								14	19																	11
22213119	6	B	276											53		6						30					23	5							111				42						6
33233249	12	C	13											4																									4					5	
33233219	13	D	6											3																									3						
33233149	17	E	6											1																									2					3	
43222118	20	F	228								7			9	23												9								171				9						
22213149	29	G	74								2		49			1					7													9				6							
22223149	32	H	4										3																									1							
22112119	35	I	1										1																																
43212118	36	J	1										1																																
22113118	37	K	67					3			4		57												3																				
22112118	39	L	73								2		71																																
43222148	44	M	264										3											43		20				1		3	119	7									68		
43222138	62	N	460																13	9										4	171	67					7				186	3			
22213139	67	O	44															1	1	18			10																			14			
12112139	69	P	13				3		2	8																																			
43233128	74	Q	16																											3						13									
43223128	75	R	12																											8						4									
43233129	76	S	24																																	23				1					
43222128	77	T	7																										1	6															
22233128	78	U	1														1																												
22223128	79	V	1																										1																
22113138	84	W	180	1	2	4	6	13	45			64	39						6																										
22113128	86	X	7					7																																					
dhgcbafi sequence of codes	Merged IDs/	Zones→	ENTITY→ COUNT↓	1	2	4	9	23	47	8	15	64	224	70	23	7	1	1	20	27	7	30	10	43	3	20	46	24	2	22	171	70	119	16	282	40	7	7	60	1	186	17	68	8	17

LEDGEND Maximum Minimum

Regional recommendations for the various building design elements have been discussed in the above sections using nine maps. Eighty-six regions with unique combinations of recommended specifications called TCD Zones have been identified by superimposing eight maps namely d, h, g, c, b, a, f and i. Note that recommendations from map j can be ascertained from map f.

5.2.4. Generalization of combined specification maps

Areas of extent of the 86 TCD Zones are found to vary from 168 grid cells to over a million grid cells. Considering that 1 grid cell approximately equals 1 sq. km. it was found that 24 out of 86 TCD Zone (28%) exist in scanty chunks of less than 100 sq. km. scattered across India. In the Regional Climate level analysis that follows, it would be redundant to discuss the tiny and sporadic TCD Zones alongside the larger TCD zones. Hence, the scanty chunks belonging to these 24 TCD Zones named A-X were merged with larger TCD Zones surrounding the respective chunks as shown in Table 5-1. Spatial distribution of the tiny TCD Zones A-X has been shown in Figure 5-12. TCD Zones A, B, C and F were found to be located in Jammu and Kashmir; while zones G, I, J, K & L were found in Himachal Pradesh; and zone M was found to be located predominantly in Uttarakhand and rarely near the border between Gujarat and Rajasthan. As seen from Figure 5-12 merged TCD Zone N was found to be located in Orissa, Chhattisgarh, Andhra Pradesh, Gujarat and Karnataka; while Zones O and P were found in predominantly in Maharashtra and rarely in Karnataka. TCD Zones Q, R, S and U were found to be located at the triple border region between Karnataka, Andhra Pradesh and Tamil Nadu, while Zone W was found to be located in Tamil Nadu and Kerala. TCD Zones D, E, H, T, U, V and X, having a cell count of less than 7, could not be represented to scale in Figure 5-12.

The extents of 62 TCD Zones (prevailing after merger) have been analyzed in comparison to various physical and analytical entities in the following.

5.2.5. Comparison between various TCD Zones

Regional recommendations of all TCD Zones have been compared in Table 5-2. Pertaining to recommendations for size of openings, while most of the TCD zones correspond with region d2; as little as 1, 3 and 6 TCD Zones were found to correspond with regions d5, d3 and d1 respectively. While all TCD Zones corresponding with regions d3, d4 and d5, correspond with region h3, pertaining with recommendations for roof design, most zones corresponding with regions d1 and d2 also correspond with regions h1 and h2 respectively. With respect to the recommendations for wall design, most of the TCD Zones correspond with region g2. Pertaining with recommendations for layout of buildings, only one TCD Zone was found to correspond with region a2, while the rest correspond with region a1.

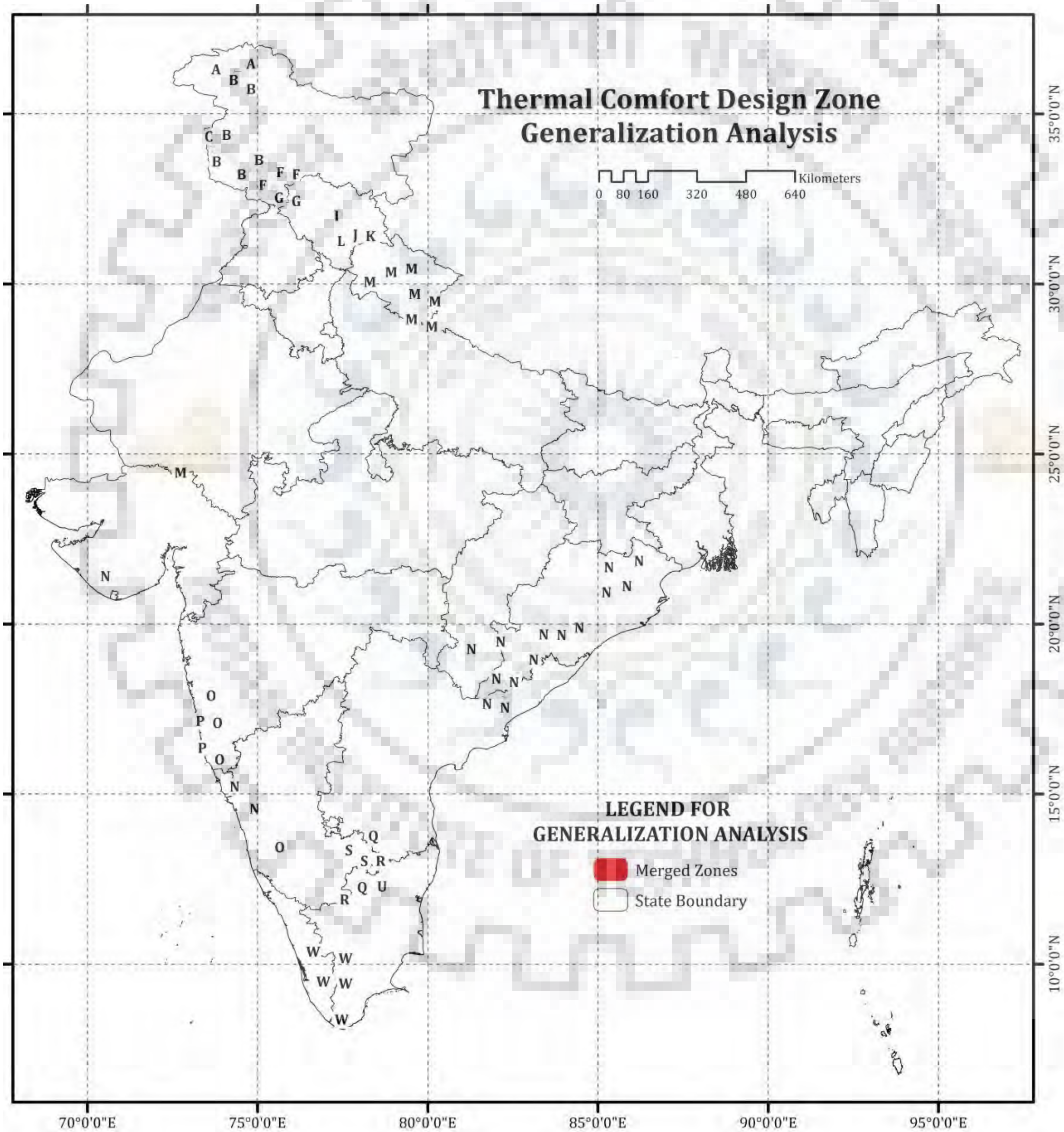


Figure 5-12 Map showing locations of TCD Zones merged during generalization

Table 5-2 TCD Zone wise regional recommendations and pixel counts

↓ TCDZ SR	SIZE OF OPENING	ROOF	WALL AND FLOOR	AIR MOVE./ OPEN. POSI.	SPACING	LAYOUT	OPENING PROTEC.	OUTDOOR SLEEPING	↓ TCDZ SR	Pixel Count	Percent Coverage
Abbrevia[n]	d	h	g	c	b	a	f	i			
1	1	1	1	1	1	1	2	1	45	1125596	27.06%
2	1	1	1	1	1	1	3	1	43	622813	14.97%
3	1	1	1	1	2	1	2	1	47	464322	11.16%
4	1	1	1	1	2	1	3	1	23	360245	8.66%
5	1	2	1	1	2	1	2	1	35	163618	3.93%
6	1	2	1	1	2	1	3	1	48	135358	3.25%
7	2	1	1	1	2	1	3	1	49	132081	3.18%
8	2	2	1	1	2	1	2	1	24	99147	2.38%
9	2	2	1	1	2	1	3	1	21	95127	2.29%
10	2	2	1	1	2	1	3	2	59	94068	2.26%
11	2	2	1	1	2	1	4	1	53	75348	1.81%
12	2	2	1	1	2	1	4	2	25	69662	1.67%
13	2	2	1	1	3	1	4	1	16	44229	1.06%
14	2	2	1	2	3	1	1	1	11	43905	1.06%
15	2	2	1	2	3	1	3	1	44	41570	1.00%
16	2	2	1	2	3	1	4	1	41	38634	0.93%
17	2	2	1	3	3	1	1	1	42	34835	0.84%
18	2	2	1	3	3	1	4	1	17	34431	0.83%
19	2	2	2	1	2	1	1	1	22	33212	0.80%
20	2	2	2	1	2	1	1	2	62	31410	0.76%
21	2	2	2	1	2	1	2	1	6	30475	0.73%
22	2	2	2	1	2	1	2	2	2	29993	0.72%
23	2	2	2	1	2	1	3	1	54	27239	0.65%
24	2	2	2	1	2	1	3	2	51	26905	0.65%
25	2	2	2	1	2	1	4	1	40	26541	0.64%
26	2	2	2	1	2	1	4	2	34	24653	0.59%
27	2	2	2	1	3	1	1	1	8	24260	0.58%
28	2	2	2	1	3	1	2	1	9	22935	0.55%
29	2	2	2	1	3	1	2	2	50	22141	0.53%
30	2	2	2	1	3	1	3	1	14	20519	0.49%
31	2	2	2	1	3	1	4	1	1	18619	0.45%
32	2	2	2	2	3	1	1	1	56	17608	0.42%
33	2	2	2	2	3	1	3	1	39	14948	0.36%
34	2	2	2	2	3	1	4	1	3	12322	0.30%
35	2	2	2	3	3	1	1	1	5	10826	0.26%
36	2	2	2	3	3	1	1	2	4	8935	0.21%
37	2	2	2	3	3	1	4	1	38	8280	0.20%
38	3	3	2	2	3	1	1	2	55	7541	0.18%
39	3	3	2	3	3	1	1	2	58	7098	0.17%
40	3	3	2	3	3	2	1	1	31	6760	0.16%
41	4	3	2	1	2	1	1	2	32	6393	0.15%
42	4	3	2	1	2	1	2	1	30	5936	0.14%
43	4	3	2	1	2	1	2	2	57	5823	0.14%
44	4	3	2	1	2	1	3	1	60	5076	0.12%
45	4	3	2	1	2	1	3	2	46	4770	0.11%
46	4	3	2	1	2	1	4	1	37	4479	0.11%
47	4	3	2	1	2	1	4	2	19	2879	0.07%
48	4	3	2	2	2	1	1	2	28	2667	0.06%
49	4	3	2	2	2	1	2	2	27	2298	0.06%
50	4	3	2	2	2	1	3	2	52	1795	0.04%
51	4	3	2	2	2	1	4	2	7	1734	0.04%
52	4	3	2	2	3	1	1	1	10	1198	0.03%
53	4	3	2	2	3	1	1	2	15	1090	0.03%
54	4	3	2	2	3	1	2	2	18	917	0.02%
55	4	3	2	2	3	1	3	1	61	857	0.02%
56	4	3	2	2	3	1	3	2	29	831	0.02%
57	4	3	2	2	3	1	4	1	36	803	0.02%
58	4	3	2	2	3	1	4	2	20	646	0.02%
59	4	3	2	3	3	1	1	1	12	480	0.01%
60	4	3	2	3	3	1	1	2	26	322	0.01%
61	4	3	2	3	3	1	4	1	13	320	0.01%
62	5	3	2	3	3	1	2	2	33	168	0.00%

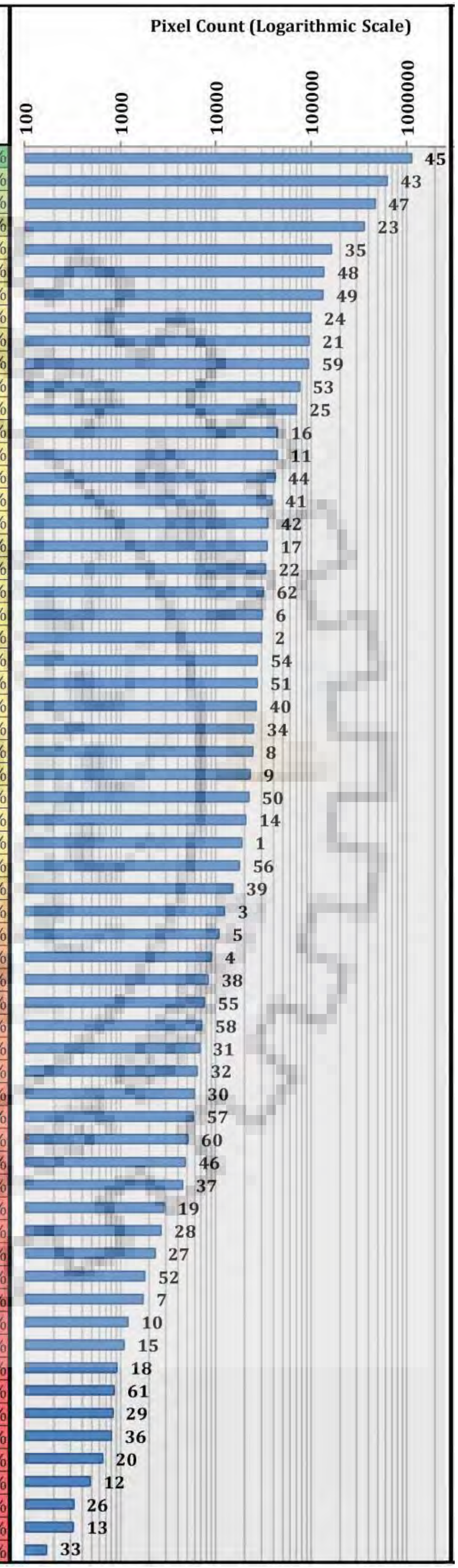


Table 5-3 TCD Zone proximity analysis

Neighbours	TCD Zone SR	Neighbour Count	
2, 3, 4, 5, 6, 8, 9, 15	1	8	2.3, ##, 0.3, 0.1, 0.9, 0.0, 0.2, 0.2
1, 3, 4, 6, 7, 9, 23	2	7	2.3, 0.0, ##, 1.6, 3.0, 1.9, 0.2
1, 2, 4, 5, 6, 8, 9, 21	3	8	##, 0.0, 0.5, 0.5, 0.0, 6.4, 0.3, 0.0
1, 2, 3, 5, 6, 9, 15, 23	4	8	0.3, ##, 0.5, 0.0, 4.1, 5.1, 0.6, 1.1
1, 3, 4, 6, 8, 9, 21, 23	5	8	0.1, 0.5, 0.0, 5.8, 2.1, 0.4, 0.0, 0.1
1, 2, 3, 4, 5, 8, 9, 15, 23, 24	6	10	0.9, 1.6, 0.0, 4.1, 5.8, 0.1, ##, 1.1, 6.1, 0.0
2, 9, 23	7	3	3.0, 0.1, 2.3
1, 3, 5, 6, 9, 16, 21, 23	8	8	0.0, 6.4, 2.1, 0.1, 4.8, 0.4, ##, 0.2
1, 2, 3, 4, 5, 6, 7, 8, 10, 11, 15, 16, 21, 23, 24, 25	9	16	0.2, 1.9, 0.3, 5.1, 0.4, 15.4, 0.1, 4.8, 0.2, 9.5, 4.1, 2.6, 1.0, 22.9, 0.1, 0.9
9, 23, 24	10	3	0.2, 0.1, 1.8
9, 12, 14, 16, 17, 23, 25, 32, 34, 35, 47	11	11	9.5, 1.0, ##, ##, 0.0, 0.2, 4.5, 1.0, 0.6, 0.1, 0.7
11, 16, 26, 47, 51	12	5	1.0, 0.2, 0.1, 1.0, 0.6
23, 25	13	2	0.8, 0.3
11, 16, 17, 19, 20, 25, 27, 32, 35, 47, 48, 53	14	12	##, ##, ##, 6.9, 0.4, 0.1, 0.1, 2.1, 6.1, 0.1, 2.0, 0.0
1, 4, 6, 9, 16	15	5	0.2, 0.6, 1.1, 4.1, 0.7
8, 9, 11, 12, 14, 15, 17, 18, 20, 23, 25, 26, 31, 32, 34, 35, 37, 46, 47, 51, 57	16	21	0.4, 2.6, 49.3, 0.2, 31.5, 0.7, 18.8, 4.6, 0.0, 1.6, 10.6, 0.7, 1.7, 0.3, 19.5, 0.2, 3.0, 0.1, 17.4, 0.3, 1.1
11, 14, 16, 18, 19, 27, 32, 35, 48, 53, 58, 59	17	12	0.0, ##, ##, 0.8, 0.0, 0.3, 1.2, ##, 2.3, 2.9, 0.0, 0.2
16, 17, 34, 35, 37	18	5	4.6, 0.8, 0.4, 0.0, 1.2
14, 17, 20, 27, 32, 35, 48, 52, 53	19	9	6.9, 0.0, 0.5, 0.9, 1.4, 0.7, 1.9, 0.2, 0.3
14, 16, 19, 47, 48, 51, 52, 53	20	8	0.4, 0.0, 0.5, 0.3, 1.0, 0.2, 0.0, 0.2
3, 5, 8, 9, 22, 23, 28, 29, 32, 34, 42, 43, 44	21	13	0.0, 0.0, ##, 1.0, 9.9, ##, 4.4, 0.0, 0.7, 0.4, ##, 1.0, 0.5
21, 23, 24, 28, 29, 30, 42, 43, 45	22	9	9.9, 0.1, 0.7, 0.5, 2.7, 0.1, 0.0, ##, 0.0
2, 4, 5, 6, 7, 8, 9, 10, 11, 13, 16, 21, 22, 24, 25, 28, 30, 31, 34, 42, 44, 45, 46, 55	23	24	0.2, 1.1, 0.1, 6.1, 2.3, 0.2, 22.9, 0.1, 0.2, 0.8, 1.6, 11.2, 0.1, 33.7, 125.6, 0.0, 7.6, 6.9, 3.9, 0.0, 19.0, 1.2, 0.1, 3.6
6, 9, 10, 22, 23, 25, 30, 45, 47, 50, 56	24	11	0.0, 0.1, 1.8, 0.7, ##, 0.0, 0.1, ##, 0.1, 0.8, 6.6
9, 11, 13, 14, 16, 23, 24, 31, 32, 34, 45, 46	25	12	0.9, 4.5, 0.3, 0.1, 10.6, ###, 0.0, 11.7, 2.0, 45.4, 0.0, 0.7
12, 16, 47	26	3	0.1, 0.7, 0.9
14, 17, 19, 35, 52, 53, 59, 60	27	8	0.1, 0.3, 0.9, 8.4, 3.6, 3.4, 0.0, 0.2
21, 22, 23, 29, 30	28	5	4.4, 0.5, 0.0, 0.8, 1.6
21, 22, 28, 30	29	4	0.0, 2.7, 0.8, 0.5
22, 23, 24, 28, 29	30	5	0.1, 7.6, 0.1, 1.6, 0.5
16, 23, 25, 34, 37, 46, 57	31	7	1.7, 6.9, ##, 4.2, 0.1, 3.3, 0.6
11, 14, 16, 17, 19, 21, 25, 34, 35, 52, 59	32	11	1.0, 2.1, 0.3, 1.2, 1.4, 0.7, 2.0, 3.8, ##, 0.2, 2.1
42	33	1	0.6
11, 16, 18, 21, 23, 25, 31, 32, 35, 37, 46, 47, 57, 59, 61	34	15	0.6, 19.5, 0.4, 0.4, 3.9, 45.4, 4.2, 3.8, 3.5, 6.7, 0.2, 10.7, 17.8, 0.0, 0.0
11, 14, 16, 17, 18, 19, 27, 32, 34, 36, 37, 48, 52, 53, 59, 60, 61	35	17	0.1, 6.1, 0.2, 52.0, 0.0, 0.7, 8.4, 18.4, 3.5, 6.7, 3.5, 0.9, 0.3, 2.0, 66.5, 5.8, 1.0
35, 60	36	2	6.7, 0.0
16, 18, 31, 34, 35, 59, 61	37	7	3.0, 1.2, 0.1, 6.7, 3.5, 4.9, 3.4
48, 53	38	2	0.3, ##
53, 54, 62	39	3	6.7, 0.1, 0.7
59	40	1	3.9
43, 45, 47, 48, 49, 51	41	6	##, 0.5, ##, ##, 0.2, 1.6
21, 22, 23, 33, 43, 44	42	6	##, 0.0, 0.0, 0.6, 7.8, 4.3
21, 22, 41, 42, 44, 45, 47, 48, 49, 50, 51, 54, 56	43	13	1.0, 19.3, 15.6, 7.8, 0.0, 75.9, 0.3, 0.6, 74.3, 3.4, 0.9, 2.4, 2.4
21, 23, 42, 43, 45, 46, 55	44	7	0.5, ##, 4.3, 0.0, ##, 0.3, ##
22, 23, 24, 25, 41, 43, 44, 46, 47, 49, 50, 51, 55, 56, 58	45	15	0.0, 1.2, 12.6, 0.0, 0.5, 75.9, 14.9, 0.0, 169.4, 0.7, 52.5, 2.9, 3.5, 18.8, 3.7
16, 23, 25, 31, 34, 44, 45, 47, 57	46	9	0.1, 0.1, 0.7, 3.3, 0.2, 0.3, 0.0, 2.5, 9.6
11, 12, 14, 16, 20, 24, 26, 34, 41, 43, 45, 46, 48, 50, 51, 57, 58	47	17	0.7, 1.0, 0.1, 17.4, 0.3, 0.1, 0.9, 10.7, 12.0, 0.3, 169.4, 2.5, 0.0, 0.0, 19.4, 6.3, 6.8
14, 17, 19, 20, 35, 38, 41, 43, 47, 49, 50, 51, 53, 54, 58	48	15	2.0, 2.3, 1.9, 1.0, 0.9, 0.3, 10.9, 0.6, 0.0, 26.0, 0.1, 16.3, 26.8, 0.2, 2.6
41, 43, 45, 48, 50, 51, 53, 54, 56	49	9	0.2, ##, 0.7, ##, 3.3, 0.0, 0.0, ##, 1.3
24, 43, 45, 47, 48, 49, 51, 55, 56, 58	50	10	0.8, 3.4, ##, 0.0, 0.1, 3.3, 1.4, 2.0, ##, 2.9
12, 16, 20, 41, 43, 45, 47, 48, 49, 50, 58	51	11	0.6, 0.3, 0.2, 1.6, 0.9, 2.9, ##, ##, 0.0, 1.4, 1.8
19, 20, 27, 32, 35, 53, 59	52	7	0.2, 0.0, 3.6, 0.2, 0.3, 1.0, 3.1
14, 17, 19, 20, 27, 35, 38, 39, 48, 49, 52, 54, 58, 60	53	14	0.0, 2.9, 0.3, 0.2, 3.4, 2.0, 17.7, 6.7, 26.8, 0.0, 1.0, 3.9, 1.0, 0.2
39, 43, 48, 49, 53, 56, 62	54	7	0.1, 2.4, 0.2, ##, 3.9, 1.5, 9.4
23, 44, 45, 50, 56	55	5	3.6, ##, 3.5, 2.0, 0.4
24, 43, 45, 49, 50, 54, 55	56	7	6.6, 2.4, ##, 1.3, ##, 1.5, 0.4
16, 31, 34, 46, 47	57	5	1.1, 0.6, ##, 9.6, 6.3
17, 45, 47, 48, 50, 51, 53	58	7	0.0, 3.7, 6.8, 2.6, 2.9, 1.8, 1.0
17, 27, 32, 34, 35, 37, 40, 52, 60, 61	59	10	0.2, 0.0, 2.1, 0.0, ##, 4.9, 3.9, 3.1, ##, 2.7
27, 35, 36, 53, 59	60	5	0.2, 5.8, 0.0, 0.2, ##
34, 35, 37, 59	61	4	0.0, 1.0, 3.4, 2.7
39, 54	62	2	0.7, 9.4

↑ Neighbours /TCD Zone SR ↑→

Neighbour Counts	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Frequency	2	4	4	2	8	2	8	7	4	3	4	3	2	1	3	1	2	0	0	0	1	0	0	1

LEDGEND: Maximum (green); Minimum (red)

With respect to the recommendations for spacing between buildings; only two TCD Zones were found to correspond with region b1, while the remaining TCD Zones were found to be equally distributed between regions b2 and b3. No remarkable correspondence of TCD Zones with other recommendations was found.

Pixel counts of all TCD Zones have also been compared in Table 5-2. Pixel count of TCDZ SR45 is maximum 27.06% followed by that of SR43 and SR47 being 14.97% and 11.16% respectively. Other significant pixel counts were found to correspond with SR23 (8.66%), SR35(3.93%), SR48 (3.25%), SR49 (3.18%), SR24 (2.38%), SR21 (2.29%), SR59 (2.26%), SR53 (1.81%), SR25 (1.67%), SR16 & SR11 (1.06%) and SR44 (1%). Pixel counts of less than 1 % were found to correspond with rest of the TCD Zones.

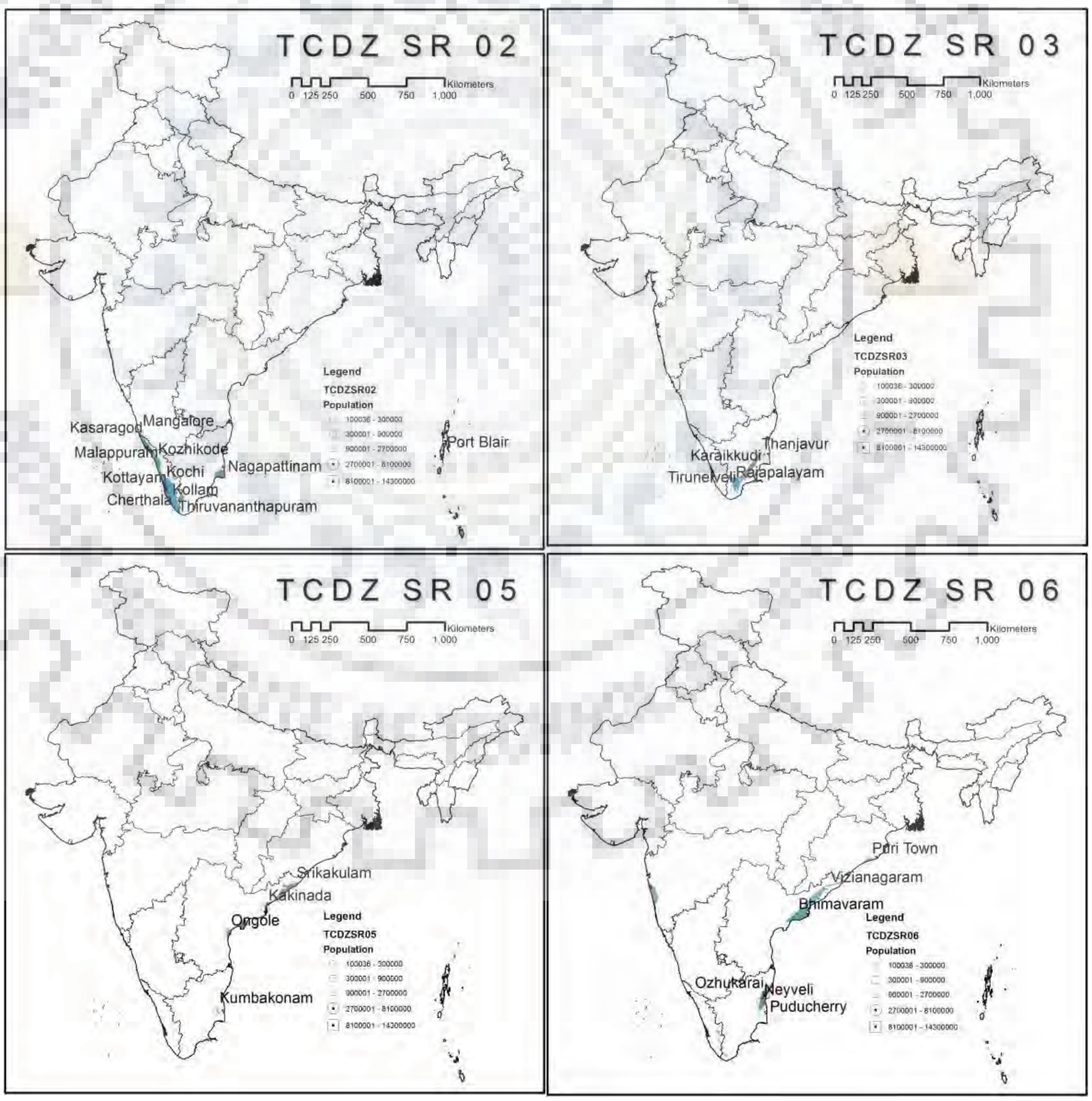


Figure 5-13 Extents of TCD Zones in Coastal India

Length of boundary shared between various TCD Zones has been assessed in Table 5-3. All the neighbors of individual TCD Zones have also been listed and counted. Most of the TCD Zones (29) were found to share boundaries with 5 to 9 other Zones. TCDZ SR23 has been found to be located adjacent to most number of i.e. 24 other TCD Zones. Other zones found in the vicinity of many neighbors are SR16 (21), SR35 and 47 (17), SR9 (16), SR33, SR45 and SR48 (15). TCDZ SR45 is found to share the longest boundary with SR47.

5.2.6. Spatial distribution of most populated TCD Zones

Locations of 530 major cities (having population more than 1 lakh) were plotted on the TCD Zone map of India as shown in Figure 5-18. All major cities belong to one of 31 TCD

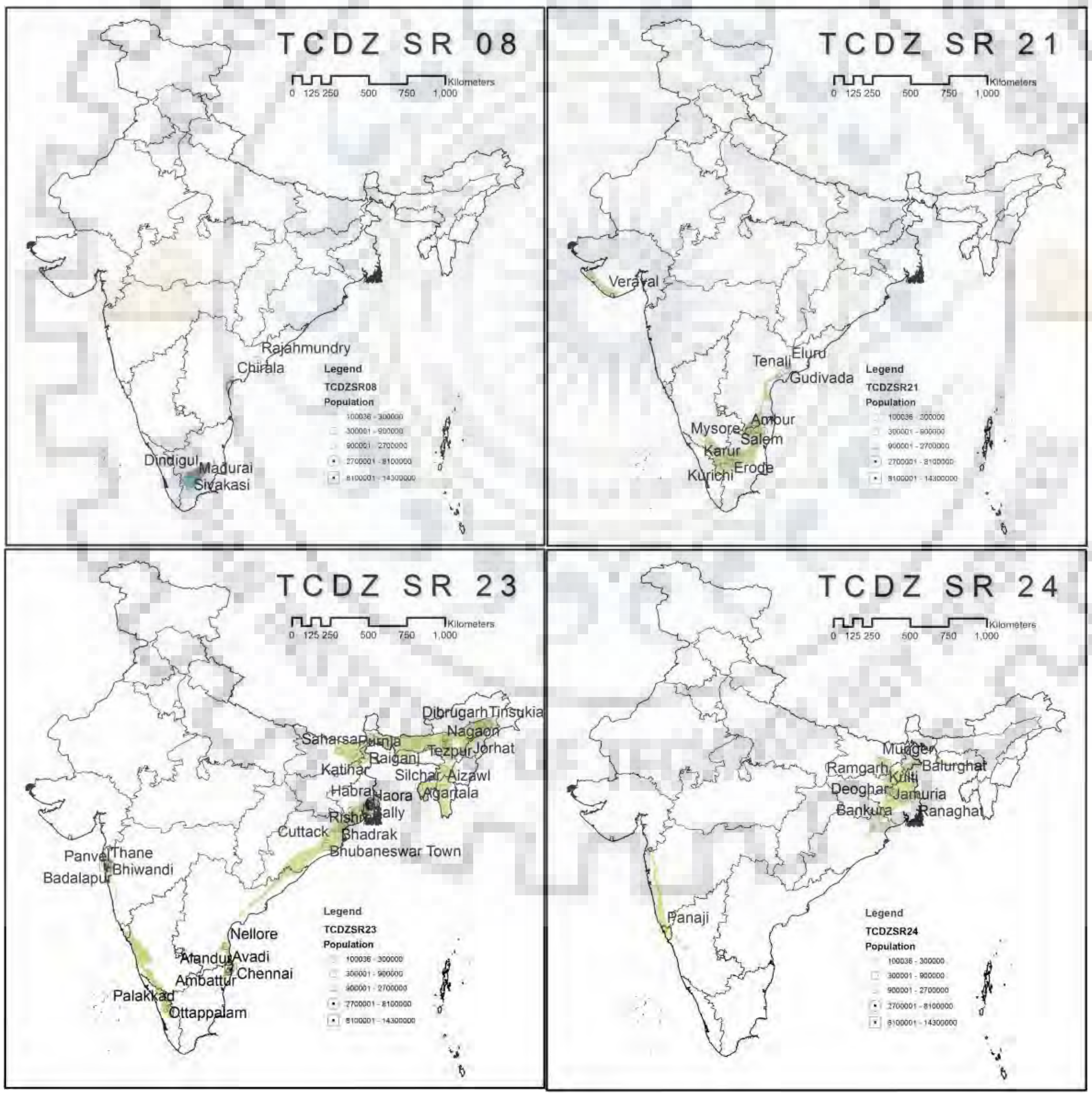


Figure 5-14 Extents of TCD Zones besides Indian Coast and eastern India

Zones listed in Table 5-7. A maximum of 109 cities fall under TCD Zone SR45, followed by 90, 89 and 74 cities in zone SR47, SR23 and SR43 respectively. Out of these 31 zones 16 TCD Zones encompass 5 or more major cities. Extents of these 16 TCD Zones have been discussed in the following.

Extents of TCDZ SR02, SR03, SR05 and SR06 have been described using respective maps shown in Figure 5-13. TCDZ SR02 is found along the Malabar Coast; SR03 is found in the Coromandel Coast; while SR05 and SR05 is dispersed along the Coromandel Coast and Northern Circars.

Extents of TCDZ SR08, SR21, SR23 and SR24 have been described using respective maps shown in Figure 5-14. TCDZ SR08 and SR21 are found inland besides the Coromandel

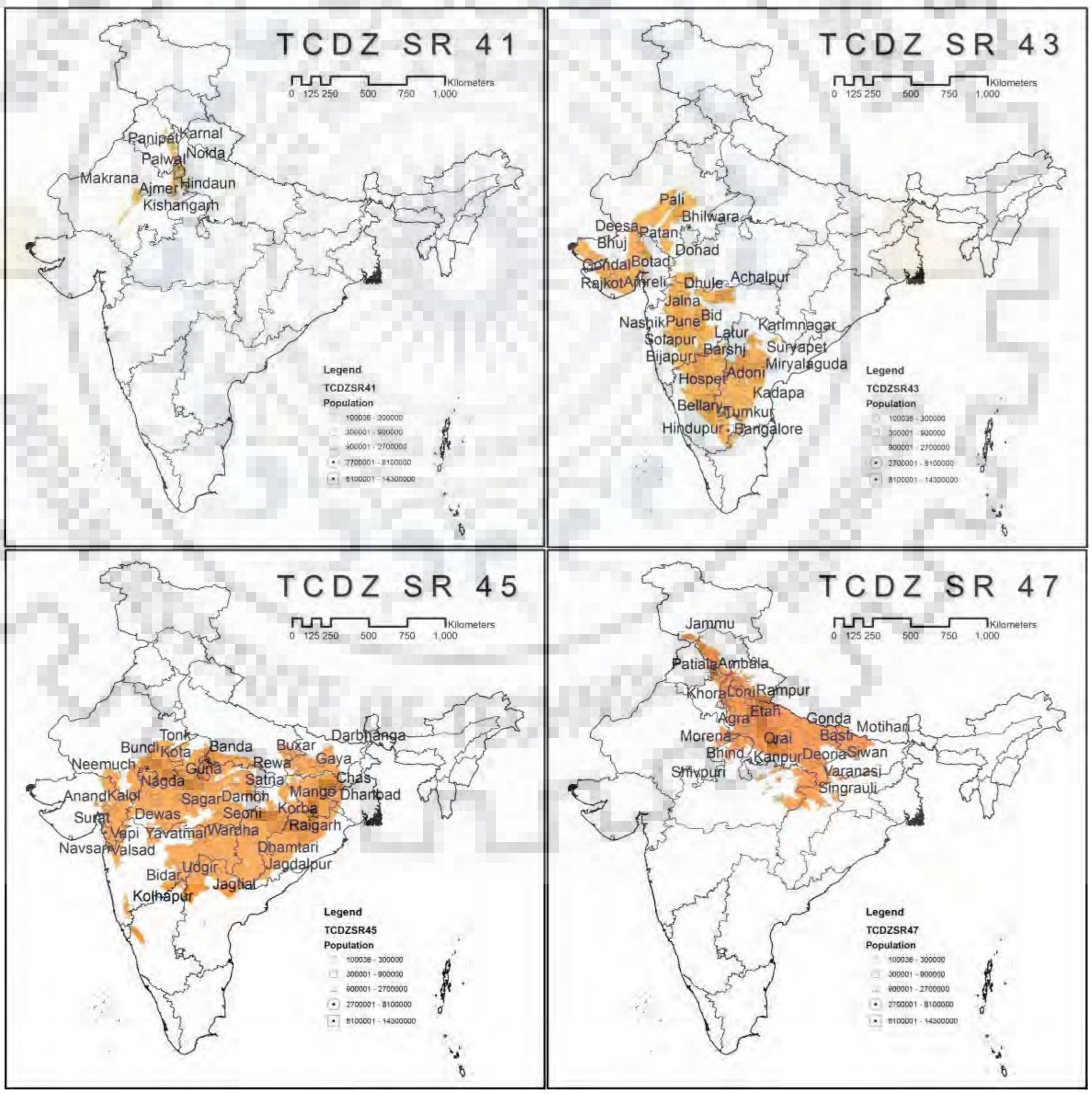


Figure 5-15 Extents of TCD Zones in northern plains and peninsular plateu

Coast; SR23 is found besides the East Coast, West Coast and majorly in the North-east; while SR24 is found sparsely inland besides Konkan Coast and in lower Gangetic plain.

Extents of TCDZ SR41, SR43, SR45 and SR47 have been described using respective maps shown in Figure 5-15. TCDZ SR41 and SR47 is found in the northern plains; while SR43 and SR45 are found distributed widely across the peninsular plateau.

Extents of TCDZ SR48, SR49, SR51 and SR53 have been described using respective maps shown in Figure 5-16. TCDZ SR48 is found across the plains of Punjab, Haryana and Rajasthan; SR49 is found majorly in part of Gujarat and Rajasthan and sparsely near the border between Maharashtra and Karnataka; while SR51 & SR53 are found sparsely in parts of J&K Punjab and Rajasthan.

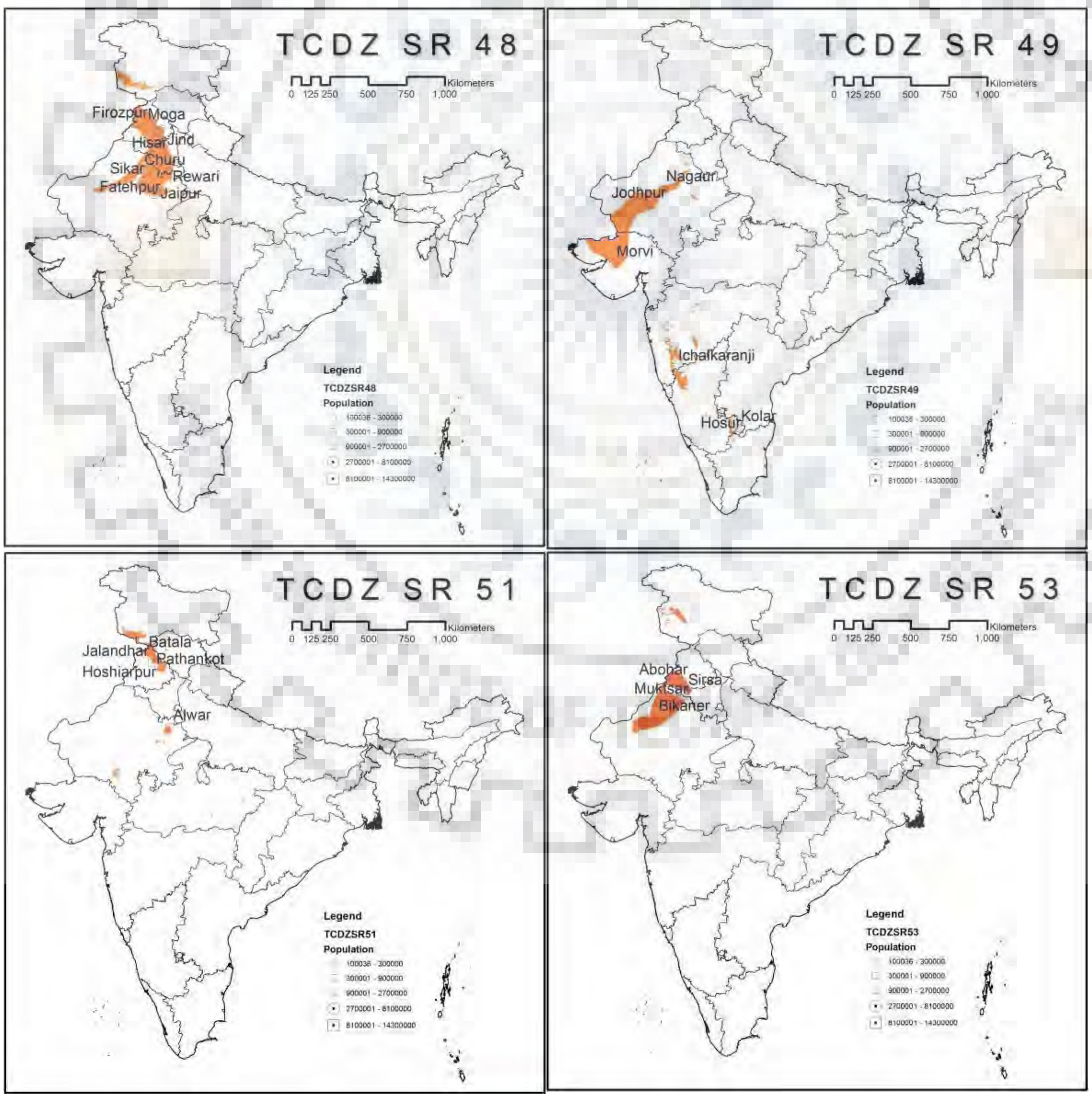


Figure 5-16 Extents of TCD Zones bordering North west India

Detailed descriptive analysis of these 16 TCD Zones has been presented in Appendix 1. Apart from the list of encompassed cities, the flyer for individual TCD Zone includes details like recommended climate responsive design specifications, range of individual climatic indicator and extents on the map of India.

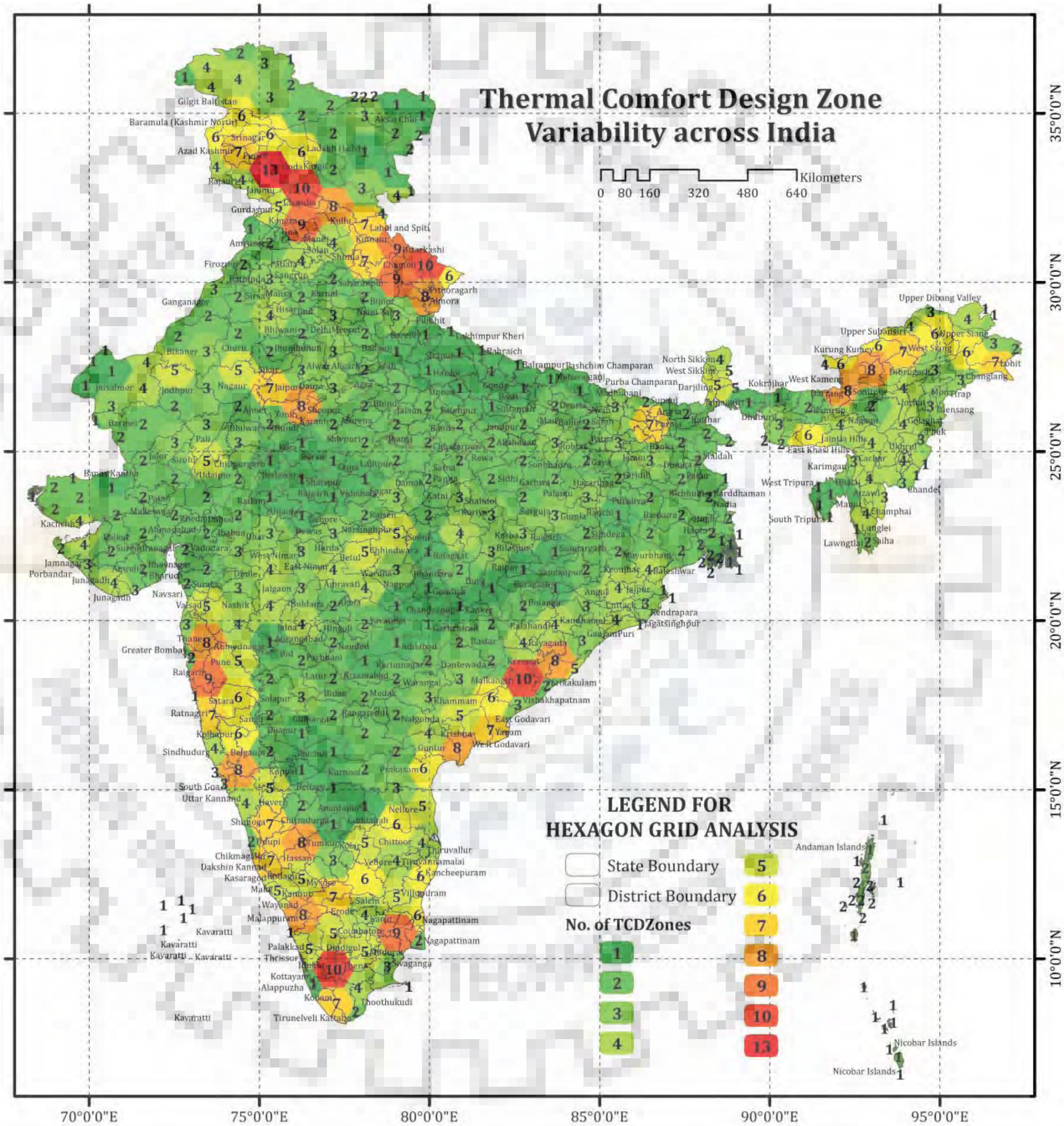


Figure 5-17 TCD Zone variability analysis using hexagonal grid

5.2.7. Comparison w. r. t. Hexagonal Grid

As discussed in section 3.5.1 with reference to Figure 3-24 variability of environmental features can be assessed over a uniform spatial reference (shape and size) using a hexagonal grid. The relative variability of TCD Zones across India has been assessed using hexagonal grid. The assessment has to be informed by the fact that the area of one pixel diminished as one proceeds from the equator towards the poles as discussed in section 3.5.3.3. Area of a hexagonal grid cell admeasures approximately 10590 sq. km. when calculated in comparison with district Kota Rajasthan falling across 25°N Latitude.

As shown in Figure 5-17, maximum variability of TCD Zones is found in a hexagonal cell spanning across districts Ananthnag, Doda and Udhampur in Jammu & Kashmir. Other cells with high TCD Zone variability span across districts Una, Kangra, Mandi, Hamirpur, BIlaspur in Himachal and Ropar, Hoshiyarpur in Punjab; across districts Kinnaur in Himachal and Uttarkashi, Rudraprayag, Tehri Garwal, Pauri Garwal, Almora in Uttarakhand; across districts Chamba in Himachal Pradesh and Chamoli cum Gopeshwar, Pithoragarh in Uttarakhand; across districts Vishakhapattanam in Andhra Pradesh and Koraput in Orrissa; across districts Perambalur, Ariyalur, Thanjavur, Thiruvarur and Pudukkottai in Tamil Nadu; across districts Pattanamtitta, Kottayam, Idukki in Kerala and Theni, Virudhunagar, Thirunelveli Kattabi in Tamil Nadu; across districts Raigarh, Pune, Satara and Ratnagiri in Maharashtra.

Table 5-4 List of TCD Zones found in one or two Administrative units

Administrative Unit Name	TCDZ SR	Administrative Unit Name	TCDZ SR
Tamil Nadu (TN)	1, 3, 33	Himachal Pradesh (HP)	12, 26
TN / KL	15	HP / J&K	52
Kerala (KL)	7	Jammu & Kashmir(J&K)	19, 20, 27, 36, 40, 60
TN / KA	28	Rajasthan (RJ)	39,62
Karnataka (KA)	29, 30	UK/Arunachal Pradesh	18, 37
Maharashtra (MH)	10	Uttarakhand (UK)	57, 61
Mizoram (MZ)	13	UK / Bihar (BR)	46

5.2.8. Comparison w. r. t. administrative boundaries

Comparison between extents of the 62 TCD Zones and the administrative districts / state / union territory of India is shown in Figure 5-18. The various TCD Zones found in each state are listed in Table 5-5. TCD Zones found in individual state are marked in this table with a green tick mark. It can be seen from Column 4 that maximum TCD Zones are found in J&K, while Tripura, Goa and Delhi have 1 TCD Zone each. Madhya Pradesh has the largest single TCD Zone of all, while Lakshadweep has the smallest single Zone. TCD Zone

Table 5-5: TCD Zones found in each State/Union Territory

SR. NO.	ADMINISTRATIVE UNIT NAME	TCDZ COUNT	AREA 10^6 KM^2 MAX	AREA 10^6 KM^2 MIN
1	Andaman and Nicobar	3	0.19	0.15
2	Andhra Pradesh	13	9.25	0.01
3	Arunachal Pradesh	12	2.99	0.01
4	Assam	6	6.32	0.00
5	Bihar	9	3.40	0.02
6	Chandigarh	1	0.01	0.01
7	Chhattisgarh	6	9.82	0.01
8	Dadra & Nagar Haveli	2	0.04	0.00
9	Daman and Diu	2	0.05	0.00
10	Delhi	3	0.11	0.00
11	Goa	5	0.19	0.00
12	Gujarat	10	7.02	0.00
13	Haryana	5	2.13	0.19
14	Himachal Pradesh	12	1.57	0.02
15	Jammu and Kashmir	18	8.86	0.04
16	Jharkhand	5	5.44	0.03
17	Karnataka	18	9.53	0.00
18	Kerala	11	1.50	0.00
19	Lakshadweep	1	0.00	0.00
20	Madhya Pradesh	7	21.35	0.05
21	Maharashtra	12	10.93	0.03
22	Manipur	4	1.09	0.02
23	Meghalaya	6	0.76	0.02
24	Mizoram	5	1.35	0.01
25	Nagaland	3	0.69	0.33
26	Orissa	10	7.65	0.02
27	Puducherry	4	0.02	0.00
28	Punjab	6	2.52	0.01
29	Rajasthan	13	5.70	0.06
30	Sikkim	4	0.37	0.05
31	Tamil Nadu	21	3.74	0.01
32	Tripura	1	0.91	0.91
33	Uttar Pradesh	3	18.66	0.21
34	Uttaranchal	14	1.58	0.01
35	West Bengal	7	3.41	0.00

TCD ZONE SR	TOTAL ←AREA_10^6 KM^2	←STATE COUNT
1	1.29	1
2	2.07	6
3	0.86	1
4	0.61	5
5	0.75	3
6	2.11	7
7	0.12	1
8	1.68	4
9	1.59	10
10	0.08	1
11	3.05	3
12	0.03	1
13	0.02	1
14	1.42	4
15	0.08	2
16	3.07	9
17	2.38	4
18	0.06	2
19	0.20	1
20	0.04	1
21	6.60	7
22	2.31	4
23	24.97	17
24	6.88	11
25	4.83	11
26	0.02	1
27	0.16	1
28	0.19	2
29	0.06	1
30	0.41	1
31	0.47	4
32	0.44	4
33	0.01	1
34	1.71	11
35	11.35	5
36	0.06	1
37	0.31	2
38	0.58	3
39	1.04	1
40	1.84	1
41	2.68	6
42	2.42	4
43	43.24	8
44	2.89	5
45	78.17	15
46	0.33	2
47	32.23	13
48	9.40	5
49	9.17	6
50	1.54	7
51	1.87	6
52	0.12	2
53	5.23	4
54	1.89	3
55	0.52	3
56	1.22	6
57	0.40	1
58	0.49	4
59	6.52	3
60	0.35	1
61	0.06	1
62	2.18	1

LEGEND: Maximum; Minimum; Area > 0.1 × 10^6 KM^2; Area < 0.1 × 10^6 KM^2

SR45 has the maximum area of extent followed by zones SR43, SR47, SR23, and SR35. These zones span across 15, 8, 13, 17 & 5 administrative units respectively. Whereas 26 other TCD Zones found in one or two administrative units each are listed in Table 5-4. Another 6 TCD Zones SR5, SR38, SR54, SR55 & SR59 were found in 3 admin units each. Thus it can be seen that the TCD Zones not only vary greatly in size and shape, their extent may also vary from a single administrative unit to seventeen. Moreover the administrative units themselves being heterogeneous in shape and size, the variability in TCD Zones may be greatly obscured.

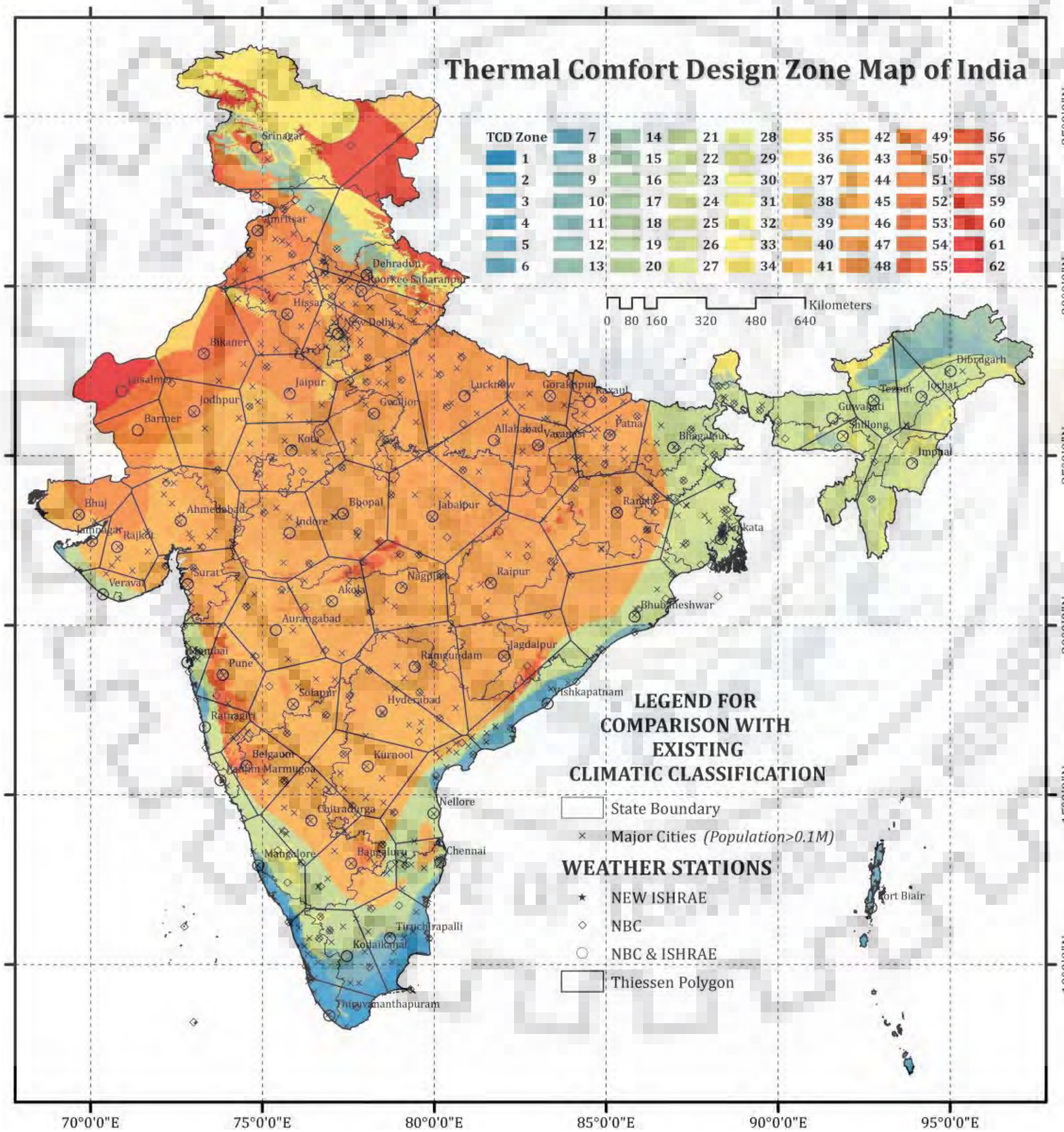


Figure 5-18 TCD Zone Map of India with ECBC/NBC and ISHRAE Weather Stations

A very high variety (18-21) of TCD Zones was found in the states of Jammu & Kashmir, Karnataka and Tamil Nadu. High variety (11-14) of Zones was found in the states of

Andhra Pradesh, Arunachal Pradesh, Himachal Pradesh, Kerala, Maharashtra, Rajasthan and Uttaranchal. State of Tripura and union territories of Chandigarh and Lakshadweep have one TCD Zone each. Whereas the union territories of Dadra & Nagar Haveli and Daman & Diu were found to have two Zones each. The most prominent Zones has been identified in Figure 5-19, Figure 5-20 and Figure 5-21 for each of the state having more than 3 TCD zones.

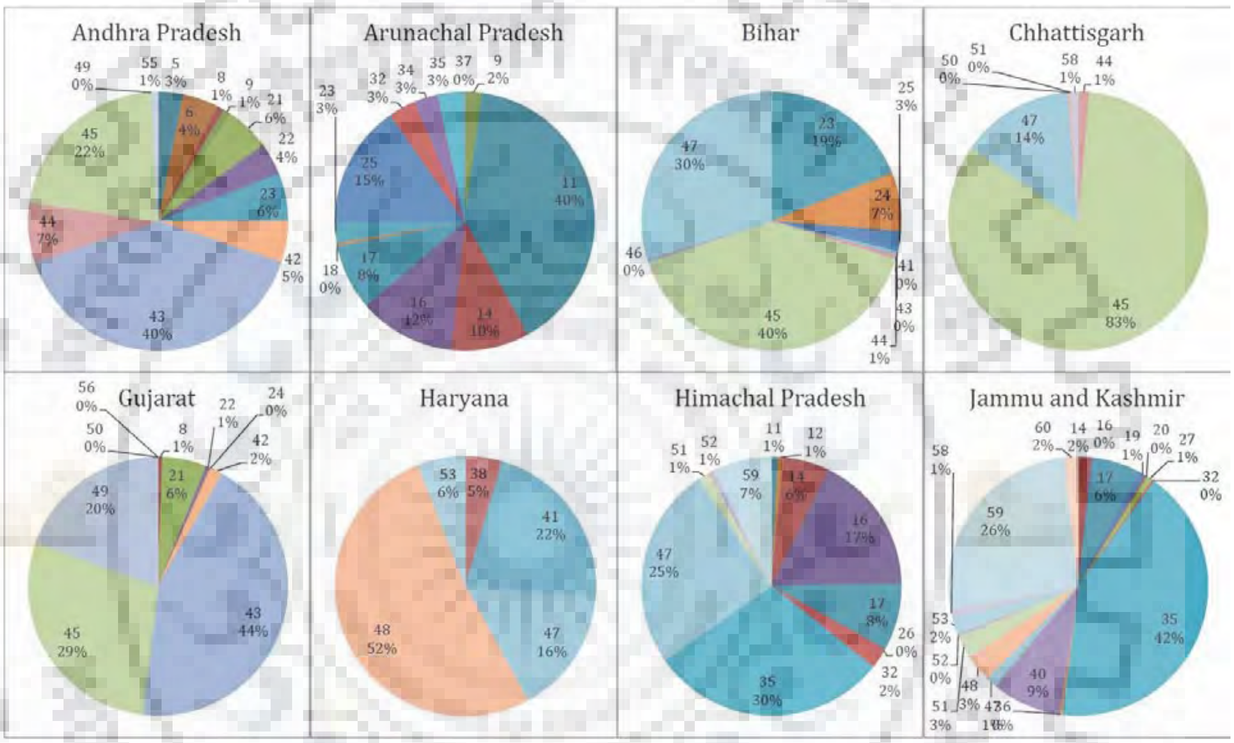


Figure 5-19 Prominent TCD Zones in States A-J

As seen from Figure 5-19 the most prominent TCD Zones for the states of Andhra Pradesh, Arunachal Pradesh, Bihar, Chhattisgarh, Gujarat, Haryana, and, Jammu and Kashmir are, SR43(40%), SR11(40%), SR45(40%), SR45(83%), SR43(44%), SR48(52%), and SR35(42%) respectively, whereas Himachal Pradesh has two somewhat equally prominent zones, SR35(30%) and SR47 (25%).

As seen from Figure 5-20 the most prominent TCD Zones for the states of Jharkhand, Karnataka, Kerala, Madhya Pradesh, Manipur and Mizoram are, SR45(77%), SR43(59%), SR02(49%) and SR45(78%), SR25(55%) and SR23(73%), respectively. Maharashtra has two equally prominent zones SR45 and SR43 (41% each), whereas Meghalaya has two somewhat equally prominent zones, SR23(38%) and SR25(31%).

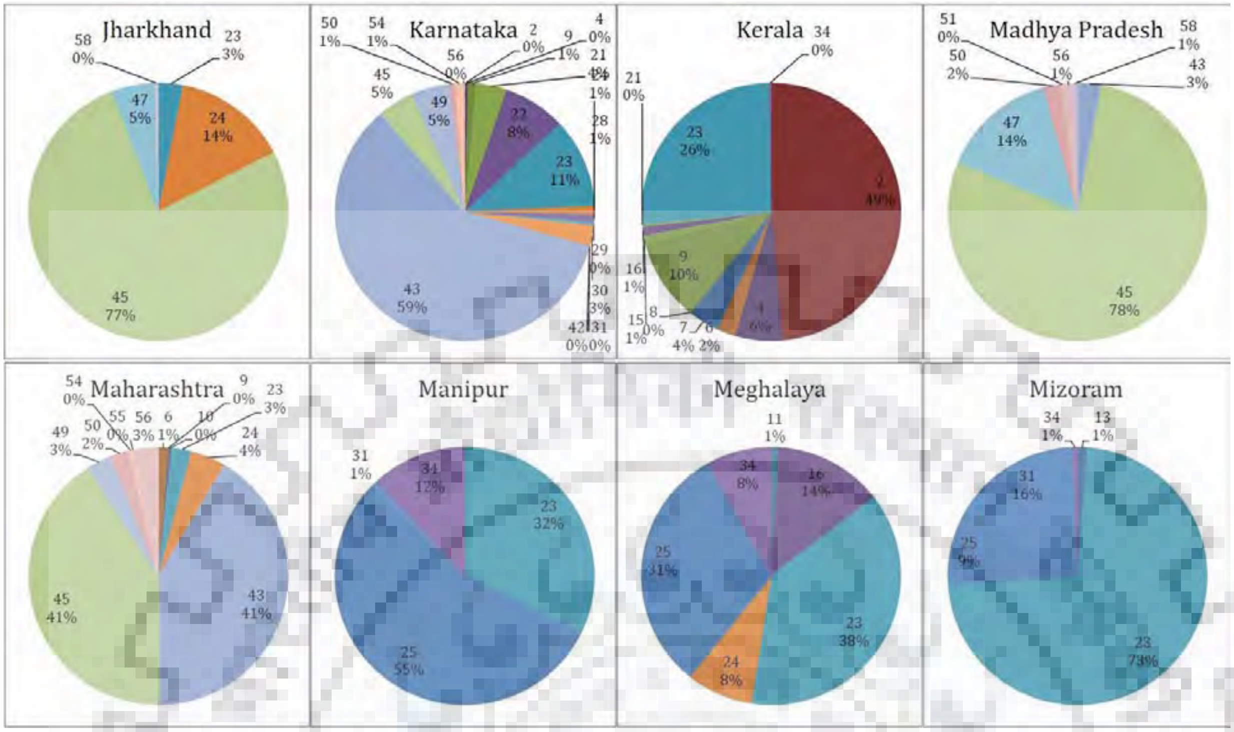


Figure 5-20 Prominent TCD Zones in States J-M

As seen from Figure 5-21 the most prominent TCD Zones for the states of, Nagaland, Orissa, Punjab, Tamil Nadu, Uttar Pradesh, Uttarkhand and West Bengal are, SR26(46%), SR45(57%), SR48(53%), SR21(35%), SR47(85%), SR47(31%) and SR23 & SR 24(each approximately 45%) respectively. The state of Rajasthan has five prominent zones SR45,

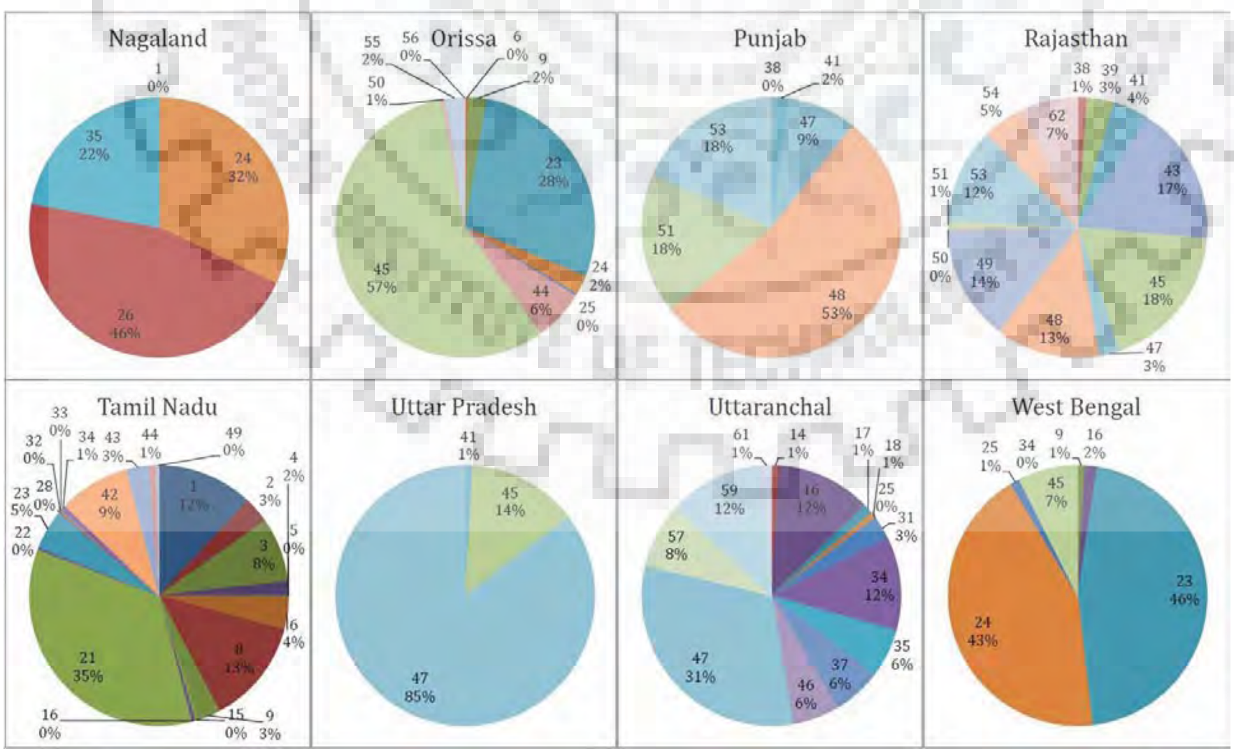


Figure 5-21 Prominent TCD Zones in States N-W

SR43, SR49, SR48 and SR53 having a share of 18%, 17%, 14%, 13% and 12% respectively, The share occupied by TCD SR47 (85%) in Uttar Pradesh was found to be the highest in any state by any zone, followed by SR45 (83%) in Chhattisgarh. TCD Zone SR45 also has a prominent share in six other states & occupies 40%, 77%, 78%, 41%, 57% and 18% share in Bihar, Jharkhand, Madhya Pradesh, Maharashtra, Orissa and Rajasthan respectively.

5.3. Regionalization of building legislation based on TCD Zone

In previous section prominent TCD zones for each state have been identified by comparing areas occupied by various TCD Zones within each state. For the purpose of regionalizing building legislations, assessment of TCD Zones encompassing various Major Cities is necessary.

5.3.1. Comparison with respect to settlements having DC&PR

Weather stations used in climatic classification for the purpose of building design provided by NBC [3,24] are listed in Table 2-17. TCD Zones corresponding to these weather stations have been identified by overlay analysis as shown in Figure 5-18. A comparison between NBC climate zones and TCD Zones assigned to each weather station has been shown in Table 5-6.

Weather files for 59 (weather station) locations were published by ISHRAE [61]; Thieseen polygons around these locations have been shown in Figure 5-18 to assess the number TCD Zones covered under each Weather file. Variability of TCD Zones with the vicinity of various weather files is discussed in following section.

Table 5-6 Comparison between climatic zones & TCD zones assigned to ECB/NBC/ISHRAE weather stations

Weather Station Count	TCD Zone SR																																Total Coun
Climatic Zones↓	×	1	2	3	4	5	6	8	9	10	16	21	22	23	24	25	34	35	38	41	43	44	45	47	48	49	50	51	53	56	58	59	62	
HD - Hot and Dry																					15		6		1	2			1				1	26
WH - Warm & Humid	2	1	7	1	2	4	4	3	3	2		6	2	25	5						5	2	4	1		1	2							82
CM - Composite															1				1	2	5		40	21	5		2	2		1				80
TM - Temperate													1								4													5
CO - Cold											8			2			3	1					1						1	1	1	2		20
Unassigned														2		1					1			1	1									6
Total Count	2	1	7	1	2	4	4	3	3	2	8	6	3	29	6	1	3	1	1	2	30	2	51	23	7	3	4	2	2	2	1	2	1	219

LEGEND: Maximum Minimum

5.3.1.1. Comparison with respect to existing climatic classification

As shown in Table 5-6 highest number (51) of weather stations used in climatic classification for ECBC / NBC codes fall under TCD Zone SR45. Six weather stations that

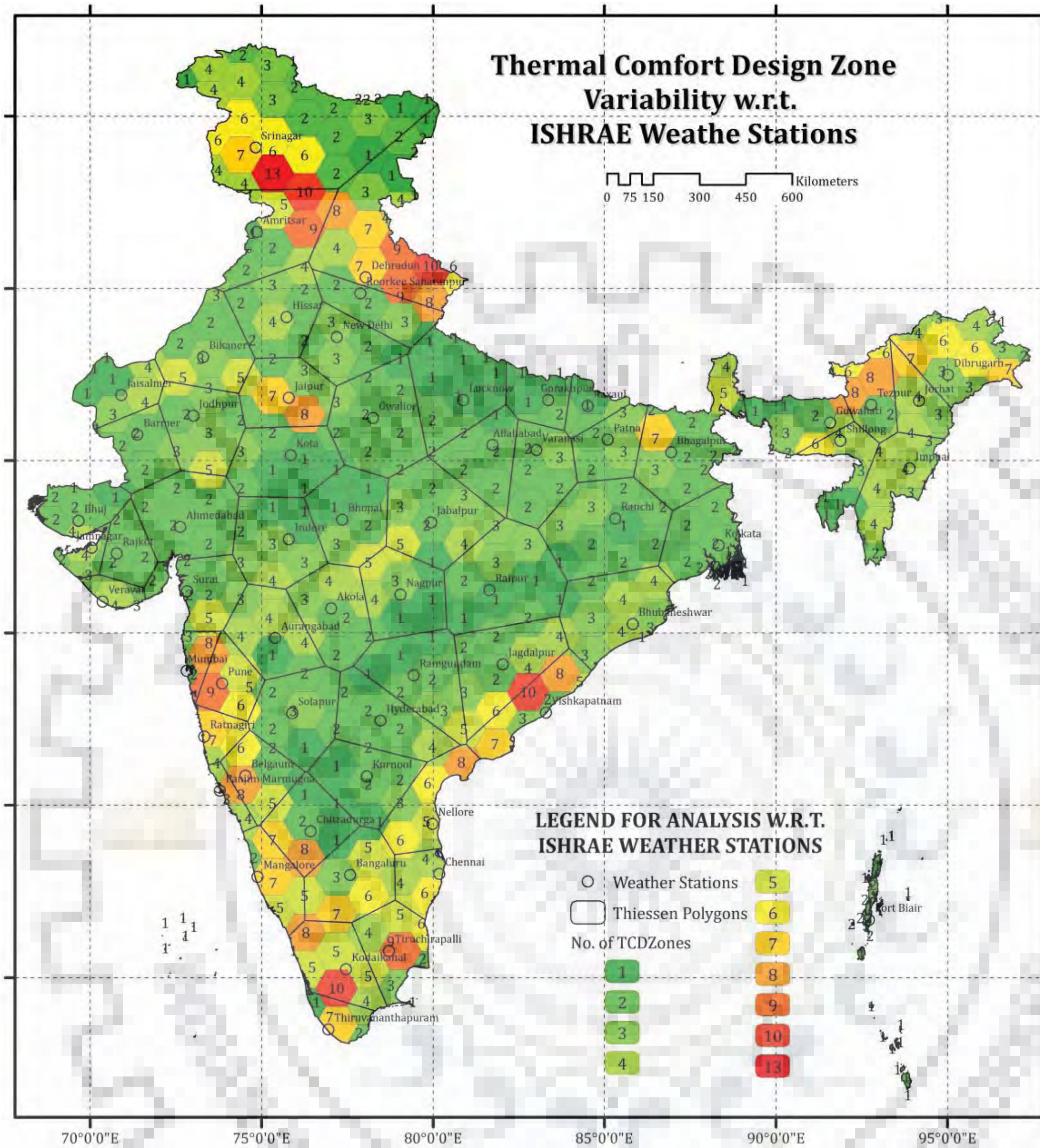


Figure 5-22 TCD Zone variability in the vicinity of ISHRAE weather stations

had a ISHRAE weather file but did not have a stated climatic class were found to fall under 5 different TCD Zones namely, SR23 (2nos), SR25, SR43, SR47 and SR48. Twenty five out of twenty nine weather stations found to overlap SR23 belong to Warm and Humid climatic zone, whereas 15 out of 30 stations found to correspond with SR43 belong to Hot and Dry zone. Similarly, 40 out of 51 stations found to correspond with SR45 and 21 out of 23 stations found to correspond with SR47 belong to Composite climatic zone. All the 8 stations found to correspond with SR16 belong to Cold climatic zone, while all the 7 stations found to correspond with SR02 and 6 stations found to correspond with SR21 belong to Warm and Humid zone.

The assignment of many TCD zones to weather stations belonging to same NBC climate zone and vice versa; highlights the need for regionalization required in development codes (ECBC / NBC). Regionalization of EBCB / NBC is discussed in following section.

5.3.1.2. Comparison with respect to Typical Weather Files

Typical Weather file (influence area) *Thiessen Polygon* map and TCD Zone map have been overlaid as shown in Figure 5-18 to ascertain the count of major cities corresponding to respective Typical Weather file and TCD Zone cross-tabulated in Table 5-7.

Seventy-one percent (42 out of 59) weather file stations were found to have a reasonable representativeness as the encompassed cities were found to be assigned with only one or two TCD Zones. On the contrary 20 cities found within the influence area of Kodaikanal weather file were assigned with 7 different TCD Zones. 11 cities in the area of Nellore weather file and 9 cities in the area of Thiruvananthpuram weather file were found to correspond with 6 different TCD Zones each. Similarly, 14 cities in the area of Amritsar weather file and 8 cities in the area of Visakhapatnam weather file were found to correspond with 5 different TCD Zones each. This means high climatic variability exists in the influence area of few weather file stations, and justifies the need for generating additional weather files. The influence areas (*Thiessen Polygons)* with higher TCD Zone variability can be identified from the hexagonal grid spatial analysis (see 0) underlain in Figure 5-22.

5.3.2. ECBC specification values corresponding to TCD Zone

TCD Zones have been regrouped based on regional recommendations for component design for ease of regionalizing prescribed design specifications for use in ECBC.

5.3.2.1. Recommended thermal performance specifications of building envelope

Four groups have been found as shown in Figure 5-23, when TCD Zones were regrouped on the basis of regional recommendations for wall and floor design and roof design. The regrouping is useful for regionalizing thermal performance specifications of building envelope as shown in Table 5-9. Indicator based criteria used in delineation of regional recommendations for wall, floor and roof design (see Table 5-8)[144], is also used for specifying thermal performance specifications as shown in Table 5-9.

Table 5-7 Number of Major Cities corresponding to each ISHRAE Weather file and various TCD Zones

ISHRAE Weather File ↓	TCD Zone SR																															City Count	TCDZ Count
	1	2	3	4	5	6	7	8	9	16	21	22	23	24	25	28	34	38	41	42	43	44	45	47	48	49	50	51	52	53	56		
Ahmedabad																					5		7									12	2
Akola																					2		5									7	2
Allahabad																							2	3								5	2
Amritsar																		1						1	6			4		2		14	5
Aurangabad																					6		1									7	2
Bangaluru											4	1									5					2						12	4
Belgaum																					4					1	1					6	3
Bhagalpur										1			8	10									3									22	4
Bhopal																							7									7	1
Bhubaneshwar						1			1				4										1									7	4
Bhuj																					2											2	1
Bikaner																										2				1		3	2
Chennai				1		2					6		8																			17	4
Chitradurga												2									7											9	2
Dehradun										1														6								7	2
Dibrugarh													2																			2	1
Gorakhpur																							3	5								8	2
Guwahati													3																			3	1
Gwalior																			1				3	13								17	3
Hissar																		2						1	10					2		15	4
Hyderabad																					7		2									9	2
Imphal													2		1																	3	2
Indore																					2		7									9	2
Jabalpur																							5									5	1
Jagdalpur																							1									1	1
Jaipur																			4				2		2			1				9	4
Jamnagar											1										1											2	2
Jodhpur																					2					1						3	2
Jorhat													2																			2	1
Kodaikanal		6	1				2	3			5		2				1															20	7
Kolkata													43	11																		54	2
Kota																					1		7									8	2
Kurnool																					8											8	1
Lucknow																							1	13								14	2
Mangalore		3							1			1				1																6	4
Mumbai													11																			11	1
Nagpur																							6				1				1	8	3
Nellore					2			1			2		1							4	1											11	6
New Delhi																			9					15	2							26	3
Panjim Marmugoa									1					1																		2	2
Patna																							8	5								13	2
Port Biair		1																														1	1
Pune																					3						1					4	2
Raipur																							8									8	1
Rajkot																					7					1						8	2
Ramgundam																					2	2	4									8	3
Ranchi																							14									14	1
Ratnagiri																							1									1	1
Raxaul																							1	5								6	2
Roorkee Saharanpur																			2					18								20	2
Shillong													1				1															2	2
Solapur																					6		1									7	2
Srinagar																													1			1	1
Surat																					2		6									8	2
Tezpur													2																			2	1
Thiruvananthapuram	2	4	1																													7	3
Tiruchirapalli		1	3		1	1		1			2																					9	6
Varanasi																							3	5								8	2
Veraval											1										1											2	2
Vishkapatnam					3	2		1	1		1																					8	5
Total Count	2	15	5	1	6	6	2	6	4	2	22	4	89	22	1	1	2	3	16	4	74	2	109	90	20	7	3	5	1	5	1	530	31

LEGEND: Maximum Minimum

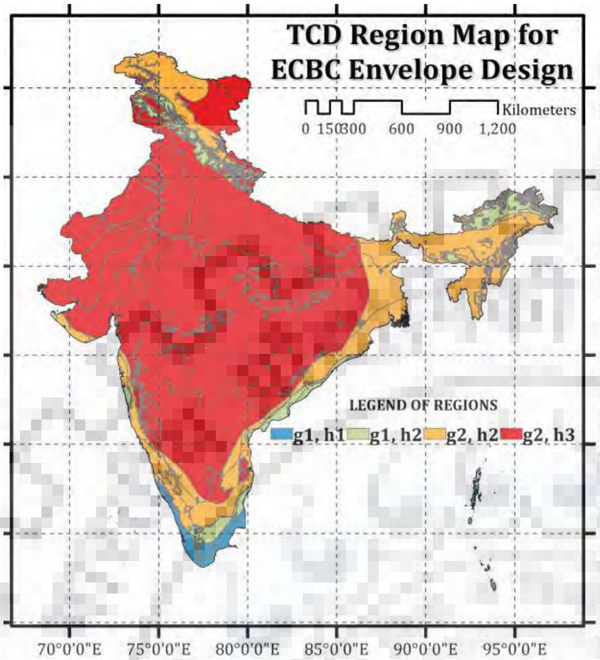


Figure 5-23 Regions for envelope design

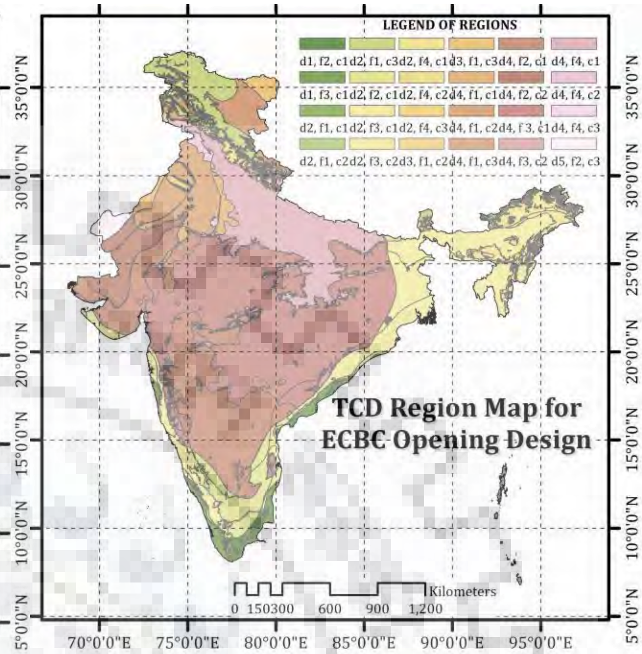


Figure 5-24 Regions for opening design

In region group g1-h1, light external walls have been specified with light roofs; while in region group g1-h2, light external walls have been specified with light and insulated roofs. On the other hand in region group g2-h2, heavy external walls have been specified with light and insulated roofs; while in region group g2-h3, heavy external walls have been specified with heavy roofs.

5.3.2.2. SHGC adjustment as per window protection recommended for specific direction

Twenty-four groups have been found (see Figure 5-24), after regrouping TCD Zones on the basis of regional recommendations for opening size, protection & position.

TCDZ regions d1-d5 (Figure 5-10), f1-f4 (Figure 5-11) and c1-c3 (Figure 5-9), were superimposed to obtain region groups for which the opening design specification codes have been listed in Table 5-10 along with the legend of detailed design recommendations.

Table 5-10 should be specified as a prescriptive requirement to be complied before SHGC adjustments are done as per window protection recommended for specific direction (See Table 2-14).

Table 5-8 Thermal performance specifications based on Indicators Source: [144]

Indicators		Recommendations			
H1	A1	Construction	"U" value	Solar heat factor (percentage)	Time lag
		External Wall			
	0-2	Light	2.80	4	3 hours max.
	3-12	Heavy	2.00	4	8 hours min.
		Roofs			
10-12	0-2	Light	1.10	4	3 hours max.
	3-12	Light and insulated	0.85	3	3 hours max.
0-9	0-5				
	6-12	Heavy	0.85	3	8 hours min.

Table 5-9 Envelope design specifications based on region group

TCDZ SRs	Group for Envelope Design	External Wall Specifications			Roof Specifications		
		"U" value	Solar heat factor (percentage)	Time lag	"U" value	Solar heat factor (percentage)	Time lag
1,2,3,4,7	g1, h1	2.80	4	3 hours max.	1.10	4	3 hours max.
5,6,8,9,10,11,12,13,14,15,16,17, 18	g1, h2	2.80	4	3 hours max.	0.85	3	3 hours max.
19,20,21,22,23,24,25,26,27,28, 29,30,31,32,33,34,35,36,37	g2, h2	2.00	4	8 hours min.	0.85	3	3 hours max.
38,39,40,41,42,43,44,45,46,47, 48,49,50,51,52,53,54,55,56,57, 58,59,60,61,62	g2, h3	2.00	4	8 hours min.	0.85	3	8 hours min.

Table 5-10 Opening design specifications based on region group

TCD Zone in Region Group	Opening design specification codes		
	Size	Protection	Position
1,3,5	d1	f2	c1
2,4,6	d1	f3	c1
19,20,27	d2	f1	c1
14,32	d2	f1	c2
17,35,36	d2	f1	c3
8,21,22,28,29	d2	f2	c1
7,9,10,23,24,30	d2	f3	c1
15,33	d2	f3	c2
11,12,13,25,26,31	d2	f4	c1
16,34	d2	f4	c2
18,37	d2	f4	c3
38	d3	f1	c2
39,40	d3	f1	c3
41	d4	f1	c1
48,52,53	d4	f1	c2
59,60	d4	f1	c3
42,43	d4	f2	c1
49,54	d4	f2	c2
44,45	d4	f3	c1
50,55,56	d4	f3	c2
46,47	d4	f4	c1
51,57,58	d4	f4	c2
61	d4	f4	c3
62	d5	f2	c3

Specification for opening size

d1	Large openings, 40-80% of wall area
d2	Medim Openings, 25-40% of wall area
d3	Composite Openings, 20-35% of wall area
d4	Small openings, 15-25% of wall area
d5	Very small openings, 10-20% of wall area

Specification for opening protection

f1	Welcome sun during winter
f2	Exclude direct sunlight
f3	Protection from rain & direct sunlight
f4	Provide protection from rain

Specification for air movement & opening position

c1 & e1	Single banked Rooms, permanent provision for air movement & Openings in N&S walls at body height on windward side
c2 & e2	Double banked Rooms with temporary provision for air movement & Openings in N&S walls at body height on windward side,openings also in internal walls
c3 & e3	No air movement required & Has no climate related value

5.3.3. State-wise Significance of TCD Zones

Table 5-11 shows significant TCD Zones for individual State or UT. The significance is identified based on two criteria; state or UT wise comparison of TCDZ area (form Table 5-5) and state or UT wise comparison of TCDZ city count (from Table 5-7). States or UTs where location/s of major city/ies coincide with TCD zone/s significant as per area comparison criteria, have been highlighted in Table 5-11. In 19 states or UTs the all major cities are located within the spatially significant TCD Zone/s. All major cities in the 4 states of Jammu & Kashmir, Madhya Pradesh, Meghalaya and Nagaland, are located the outside spatially significant TCD Zone/s. Few major cities in the 6 states of Andhra Pradesh, Karnataka, Kerala, Maharashtra, Rajasthan and Tamil Nadu are located outside the spatially significant TCD Zone/s. There is no spatially significant TCD Zone in the state of Goa. There is no major city located in the state of Arunachal Pradesh.

Table 5-11 State or UT wise list of significant TCD Zone/s

State or UT \ TCDZ	by Area	by City Count	State or UT \ TCDZ	by Area	by City Count
Andaman & Nicobar	2	2	Madhya Pradesh	45, 47	**25, 5**
Andhra Pradesh	43, 45	43, 45, **21, 5**	Maharashtra	45, 43	**23**, 43, 45
Arunachal Pradesh	11, 25	-	Manipur	25, 23	25
Assam	23	23	Meghalaya	23, 25, 16	**34**
Bihar	45, 47, 23	45, 47	Mizoram	23, 31	23
Chandigarh	47	47	Nagaland	26, 24, 22	**23**
Chhattisgarh	45	45	Orissa	45, 23	23, 45
Delhi	47	47	Puducherry	6	6
Goa		**9, 24**	Punjab	48, 51, 53	48, 51
Gujarat	43, 45, 49	43, 45	Rajasthan	45, 43, 49	**41**, 45, **48**
Haryana	48, 47, 41	41, 47, 48	Tamil Nadu	21, 8, 1	**3**, 21, **23**
Himachal Pradesh	35, 47, 16	16	Tripura	23	23
Jammu & Kashmir	35, 57	**47, 52**	Uttar Pradesh	47, 45	45, 47
Jharkhand	45, 24	45	Uttarakhand	47, 59, 16	47
Karnataka	43	43, **22**	West Bengal	23, 24	23, 24
Kerala	2, 23	2, **7**, 23			

5.3.4. Zone Identification of Urban Local Bodies in Maharashtra

TCD Zones of all 252 ULBs in Maharashtra (see section 4.3.3.1) were identified by overlaying their geographical coordinates as shown in Figure 5-25 on TCD Zone map.

High number of ULBs 113 (45%) and 96 (38%) were found to correspond with TCD Zone SR 43 and SR 45 respectively. Significant number of ULBs 16 (6%) and 10 (4%) were found to correspond with TCD Zone SR 23 and SR 49 respectively. Scant number of ULBs 7(3%), 5(2.5%) and 4(2%) were found to correspond with TCD Zone SR 24, SR 50 and SR6, respectively. One ULB each was found to correspond with TCD Zone SR 10, SR 54 and SR 56. No ULB was found to correspond with TCD Zone SR 9 and SR 55. Complete list of ULBs with respective TCD Zones is included as APPENDIX 2.

5.3.5. Regionalization of DC & PR in Maharashtra

Significantly out of the 12 TCD Zones of Maharashtra, extents of 5 zones fall exclusively within Konkan (the western coastal region abutting the Arabian Sea). The remaining TCD Zones gradually change as the transect moves inland across the Western Ghats towards east. The most populous Zones TCD SR 43 and SR 45 are adjoining each other and correspond with the Deccan Plateau. In these two zones all but two design specifications were found to be similar. Recommended specifications of opening protection and rain protection features varied in these zones, due to variation in intensity of rainfall received (see APPENDIX 2). In contrast the recommended specifications for the most populous Zone from Konkan TCD SR 23, were found to be significantly different. Most of the zones in Konkan have been specified with high to medium window size, light roof material and no recommendation for sleeping space. Relevant clauses in the Standardized DC&PR pertaining to climate responsive design specifications can thus be differentiated on the basis of TCD Zone identified for the ULB.

5.4. Local climate level assessment

As seen in section 2.3 meteorological instruments are usually located at a place where readings are not affected by special topographical features, nearby buildings or vegetation. Data recorded by such instruments are bound to differ from readings in the streets of large cities or on the shores of a lake. Narrow streets like narrow valleys or gorges, affect the direction and velocity of wind; large built up areas have higher night temperatures, and ponds, woods and parks exercise a moderating influence on the daily rhythm of heating and cooling. The shores of the sea or the large lakes produce their own wind patterns which may differ markedly from those further inland.

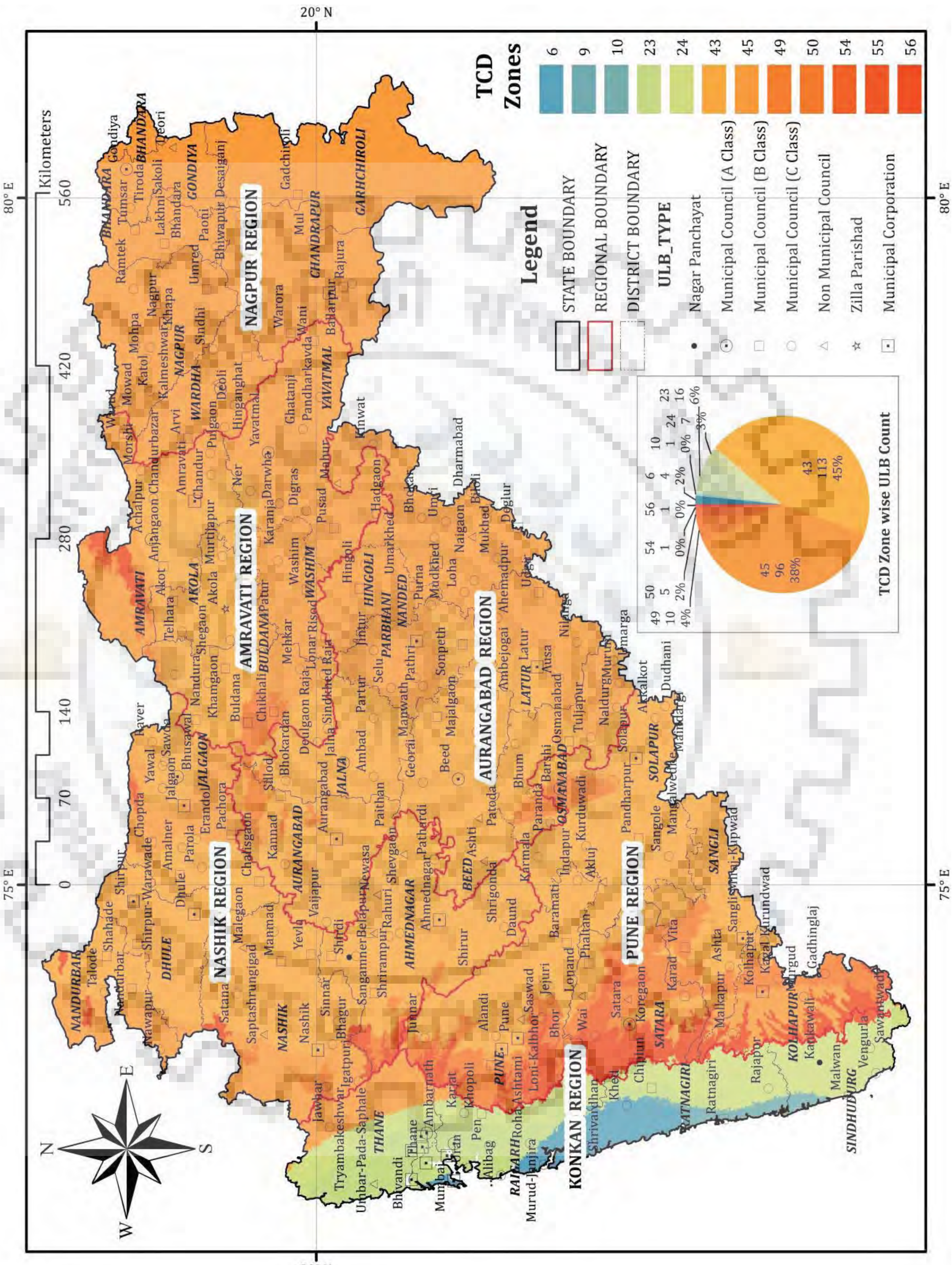


Figure 5-25 TCD Zone wise ULB Count in Maharashtra

Earlier scientists held that, the differences between the regional climate (as recorded at the meteorological observatory) and the actual site (local) climate are rarely large enough to affect the decisions that have to be taken during the design stage[144]. However the validity of this opinion needs to be ascertained in view of the heavy influence of urbanization on the earth's atmosphere. While using the regional climate data the designer should be aware of the possible climatic advantages and disadvantages of his particular site. The significance of local climate variation needs to be assessed using two types of information. Firstly the variation of Local Climate zones across the city and the variation in climatic parameters measured at sites representing contrasting local climate zones. The results of methodology implemented for establishing Local climate zones is discussed in a published article [162] attached as appendix PAPER 4. The assessment of thermal behavior of LULC typically found in an institutional campus has been discussed at length in a published article [160] attached as appendix PAPER 2.

Further research is needed to establish Local Climate zones to a satisfactory level for explaining observed thermal variation and its estimation over the entire study area.

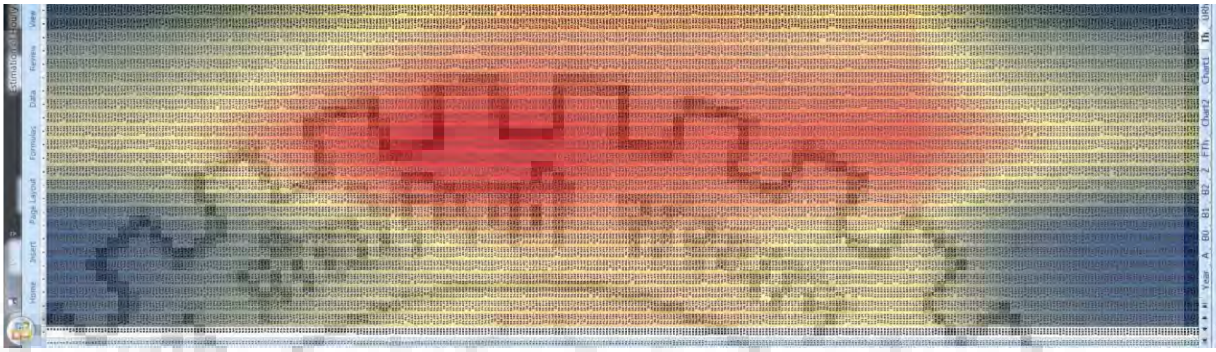
5.5. Typical climate level assessment

As can be seen from section 5.3.1.2, additional typical weather files may need to be generated for cities located in the influence area of weather file stations that have high TCD Zone variability. 14 major cities in the influence area of Amritsar weather file correspond to 5 different TCD zones. As part of typical climate level assessment the workflow developed in section 4.5.1 has been implemented for generating a regionalized typical weather file for Amritsar. Values estimated during the regionalized typical weather file generation have been compared with the published typical weather file of that station.

5.5.1. Estimated hourly DBT values

Diurnal variation in estimated dry bulb temperature values across the year has been color graded in Table 5-12. Sinusoidal variation may be observed in diurnal as well as seasonal direction. The correlation between the estimated temperature values and corresponding values from the published typical weather file is shown in Figure 5-26. The estimated and observed hourly dry bulb temperature values are correlated with a R^2 value of 0.8795.

Table 5-12 Hourly Temperature estimated using algorithm automated in excel



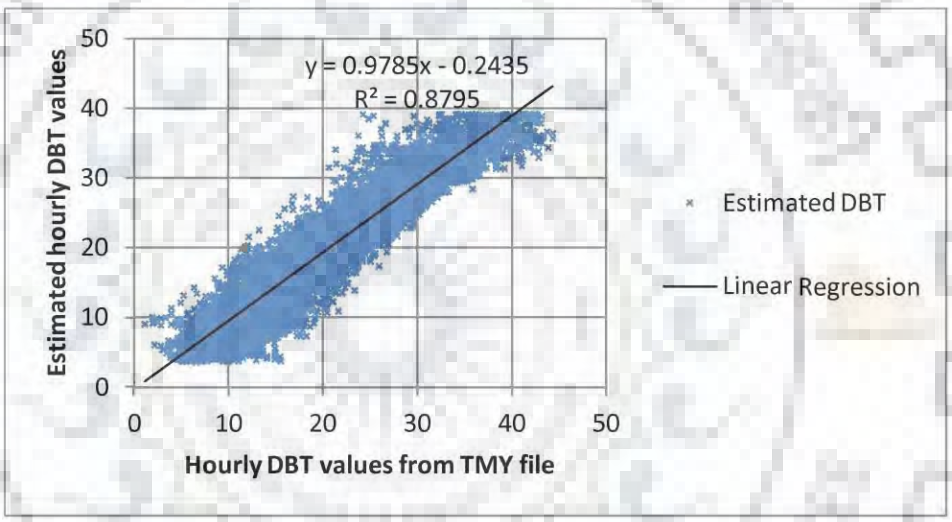


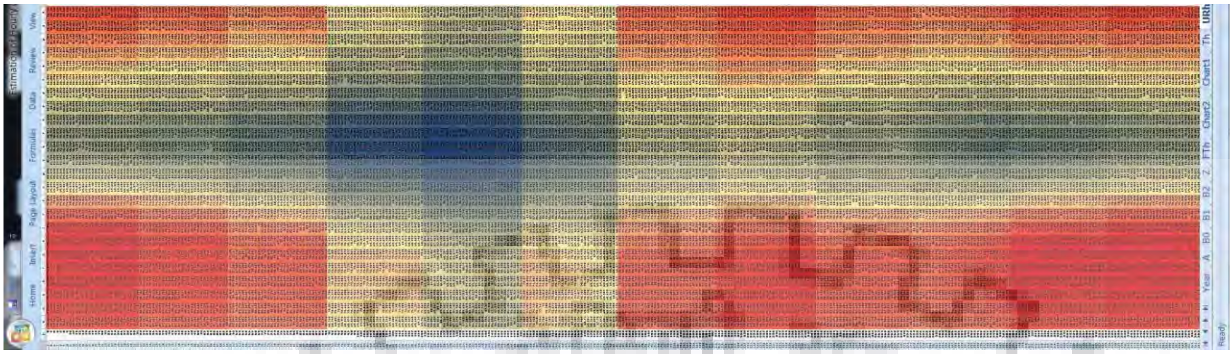
Figure 5-26 Estimated hourly DBT values compared with TMY file

5.5.2. Estimated hourly RH values

Diurnal variation in estimated hourly relative humidity values has been color graded in Table 5-13. The estimated humidity values are found to exhibit sinusoidal variation in diurnal direction, while the sinusoidal variation in seasonal direction is found to be reset approximately every 730 hours, i.e. on monthly basis. The reset tendency is due to the jerks existing in monthly average maximum and minimum humidity values for 12 months.

The correlation between the estimated relative humidity values and corresponding values from the published typical weather file is shown in Figure 5-27. The estimated and observed hourly relative humidity values are correlated with a R^2 value of 0.6297.

Table 5-13 Hourly humidity values estimated using algorithm automated in excel



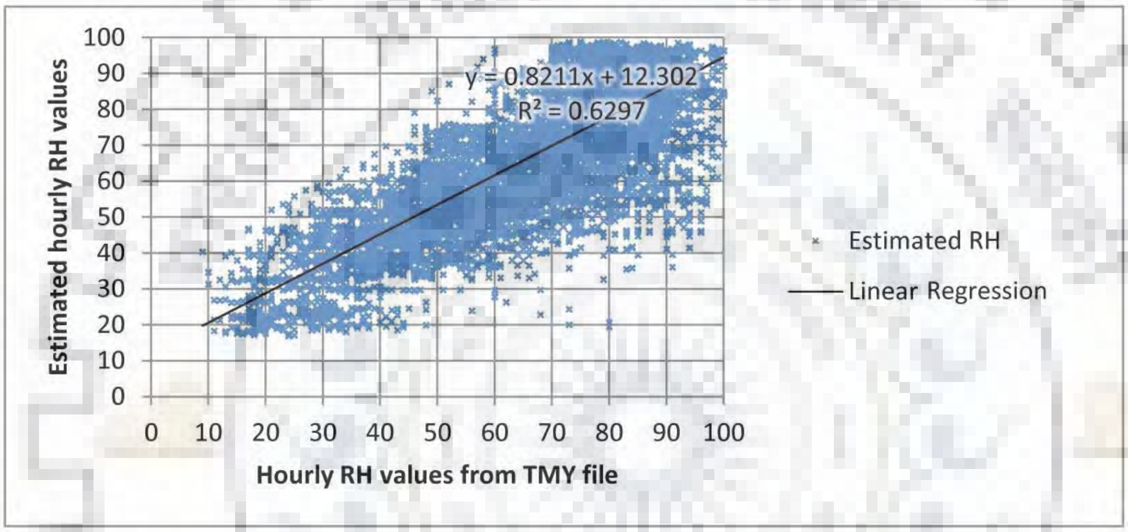


Figure 5-27 Estimated hourly RH values compared with TMY file

5.6. Summary

Many useful inferences can be drawn from the Result Assessment. Though 62 TCD Zones have been delineated at national level, most of these zones are regional and exist only within remote and relatively small areas. Detailed assessment of the smaller zones is best done at state level assessment. Few TCD Zones though span across many administrative units and may be considered for development of strategic planning and design interventions.

Spatial analysis using uniform grid, revealed particular districts with high variability of TCD Zones. Such districts need special attention during state level assessment. State level assessment helps in identifying not only the spatially significant TCD Zone/s but also those populated with major cities in each state or UT. This information is of crucial significance in the planning for regionalized development control regulations. The correspondence between the continental edge of administrative boundary of coastal (Konkan) region in Maharashtra state with its distinct set of climatic zones signifies the efficacy of TCD Zone as a basis of regionalization of DC & PR.

Assessment of recommended specifications applicable to major settlements and corresponding weather files revealed a reasonable representativeness of many weather stations. The assessment also revealed a few weather stations completely alien to its constituent cities, highlighting the need for generation of additional weather files for areas having high variability in TCD Zones. Exploratory research revealed the possibility of estimating hourly values of dry bulb temperature and relative humidity based on climatic normals for the parameters.

CHAPTER 6. CONCLUSION

6.1. General

One of the chief outcomes of this research is the identification of the possibility of an interlink between the climatic data measured, archived, summarized, synthesized for use in analysis at various levels of climate study pertaining to legislation, design and monitoring of sustainable built environment. In the scenario of increased rate of immigration to urban areas, increased requirement of building stock has improved the scope for construction industry, leading to more investors entering this business. Growth created competition which led to a tendency to economize on every aspect of building construction. An absence of legislation to ensure mandatory provision of (intangible goods such as) basic passive design strategies to all for climate modulation led to its neglect; and active methods taking over the role of chief strategy for achieving thermal comfort [75,85,126].

Not only is the existing climatic classification for building design limited by the availability of data and analysis techniques at the time of its development [3], but also it is not an effective representation of the climatic diversity of India[130]. Hence the task of mandating building design specifications in response to the variation in thermal stresses becomes difficult. It is also necessary to regulate the climate modulation caused by conversion of rural vegetated fringe areas into densely built urban areas[132]. As compared to the growing number of urban settlements [101] very few weather files are available for comparing the whole building performance of innovative designs[61]. For implementation of an effective legislation, state of the art in climatic assessment needs to be brought up to mark.

Latest data available from expanded weather station network of IMD needs to be used in climatic classification for building design and generation of weather files for performance appraisal. To ensure that all stake holders make informed decisions, they should be able to ascertain appropriate design strategies based on the duration of various thermal stresses expected throughout the year at the construction site, in response to normal climatic conditions.

Towards this intent, a framework has been developed for thermal comfort analysis at the regional climate level, local climate level and typical climate level.

6.2. Conclusion

At Regional Climate Level the complex task of identifying regions with identical thermal comfort requirements across India has been achieved. As seen from section 2.2 various sources and methods of climatic data collection, storage and decimation exist based on their particular needs. Gradual evolution seen in the thermal comfort analyses methods used for identifying recommended climate responsive design specifications has been reviewed in section 2.4.3. Mahoney Tables method discussed in section 3.2.2 and 3.4.2 is found useful for prioritizing between the specifications where conflicting thermal stresses exist and as such is suitable for legislation purpose. In order to objectively represent variation in climate interpolated data available at world scale has been subset for India and analyzed using GIS, based on design strategy selection criteria provided in Mahoney Tables.

As seen from result assessment at regional climate level, out of the 62 TCD Zones delineated across India, all major cities are located within 31 Zones. Further, only 16 Zones encompass 5 or more major cities and hence are used for detailed exploration in APPENDIX 1. A Google Earth app has also been developed to interactively zoom to the location of any given settlement in India and instantly identify the unique combination of climate responsive building design specifications recommended for that location. For implementation of relevant mandatory requirements as per ECBC, India has been regionalized based on Mahoney Tables criteria of envelope design and opening design. Regional maps and legislative tools for implementation of other design strategies can also be developed. Most of the typical weather files are representative of thermal comfort requirements of most cities in their neighborhood. The typical weather files representing neighborhoods with high variability in TCD Zone have been identified for generation of additional local typical weather files using climate normals or gridded climate data collated for regional climate level analysis.

The TCD Zones have been analyzed in further detail for the context of Maharashtra state in order to demonstrate their capability of regionalizing building bye-laws. Out of the 12 TCD Zones found across Maharashtra, 7 are restricted in the coastal region called Konkan. This demonstrates the efficacy of TCD Zones to identify geographical regions with distinct thermal comfort requirements and applicable combinations of responsive design specifications. TCD Zones applicable to 254 Urban Local Bodies in Maharashtra have been Identified and listed in APPENDIX 2. A tabular analysis helps to identify the variation in design specifications that needs to be implemented in appropriate building bye laws.

At Local Climate Level a methodology has been evolved based on discussions in section 3.3.2, section 4.4 and section 5.4. On the one hand this methodology consists of a procedure initiated in [162] (see attached PAPER 4) for compiling a ratio between the built-up and vegetation densities. While on the other hand it consist of a procedure initiated in [160] (see attached PAPER 2) for collecting Local climate measurements and establishing variation in the same for assessing desirable urban built form.

At Typical Climate Level, a methodology has been evolved based on discussions in section 4.5.1 and section 5.5 for the generation of weather files for any city. The algorithm detailed out in APPENDIX 3 has been automated in a spreadsheet and can estimate hourly DBT with a RMSE of 0.86795, and hourly RH with a RMSE of 0.6297, by using climate normals available from IMD weather station data or (if not available) gridded climate data as input.

6.3. Recommendations

For getting published gridded climatic data of parameters required in thermal comfort analysis at par with state of the art interpolated data; efforts should be made in collaboration with IMD.

Climatic classification for building design / TCD Zone analysis should be carried out using gridded data based on climate normals from all available IMD weather stations.

Deployment of weather stations at representative local climate zones in all major cities will enable refinement of TCD Zone analysis.

Hourly weather files should be generated for all IMD weather stations using respective climate normals / gridded data and Roriz algorithm[124].

Recommendations have been drawn for adoption of TCDZ map by all urban local bodies and making provisions in building byelaws and town planning regulations to facilitate implementation of identified zone specific strategies.

Architects attempting to influence legislation and environmental design rules based on professional research in a country as large as India have the additional responsibility to ensure that these are uniformly, intelligently and fairly handled everywhere by lesser-trained individuals [83,112]. For the environmental design rules to be effective in the given circumstances, their formulation needs to be broader and easier to implement. Accordingly based on the proposed Climatography model for sustainable urban built environment recommendations have been made for:

- inclusion of climate responsive considerations in design decisions
- standardizing building performance evaluation criteria
- incentivizing achievement of desirable urban built form

6.3.1. for inclusion of climate responsive considerations in design decisions

To ensure that the stakeholders' decision making process is informed by the proposed Climatography model, the following statements may be included in the declaration to be signed while applying for building permission / loan sanction:

"I have verified the TCDZ SR applicable to my city / town by referring to the TCD Zone map of India (online app) / Maharashtra State (reference to APPENDIX 2).

"I am aware that TCD Zone map has been developed based on duration of various thermal stresses expected throughout the year in response to normal climatic conditions at the proposed building site."

"I have referred to the TCD Zone Recommended Specifications flyer (reference to APPENDIX 1) applicable to the proposed building site, and fully understood the various design specifications recommended for built form, building envelops, and openings."

"I have incorporated the recommended design specifications in the proposed design the best of my knowledge and belief and will provide / use all resources required for the effective implementation of the same on site."

6.3.2. for standardizing building performance evaluation criteria

Urban local bodies shall mandate the use of climate responsive design specifications recommended vide TCD Zone map for developing base case for ECBC compliance through whole building performance.

Where weather files provided by ISHRAE are not available, the ULB shall mandate use of weather files complied – by performing temporal interpolation on spatially interpolated climate normals – using proposed methodology.

6.3.3. for incentivizing achievement of desirable urban built form

Urban local bodies shall incentivize the implementation of prescriptive guidelines for a desirable urban built form, generated after proposed local climate level analysis. If such an analysis has not been done for any city/town belonging to the relevant TCDZ SR, the ULB shall initiate / support conduct of the same for their city.

6.4. Future scope

Scope for future research has been identified, considering the availability of better resolution datasets based on remotely sensed satellite images, useful for improving the quality of generated local and typical climatic data.

All Strategic Intervention Models inherently have a Coverage Phase and an Impact Phase. As of now the proposed *Climatography Model* is in Coverage Phase where an attempt has been made to regionalize the Indian Territory for incorporation of broad aspects of climate analyses into legislative instruments namely National Building Code, Standardized Building Byelaws. Multiple approaches to detailed climate responsive design analysis using strategy bundles [33] and software packages [70] have been developed recently. Integration of such approaches into the proposed *Climatography Model* should be considered during the Impact Phase for imparting a refined edge to the climate responsive design recommendations.

State of the art land cover classification schemes [9][29] are now being used in energy flux models [123] to simulate the spatial distribution of climate variables at (a finer resolution) Local Scale. Such high resolution climate variables can be used as input in

Climatography Model for identifying urban built forms appropriate for various TCD Zones.

It is possible to counter a particular thermal stress by adopting multiple approaches using a variety of strategy bundles [33]. For enabling compliance through alternative means, lists of innovative developments in materials and technologies pertaining to each building design strategy need to be updated from time to time. Studies need to be initiated for formulating of selection criteria covering new and emerging climate responsive design strategies based on analysis similar to Mahoney Tables.

The developed TCD Zone delineation also has application in various other fields like:

- Identification of regions for honing distinct indigenous building technologies that have emerged over centuries using local materials and construction techniques by trial and error.
- Implementation of legislative reforms pertaining to regionalized codes and standards based on climatology applied not only in building construction but also in various other sectors of human endeavor; like planning for manufacture and sale of clothing or packaged food etc.

TCD zones are a delineated by classifying the natural climatic environment (prevalent stresses) into unique combinations of responsive design strategies based on Mahoney Tables recommendations. Whereas the vernacular architecture, an abundant variety of which may be found in each TCD zone; is also determined by other techno-cultural determinants (discussed in section 2.4.4.1). Further studies may be undertaken to ascertain the efficacy of vernacular buildings documented in individual TCD zone against prevalent climatic stresses.

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APPENDIX 1: CLIMATE RESPONSIVE DESIGN SPECIFICATIONS FOR 1LAKH PLUS CITIES

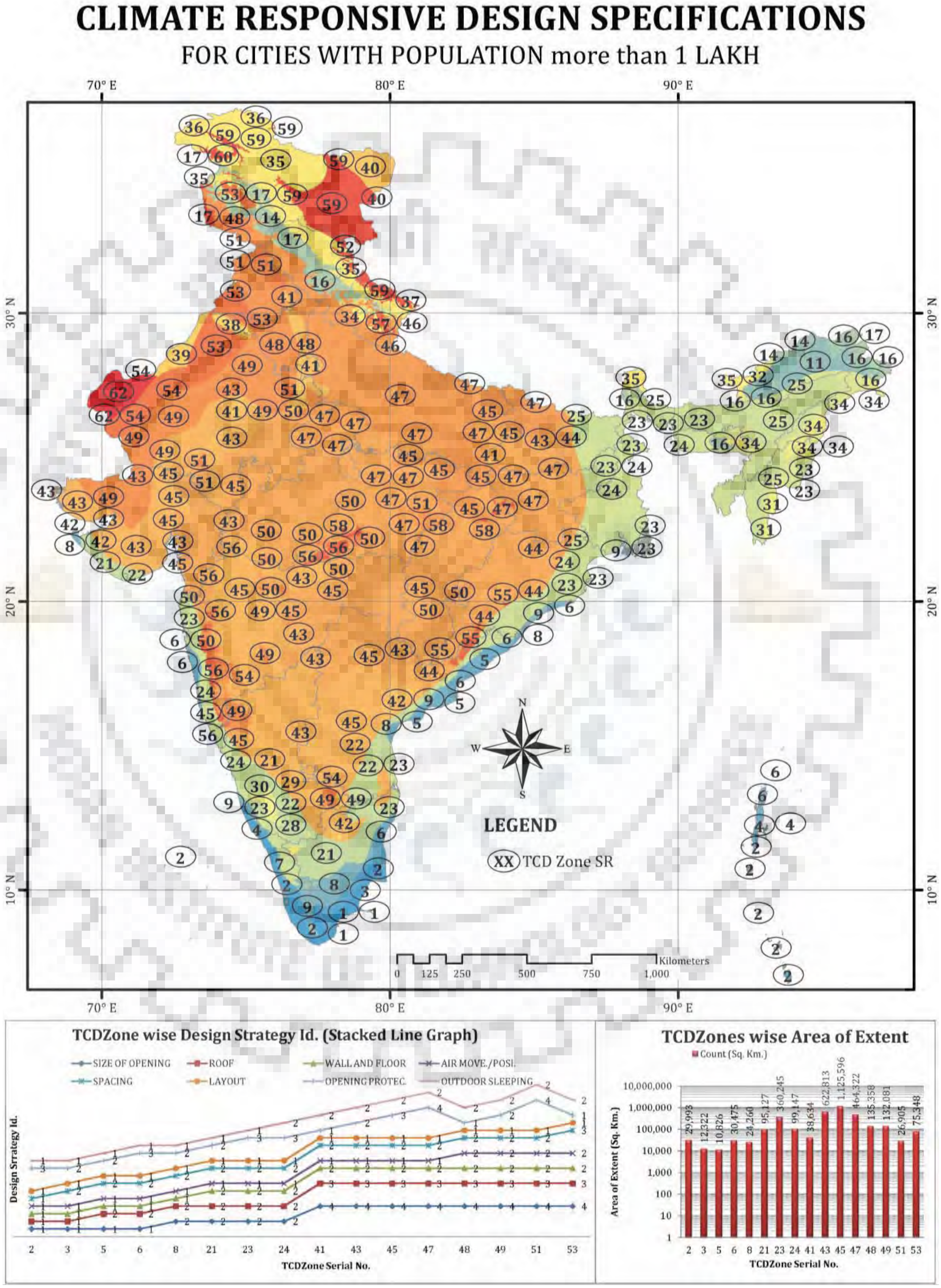


Table 6-1 TCD Zone wise City Count for each State

State & TCDZ	City Count
Andaman & Nicobar	**1**
2	1
Andhra Pradesh	**47**
5	5
6	2
8	2
9	1
21	5
23	1
42	4
43	20
44	2
45	5
Assam	**7**
23	7
Bihar	**27**
23	4
24	2
45	11
47	10
Chandigarh	**1**
47	1
Chhattisgarh	**10**
45	10
Delhi	**1**
47	1
Goa	**2**
9	1
24	1
Gujarat	**33**
21	2
43	18
45	12
49	1
Haryana	**20**
41	8
47	5
48	6
53	1
Himachal Pradesh	**1**
16	1
Jammu & Kashmir	**2**
47	1
52	1
Jharkhand	**14**
24	2
45	12
Karnataka	**26**
2	1
9	1
21	1
22	4
28	1
43	15
45	1
49	1
50	1
Kerala	**16**
2	12
7	2
23	2
Madhya Pradesh	**33**
43	1
45	25
47	5
50	1
56	1
Maharashtra	**42**
23	11
43	17
45	12
49	1
50	1
Manipur	**1**
25	1
Meghalaya	**1**
34	1
Mizoram	**1**
23	1
Nagaland	**1**
23	1
Orissa	**10**
6	1
9	1
23	5
45	3
Puducherry	**1**
6	1
Punjab	**18**
47	2
48	9
51	4
53	3
Rajasthan	**32**
38	3
41	6
43	3
45	9
47	1
48	5
49	3
51	1
53	1
Tamil Nadu	**40**
1	2
2	1
3	5
4	1
5	1
6	2
8	4
21	14
23	8
34	1
49	1
Tripura	**1**
23	1
Uttar Pradesh	**66**
41	2
45	8
47	56
Uttarakhand	**8**
47	8
West Bengal	**67**
16	1
23	48
24	17
45	1
Grand Total	**530**

Thermal Comfort Design Zone 2

MAJOR CITIES	LATITUDE	LONGITUDE
Thiruvananthapuram	8.52 °N	76.94 °E
Mangalore	12.91 °N	74.85 °E

OTHER CITIES:
Kollam, Kayamkulam, Kottayam, Cherthala, Kochi, Nagapattinam, Malappuram, Kozhikode, Port Blair, Kasaragod

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Air movement essential (H1) for 11 to 12 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide LARGE openings, between 40 and 80% area of north and south walls. These need not be fully glazed, but should be protected from the sun, sky glare and rain, preferably by horizontal overhangs. Thermal storage is needed for not more than 1 month (A1) and there is no cold season (A3).

5. PROTECTION OF OPENINGS
PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS
Provide LIGTH external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Thermal storage requirement is less than 2 months (A1). Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity (in case of latter option provide protection against insects and vermin).

7. ROOF SPECIFICATIONS
Provide LIGTH roof with REFLECTIVE surface and good INSULATION. Time-lag should never exceed 3 hours. A cavity within the roof or a roof-ceiling combination is advantageous. The roof-ceiling overall U-value should be in the region of 1 W/m2degC. Thermal storage requirement is less than 2 months (A1) with an air movement requirement for 10 to 12 months (H1).

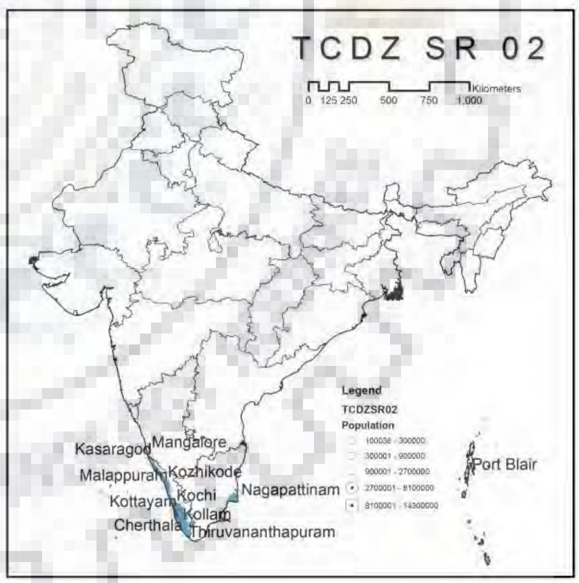
8. OUTDOOR SLEEPING SPACE
Space for out-door sleeping NOT RECOMMENDED.

9. RAIN PROTECTION FEATURES
PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	0-1
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	11-12
H2: Air movement desirable	0-4
H3: Rain protection necessary	0-8

Key Map



Thermal Comfort Design Zone 3

MAJOR CITIES	LATITUDE	LONGITUDE
Tirunelveli	8.74 °N	77.69 °E
Thanjavur	10.78 °N	79.13 °E

OTHER CITIES:
Rajapalayam, Karaikkudi, Pudukkottai

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS

Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS

Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS

Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS

Provide LARGE openings, between 40 and 80% area of north and south walls. These need not be fully glazed, but should be protected from the sun, sky glare and rain, preferably by horizontal overhangs. Thermal storage is needed for not more than 1 month (A1) and there is no cold season (A3).

5. PROTECTION OF OPENINGS

Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS

Provide LIGTH external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Thermal storage requirement is less than 2 months (A1). Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity (in case of latter option provide protection against insects and vermin).

7. ROOF SPECIFICATIONS

Provide LIGTH roof with REFLECTIVE surface and good INSULATION. Time-lag should never exceed 3 hours. A cavity within the roof or a roof-ceiling combination is advantageous. The roof-ceiling overall U-value should be in the region of 1 W/m2degC. Thermal storage requirement is less than 2 months (A1) with an air movement requirement for 10 to 12 months (H1).

8. OUTDOOR SLEEPING SPACE

Space for out-door sleeping NOT RECOMMENDED.

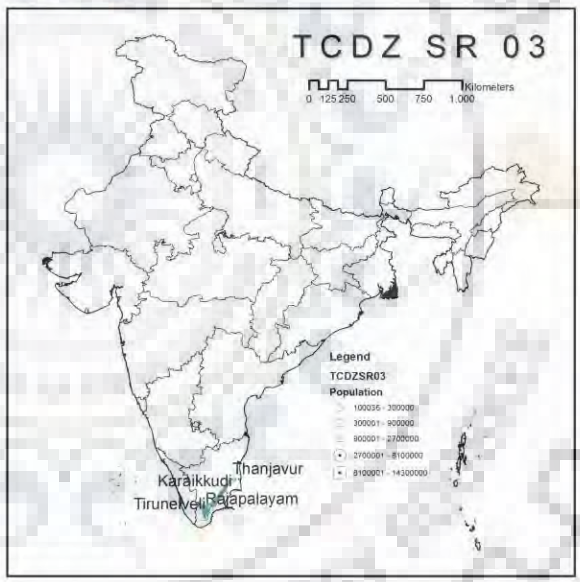
9. RAIN PROTECTION FEATURES

NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	0-1
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	10
H2: Air movement desirable	1
H3: Rain protection necessary	0-3

Key Map



Thermal Comfort Design Zone 5

MAJOR CITIES	LATITUDE	LONGITUDE
Kumbakonam	10.96 °N	79.38 °E
Srikakulam	18.29 °N	83.89 °E

OTHER CITIES:
Ongole, Machilipatnam, Kakinada, Visakhapatnam

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide LARGE openings, between 40 and 80% area of north and south walls. These need not be fully glazed, but should be protected from the sun, sky glare and rain, preferably by horizontal overhangs. Thermal storage is needed for not more than 1 month (A1) and there is no cold season (A3).

5. PROTECTION OF OPENINGS
Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS
Provide LIGTH external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Thermal storage requirement is less than 2 months (A1). Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity (in case of latter option provide protection against insects and vermin).

7. ROOF SPECIFICATIONS
Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

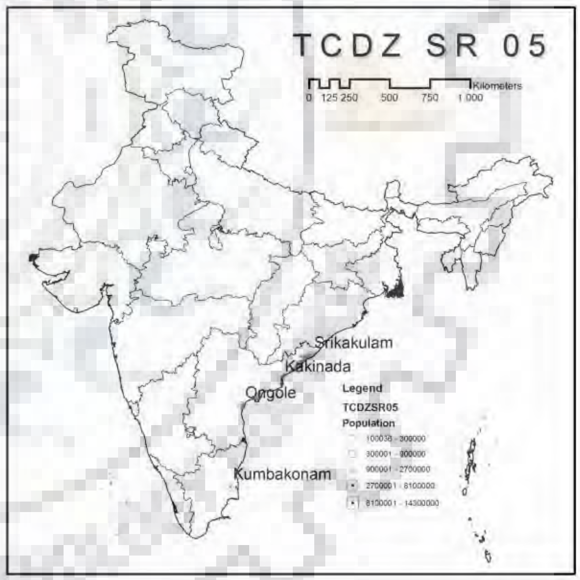
8. OUTDOOR SLEEPING SPACE
Space for out-door sleeping NOT RECOMMENDED.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	0-1
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	6-7
H2: Air movement desirable	0-3
H3: Rain protection necessary	0-4

Key Map



Thermal Comfort Design Zone 6

MAJOR CITIES	LATITUDE	LONGITUDE
Neyveli	11.54 °N	79.47 °E
Puri Town	19.80 °N	85.83 °E

OTHER CITIES:
Puducherry, Ozhukarai, Bhimavaram, Vizianagaram

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide LARGE openings, between 40 and 80% area of north and south walls. These need not be fully glazed, but should be protected from the sun, sky glare and rain, preferably by horizontal overhangs. Thermal storage is needed for not more than 1 month (A1) and there is no cold season (A3).

5. PROTECTION OF OPENINGS
PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS
Provide LIGTH external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Thermal storage requirement is less than 2 months (A1). Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity (in case of latter option provide protection against insects and vermin).

7. ROOF SPECIFICATIONS
Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

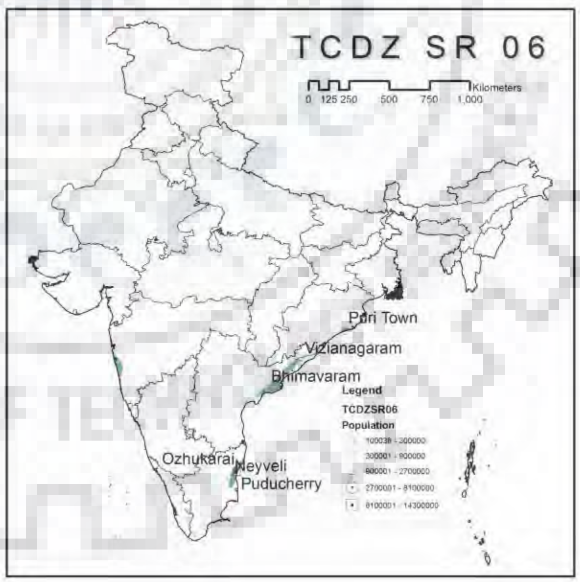
8. OUTDOOR SLEEPING SPACE
Space for out-door sleeping NOT RECOMMENDED.

9. RAIN PROTECTION FEATURES
PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	0-1
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2-9
H2: Air movement desirable	0-8
H3: Rain protection necessary	0-7

Key Map



Thermal Comfort Design Zone 8

MAJOR CITIES	LATITUDE	LONGITUDE
Sivakasi	9.45 °N	77.81 °E
Rajahmundry	17.00 °N	81.78 °E

OTHER CITIES:
Madurai, Dindigul, Tiruchirappalli, Chirala

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide MEDIUM openings, 25-40% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates, but under no circumstances in the tropics. Thermal storage is needed for not more than 1 month (A1) and there is a cool season (A3) OR Thermal storage is needed for 2 to 5 month (A1).

5. PROTECTION OF OPENINGS
Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS
Provide LIGTH external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Thermal storage requirement is less than 2 months (A1). Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity (in case of latter option provide protection against insects and vermin).

7. ROOF SPECIFICATIONS
Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

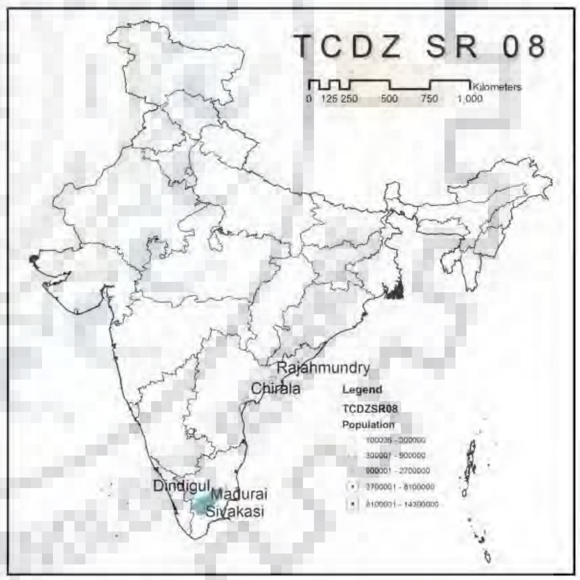
8. OUTDOOR SLEEPING SPACE
Space for out-door sleeping NOT RECOMMENDED.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	1-2
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2-9
H2: Air movement desirable	0-6
H3: Rain protection necessary	0-4

Key Map



Thermal Comfort Design Zone 21

MAJOR CITIES	LATITUDE	LONGITUDE
Coimbatore	11.01 °N	76.95 °E
Porbandar	21.64 °N	69.61 °E

OTHER CITIES:
Karur, Erode, Salem, Tiruvannamalai, Mysore, Kancheepuram, Vellore, Tirupati, Eluru, Veraval

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide MEDIUM openings, 25-40% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates, but under no circumstances in the tropics. Thermal storage is needed for not more than 1 month (A1) and there is a cool season (A3) OR Thermal storage is needed for 2 to 5 month (A1).

5. PROTECTION OF OPENINGS
Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

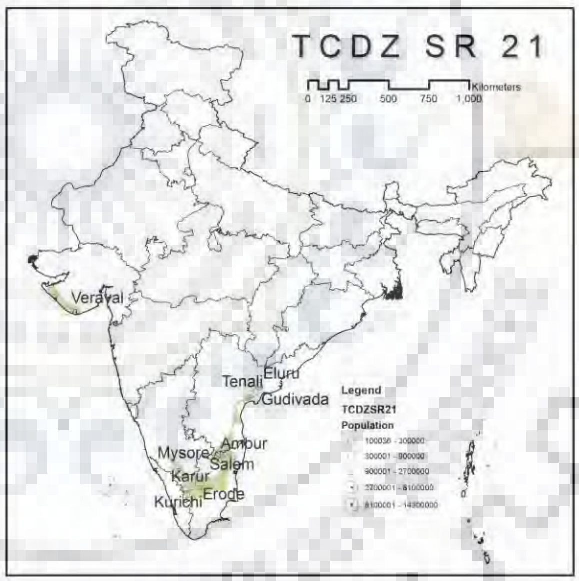
8. OUTDOOR SLEEPING SPACE
Space for out-door sleeping NOT RECOMMENDED.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	3-5
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2-8
H2: Air movement desirable	0-6
H3: Rain protection necessary	0-3

Key Map



Thermal Comfort Design Zone 23

MAJOR CITIES	LATITUDE	LONGITUDE
Chennai	13.09 °N	80.22 °E
Guwahati	26.14 °N	91.73 °E

OTHER CITIES:
Palakkad, Nellore, Mumbai, Bhubaneswar, Kolkata, Baleshwar Town, Panihati, Bhatpara, Bongaon, Aizawl, Agartala, Katihar, Dimapur

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS

Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS

Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS

Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS

Provide MEDIUM openings, 25-40% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates, but under no circumstances in the tropics. Thermal storage is needed for not more than 1 month (A1) and there is a cool season (A3) OR Thermal storage is needed for 2 to 5 month (A1).

5. PROTECTION OF OPENINGS

PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS

Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS

Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

8. OUTDOOR SLEEPING SPACE

Space for out-door sleeping NOT RECOMMENDED.

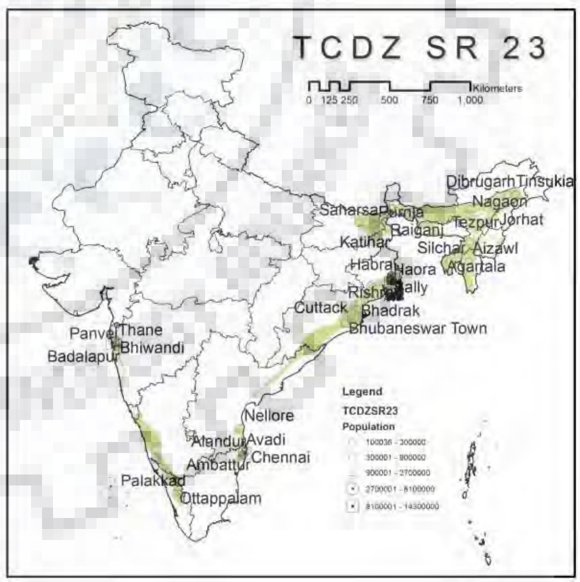
9. RAIN PROTECTION FEATURES

PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	3-5
A2: Outdoor sleeping desirable	0
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2-9
H2: Air movement desirable	0-6
H3: Rain protection necessary	0-7

Key Map



Thermal Comfort Design Zone 24

MAJOR CITIES	LATITUDE	LONGITUDE
Panaji	15.50 °N	73.83 °E
Bhagalpur	25.25 °N	86.99 °E

OTHER CITIES:

Jamalpur, Barddhaman, Bankura, Santipur, Durgapur, Asansol, Baharampur, Deoghar, English Bazar, Balurghat

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS

Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS

Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS

Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS

Provide MEDIUM openings, 25-40% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates, but under no circumstances in the tropics. Thermal storage is needed for not more than 1 month (A1) and there is a cool season (A3) OR Thermal storage is needed for 2 to 5 month (A1).

5. PROTECTION OF OPENINGS

PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS

Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS

Provide LIGTH roof with better INSULATION. The roof-ceiling with overall U-value not exceeding 0.85 W/m2degC is recommended. This performance could be provided by an external sheet with a reflective surface, a cavity and a ceiling incorporating atleast 25 mm insulation and a reflective top (aluminium foil, for instance). Thermal storage requirement is more than 3 months (A1) with an air movement requirement for 10 to 12 months (H1) OR Thermal storage requirement is less than 5 months (A1) with an air movement requirement less than 9 months (H1).

8. OUTDOOR SLEEPING SPACE

PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

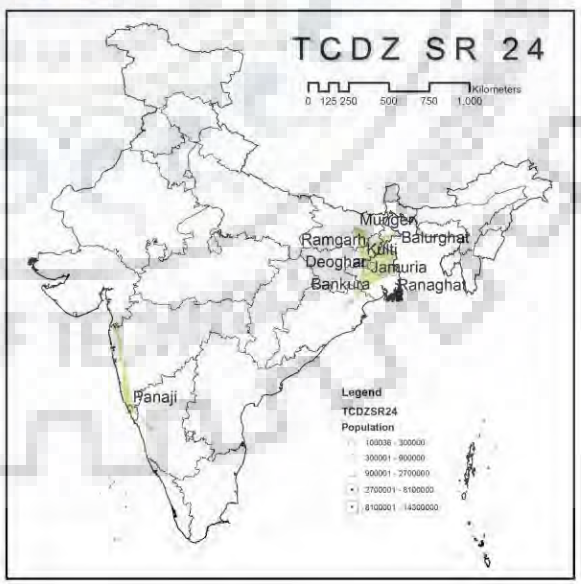
9. RAIN PROTECTION FEATURES

PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	3-5
A2: Outdoor sleeping desirable	1-5
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2-8
H2: Air movement desirable	0-4
H3: Rain protection necessary	1-6

Key Map



Thermal Comfort Design Zone 41

MAJOR CITIES	LATITUDE	LONGITUDE
Ajmer	26.45 °N	74.64 °E
Panipat	29.39 °N	76.98 °E

OTHER CITIES:
Hindaun, Makrana, Bharatpur, Mathura, Faridabad, Noida, Bahadurgarh, Sonipat, Karnal, Thanesar

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
NO special PROTECTION from sun or rain is necessary.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

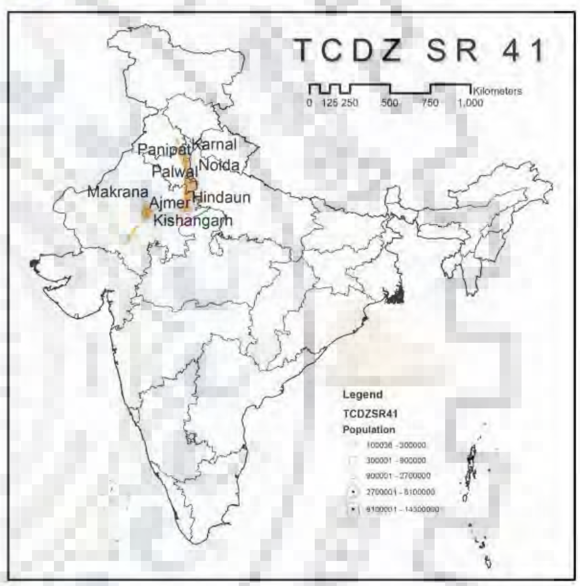
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-8
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	3-5
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	3-4
H2: Air movement desirable	0
H3: Rain protection necessary	0-2

Key Map



Thermal Comfort Design Zone 43

MAJOR CITIES	LATITUDE	LONGITUDE
Bangalore	12.97 °N	77.58 °E
Rajkot	22.31 °N	70.82 °E

OTHER CITIES:
Davanagere, Anantapur, Bellary, Hubli-Dharwad, Kurnool, Sangli-Miraj-Kupwad, Hyderabad, Pune, Nashik, Akola, Khargone, Bhilwara

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

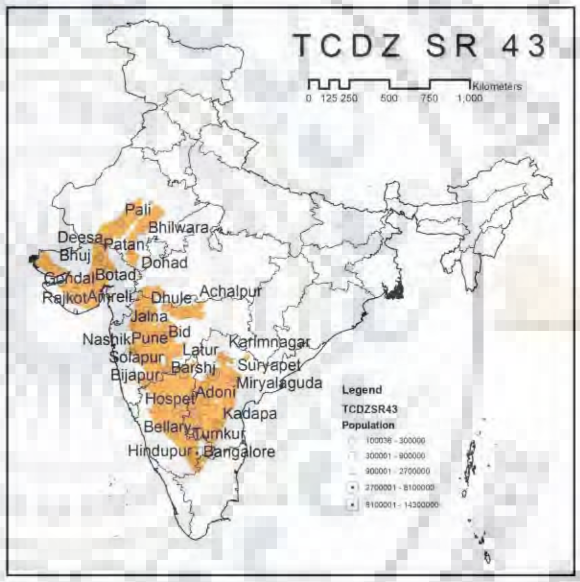
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-8
A2: Outdoor sleeping desirable	1-5
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	3-5
H2: Air movement desirable	0-2
H3: Rain protection necessary	0-3

Key Map



Thermal Comfort Design Zone 45

MAJOR CITIES	LATITUDE	LONGITUDE
Kolhapur	16.70 °N	74.24 °E
Darbhanga	26.15 °N	85.90 °E

OTHER CITIES:
Bidar, Nizamabad, Amravati, Nagpur, Surat, Raipur, Burhanpur, Raurkela Town, Vadodara, Jamshedpur, Ahmedabad, Jabalpur, Bhopal, Ranchi, Dhanbad, Udaipur, Satna, Gaya, Kota, Jhansi

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

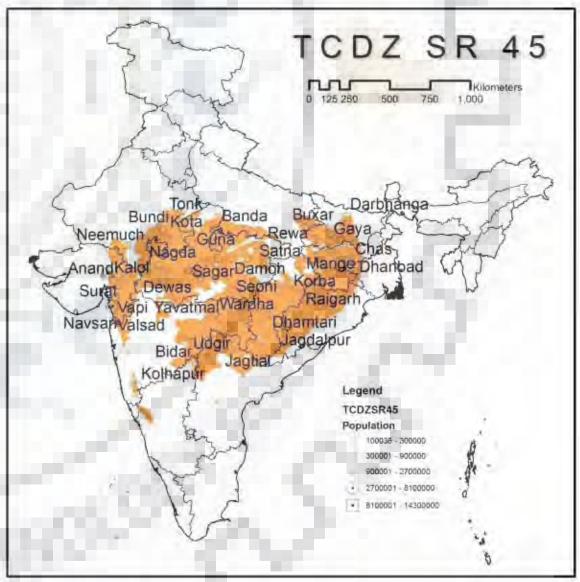
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-8
A2: Outdoor sleeping desirable	1-5
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	3-5
H2: Air movement desirable	0-2
H3: Rain protection necessary	0-4

Key Map



Thermal Comfort Design Zone 47

MAJOR CITIES	LATITUDE	LONGITUDE
Patna	25.61 °N	85.16 °E
Jammu	32.73 °N	74.86 °E

OTHER CITIES:
Varanasi, Shivpuri, Gwalior, Kanpur, Dhaulpur, Gorakhpur, Lucknow, Agra, Aligarh, Bareilly, New Delhi, Ghaziabad, Moradabad, Meerut, Haldwani-cum-Kathgodam, Roorkee, Saharanpur, Srinagar, Dehradun, Chandigarh

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
PROTECT openings from RAIN PENETRATION. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

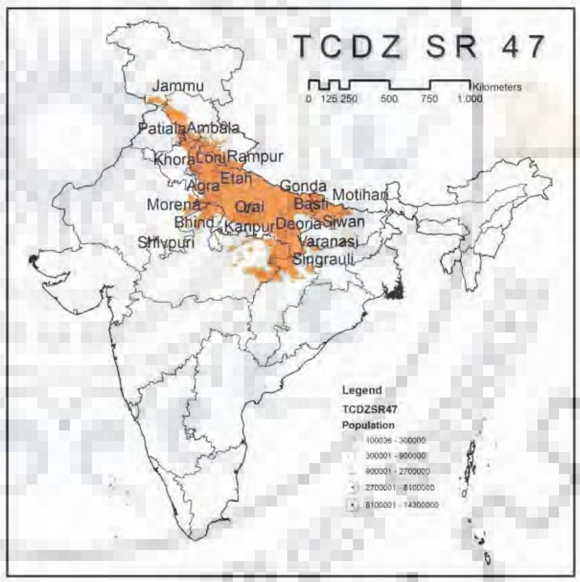
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-8
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	3-5
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	3-5
H2: Air movement desirable	0-2
H3: Rain protection necessary	0-4

Key Map



Thermal Comfort Design Zone 48

MAJOR CITIES	LATITUDE	LONGITUDE
Jaipur	26.92 °N	75.78 °E
Amritsar	31.63 °N	74.87 °E

OTHER CITIES:
Sikar, Rewari, Bhiwani, Rohtak, Hisar, Jind, Kaithal, Malerkotla, Moga, Ludhiana

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Provide windows in walls oriented toward North and South. In case of DOUBLE BANKED Rooms, enable TEMPORARY cross ventilation by providing large interconnecting doors / ventilators. Air movement (H1) is essential for 1 or 2 months and thermal storage (A1) is needed for more than half a year OR air movement is desirable (H2) for 2 or more months.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
NO special PROTECTION from sun or rain is necessary.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

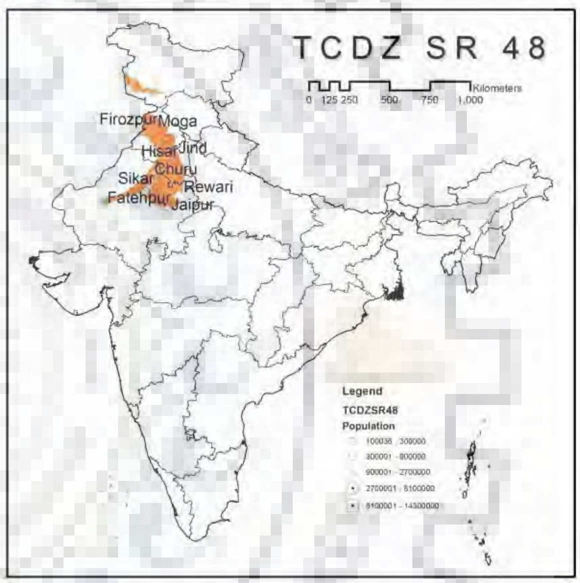
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-10
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	3-6
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2
H2: Air movement desirable	0-1
H3: Rain protection necessary	0-2

Key Map



Thermal Comfort Design Zone 49

MAJOR CITIES	LATITUDE	LONGITUDE
Hosur	12.73 °N	77.83 °E
Sujangarh	27.69 °N	74.45 °E

OTHER CITIES:
Kolar, Ichalkaranji, Morvi, Jodhpur, Nagaur

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS
Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS
Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS
Provide windows in walls oriented toward North and South. In case of DOUBLE BANKED Rooms, enable TEMPORARY cross ventilation by providing large interconnecting doors / ventilators. Air movement (H1) is essential for 1 or 2 months and thermal storage (A1) is needed for more than half a year OR air movement is desirable (H2) for 2 or more months.

4. SIZE OF OPENINGS
Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS
Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.

6. WALL AND FLOOR SPECIFICATIONS
Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS
Provide MASSIVE roof with a time-lag of 8 hours or more.

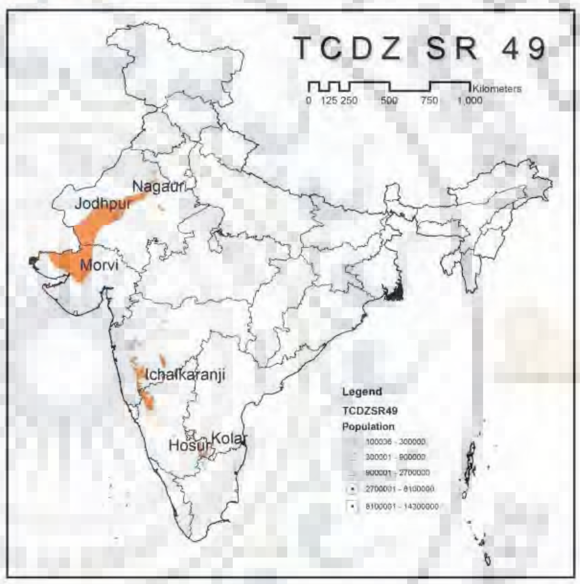
8. OUTDOOR SLEEPING SPACE
PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

9. RAIN PROTECTION FEATURES
NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-10
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	0-2
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2
H2: Air movement desirable	0-3
H3: Rain protection necessary	0-2

Key Map



Thermal Comfort Design Zone 51

MAJOR CITIES	LATITUDE	LONGITUDE
Alwar	27.56 °N	76.62 °E
Pathankot	32.26 °N	75.65 °E

OTHER CITIES:
Jalandhar, Hoshiarpur, Batala

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS

Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS

Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot & Cold winds. Air movement essential (H1) for 2 to 10 months.

3. AIR MOVEMENT AND POSITION OF OPENINGS

Provide windows in walls oriented toward North and South. In case of DOUBLE BANKED Rooms, enable TEMPORARY cross ventilation by providing large interconnecting doors / ventilators. Air movement (H1) is essential for 1 or 2 months and thermal storage (A1) is needed for more than half a year OR air movement is desirable (H2) for 2 or more months.

4. SIZE OF OPENINGS

Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS

PROTECT openings from RAIN PENETRATION. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

6. WALL AND FLOOR SPECIFICATIONS

Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS

Provide MASSIVE roof with a time-lag of 8 hours or more.

8. OUTDOOR SLEEPING SPACE

PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

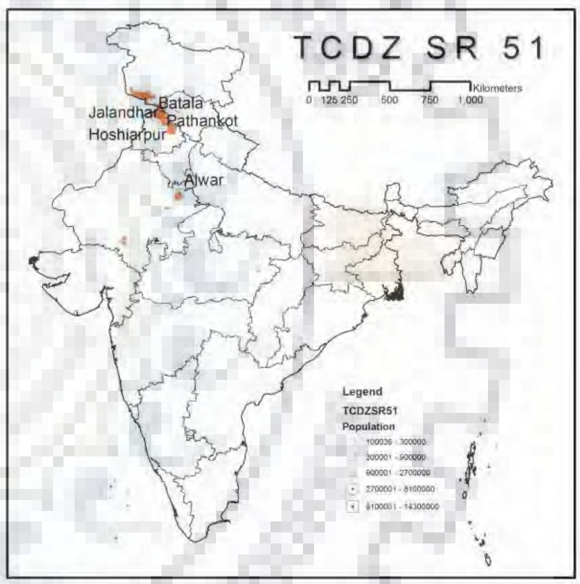
9. RAIN PROTECTION FEATURES

PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-9
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	3-5
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	2
H2: Air movement desirable	0-3
H3: Rain protection necessary	0-4

Key Map



Thermal Comfort Design Zone 53

MAJOR CITIES	LATITUDE	LONGITUDE
Bikaner	28.03 °N	73.31 °E
Muktsar	30.47 °N	74.51 °E

OTHER CITIES:
Sirsa, Abohar, Bathinda

Recommended Climate Responsive Design Specifications

1. LAYOUT OF BUILDINGS

Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is requried for 5 to 12 months.

2. SPACING BETWEEN BUILDINGS

Space buildings in a compact layout of estates. Air movement essential (H1) for 1 month or less.

3. AIR MOVEMENT AND POSITION OF OPENINGS

Provide windows in walls oriented toward North and South. In case of DOUBLE BANKED Rooms, enable TEMPORARY cross ventilation by providing large interconnecting doors / ventilators. Air movement (H1) is essential for 1 or 2 months and thermal storage (A1) is needed for more than half a year OR air movement is desirable (H2) for 2 or more months.

4. SIZE OF OPENINGS

Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates. Thermal storage is needed for 6 to 10 month (A1).

5. PROTECTION OF OPENINGS

NO special PROTECTION from sun or rain is necessary.

6. WALL AND FLOOR SPECIFICATIONS

Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.

7. ROOF SPECIFICATIONS

Provide MASSIVE roof with a time-lag of 8 hours or more.

8. OUTDOOR SLEEPING SPACE

PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.

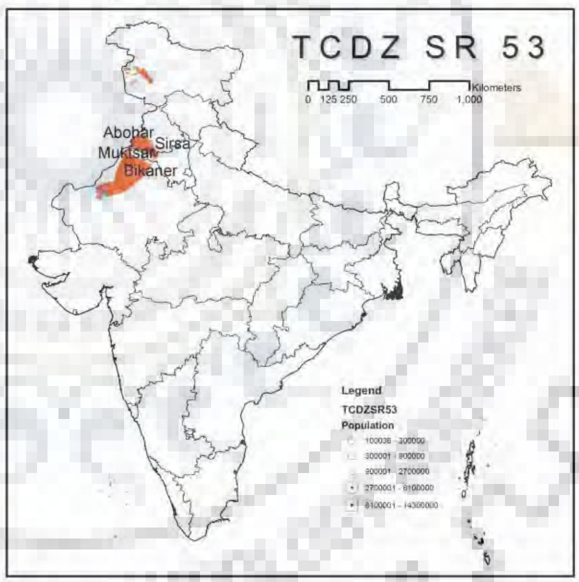
9. RAIN PROTECTION FEATURES

NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.

Climate Indicators (Mahoney Tables)

ARIDITY INDICATORS	Duration (Months)
A1: Thermal capacity necessary	6-10
A2: Outdoor sleeping desirable	1-4
A3: Protection from cold	3-6
HUMIDITY INDICATORS	**Duration (Months)**
H1: Air movement essential	1
H2: Air movement desirable	0-1
H3: Rain protection necessary	0-2

Key Map



APPENDIX 2: T.C.D. ZONE BASED REGIONALISATION OF D.C.&P.R. IN MAHARASHTRA

Standardised Development Control & Promotion Regulations

Regionalized based on TCD Zones of Maharashtra

<table>
<tr><th>DESIGN SPECIFICATION↓</th><th>TCDZ → RULE ↓</th><th>ZONE 6</th><th>ZONE 9</th><th>ZONE 10</th><th>ZONE 23</th><th>ZONE 24</th><th>ZONE 43</th><th>ZONE 45</th><th>ZONE 49</th><th>ZONE 50</th><th>ZONE 54</th><th>ZONE 55</th><th>ZONE 56</th></tr>
<tr><td>LAYOUT OF BUILDINGS</td><td></td><td colspan="12">a1: Reduce exposure to the sun by orienting buildings along East-West axis. Long elevations should face North South direction. Only thermal capacity is necessary (A1) for upto 10 months OR thermal capacity is necessary (A1) for 11 to 12 months and protection from cold (A3) is required for 5 to 12 months.</td></tr>
<tr><td rowspan="2">SPACING BETWEEN BUILDINGS</td><td rowspan="2"></td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b2</td><td>b3</td><td>b3</td><td>b3</td></tr>
<tr><td colspan="12">b2: Space buildings broadly for breeze penetration, roughly space between long rows of buildings should be more than five times the height. Protect buildings from Hot or Cold winds. Air movement essential (H1) for 2 to 10 months.
b3: Space buildings in a compact layout of estates. Air movement essential (H1) for 1 month or less.</td></tr>
<tr><td rowspan="2">AIR MOVEMENT AND POSITION OF OPENINGS</td><td rowspan="2"></td><td>c1</td><td>c1</td><td>c1</td><td>c1</td><td>c1</td><td>c1</td><td>c1</td><td>c2</td><td>c2</td><td>c2</td><td>c2</td><td>c2</td></tr>
<tr><td colspan="12">c1: Ensure PERMANENT cross ventilation by providing SINGLE BANKED Rooms. Provide windows at body height in walls oriented toward North and South or windward side. Air movement (H1) is essential for more than 3 months OR for lesser period but thermal storage (A1) is needed for less than half a year.
c2: Provide windows in walls oriented toward North and South. In case of DOUBLE BANKED Rooms, enable TEMPORARY cross ventilation by providing large interconnecting doors / ventilators. Air movement (H1) is essential for 1 or 2 months and thermal storage (A1) is needed for more than half a year OR air movement is desirable (H2) for 2 or more months.</td></tr>
<tr><td rowspan="2">OPENING SIZE PROPORTION OF WALL AREA</td><td rowspan="2"></td><td>d1</td><td>d2</td><td>d2</td><td>d2</td><td>d2</td><td>d4</td><td>d4</td><td>d4</td><td>d4</td><td>d4</td><td>d4</td><td>d4</td></tr>
<tr><td colspan="12">d1: Provide LARGE openings, between 40 and 80% area of north and south walls. These need not be fully glazed, but should be protected from the sun, sky glare and rain, preferably by horizontal overhangs.
d2: Provide MEDIUM openings, 25-40% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates, but under no circumstances in the tropics.
d4: Provide SMALL openings, 15-25% of wall area. Openings in the east wall may be desirable where cold season is long. In west walls openings are acceptable in cold climates.</td></tr>
<tr><td rowspan="2">OPENING PROTECTION</td><td rowspan="2"></td><td colspan="12">f2: Completely EXCLUDE DIRECT SUNLIGHT. Cool season (A3) last not more than 2 months.
f3: PROTECT openings from DIRECT SUNLIGHT and RAIN PENETRATION. Cool season (A3) last not more than 2 months and rainfall exceeding 200 mm (H1) occurs in more than 1 month.</td></tr>
<tr><td>f3</td><td>f3</td><td>f3</td><td>f3</td><td>f3</td><td>f2</td><td>f3</td><td>f2</td><td>f3</td><td>f2</td><td>f3</td><td>f3</td></tr>
<tr><td rowspan="2">RAIN PROTECTION</td><td rowspan="2"></td><td>j1</td><td>j1</td><td>j1</td><td>j1</td><td>j1</td><td>j2</td><td>j1</td><td>j2</td><td>j1</td><td>j2</td><td>j1</td><td>j1</td></tr>
<tr><td colspan="12">j1: PROVIDE deep verandahs, wide overhangs and covered passages. Make special provisions for roof drainage. Avoid level gutters. In case of low-cost spouts at roof level or eaves discharge, protect foot of the walls with 0.5m wide concrete path or apron, sloping away from the building. Rainfall exceeding 200 mm (H1) occurs in more than 1 month.
j2: NO RECOMMENDATIONS for rain protection. Rainfall exceeding 200 mm (H1) never occurs.</td></tr>
<tr><td rowspan="2">ROOF SPECIFICATIONS</td><td rowspan="2"></td><td>h2</td><td>h2</td><td>h2</td><td>h2</td><td>h2</td><td>h3</td><td>h3</td><td>h3</td><td>h3</td><td>h3</td><td>h3</td><td>h3</td></tr>
<tr><td colspan="12">h2: Provide LIGTH roof with better INSULATION. Overall U-value not exceeding 0.85 W/m2degC is recommended. Use external sheet with a reflective surface, a cavity & a ceiling incorporating at least 25 mm insulation & a reflective top (e.g. aluminum foil).
h3: Provide MASSIVE roof with a time-lag of 8 hours or more.</td></tr>
<tr><td rowspan="2">WALL AND FLOOR SPECIFICATIONS</td><td rowspan="2"></td><td>g1</td><td>g1</td><td>g1</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td><td>g2</td></tr>
<tr><td colspan="12">g1: Provide LIGHT external walls with REFLECTIVE exterior surface. Short time-lag is required. If Annual Mean Range of temperature is large (over 20 degC), provide heavy and massive internal walls and floors. Provide hollow walls made of blocks or bricks with more than 40% void, OR thin solid walls say 50 mm dense concrete, OR sheeted walls enclosing a cavity.
g2: Provide HEAVY / MASSIVE external and internal walls with over 8 hour time-lag. This requirement can be satisfied by using solid bricks, blocks, concrete or adobe of about 300 mm thickness. External walls can alternatively have LESS THICKNESS (down to 100 mm) with sufficient INSULATION on exterior face.</td></tr>
<tr><td rowspan="2">OUTDOOR SLEEPING SPACE</td><td rowspan="2"></td><td>i1</td><td>i1</td><td>i2</td><td>i1</td><td>i2</td><td>i2</td><td>i2</td><td>i2</td><td>i2</td><td>i2</td><td>i1</td><td>i2</td></tr>
<tr><td colspan="12">i1: Space for out-door sleeping NOT RECOMMENDED.
i2: PROVIDE space for out-door sleeping either on roofs, balconies or in patios, so that sleepers are exposed to the coldest part of the night sky (the zenith) to increase heat loss by outgoing radiation.</td></tr>
</table>

Regionwise Districts of Maharashtra

AMRAVATI	KONKAN	NASHIK
Akola	Greater Bombay	Ahmednagar
Amravati	Raigarh	Dhule
Buldana	Ratnagiri	Jalgaon
Washim	Sindhudurg	Nandurbar
Yavatmal	Thane	Nashik
AURANGABAD	**NAGPUR**	**PUNE**
Aurangabad	Bhandara	Kolhapur
Beed	Chandrapur	Pune
Hingoli	Garhchiroli	Sangli
Jalna	Gondiya	Satara
Latur	Nagpur	Solapur
Nanded	Wardha	
Osmanabad	XXXX	
Parbhani	XXXX	

Urban Local Body wise TCD Zones for Regionalisation of Development C&P Regulations

URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ
		Amravati Region			
District Akola		**District Amravati**		**District Washim**	
Akola	*43*	Morshi	45	Karanja	45
Akot	43	Warud	45	Malegaon	43
Balapur	43	**District Buldana**		Mangrulpir	45
Barsi Takli	43	Buldana	50	Risod	45
Murtijapur	43	Chikhali	50	Washim	45
Patur	45	Deulgaon Raja	43	**District Yavatmal**	
Telhara	43	Khamgaon	43	Darwha	45
District Amravati		Lonar	45	Digras	45
Achalpur	43	Mehkar	45	Ghatanji	45
Amravati	*45*	Nandura	43	Ner	43
Anjangaon	43	Shegaon	43	Pandharkavda	45
Chandur	43	Sindkhed Raja	43	Pusad	45
Chandurbazar	43	Jalgaon Jamod	43	Umarkhed	45
Daryapur Banosa	43	Malkapur-Buldhana	43	Wani	45
Dhamangaon Railway	45			Yavatmal	45

URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ
		Aurangabad Region			
District Aurangabad		**District Hingoli**		**District Nanded**	
Aurangabad	*43*	Basmathnagar	45	Mukhed	45
Gangapur	43	Hingoli	45	Naigaon	45
Kannad	43	Kalamnuri	45	*Nanded-Waghala*	*45*
Paithan	43	**District Latur**		Umri	45
Sillod	43	Ahemadpur	45	**District Osmanabad**	
Vaijapur	43	Ausa	45	Bhum	43
District Beed		*Latur*	*43*	Kalamb-Osmanabad	43
Ashti	43	Nilanga	45	Murum	45
Beed	43	Udgir	45	Naldurg	43
Georai	43	**District Nanded**		Osmanabad	43
Kaij	43	Bhokar	45	Paranda	43
Kille Dharur	43	Biloli	45	Tuljapur	45
Majalgaon	43	Deglur	45	Umarga	43
Parali-Waijanath	43	Dharmabad	45	**District Parbhani**	
Patoda	43	Hadgaon	45	Gangakhed	43
Ambejogai	43	Kandhar	45	Jintur	45
District Jalna		Kinwat	45	Manwath	45
Ambad	43	Kundalwadi	45	*Parbhani*	*45*
Bhokardan	43	Loha	45	Pathri	45
Jalna	43	Mahur	45	Purna	45
Partur	43	Mudkhed	45	Selu	45
				Sonpeth	43
		Konkan Region			
District Mumbai		**District Raigad**		**District Thane**	
Bruhan Mumbai	*6*	Alibag	23	Ambarnath	23
District Ratnagiri		Karjat	24	*Bhivandi-Nizampur*	*23*
Chiplun	23	Khopoli	24	Jawhar	45
Khed	6	Mahad	23	*Kalyan-Dombivli*	*23*
Rajapur	24	Murud-Janjira	6	Kulgoan-Badalapur	23
Ratnagiri	10	Panvel	23	*Mira-Bhaindar*	*23*
District Sindhudurg		Pen	23	*Navi Mumbai*	*23*
Kankawali	24	*Raigad*	*23*	*Thane*	*23*
Malwan	24	Roha Ashtami	23	*Ulhasnagar*	*23*
Sawantwadi	24	Shrivardhan	6	Umbar Pada-Saphale	23
Vengurla	24	Uran	23		
		Nagpur Region			
District Gadchiroli		Gondia	45	**District Chandrapur**	
Armori	45	**District Bhandara**		Ballarpur	45
Desaiganj	45	Bhandara	45	Brahmapuri	45
Gadchiroli	45	Lakhni	45	*Chandrapur*	*45*
District Gondia		Paoni	45	Mul	45
Deori	45	Sakoli	45	Rajura	45
Tiroda	45	Tumsar	45	Warora	45

URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ	URBAN LOCAL BODY	TCDZ
Nagpur Region					
District Wardha		Wardha	45	Mohpa	45
Arvi	45	**District Nagpur**		Mowad	45
Deoli	45	Bhiwapur	45	*Nagpur*	*45*
Hinganghat	45	Kalmeshwar	45	Narkhed	45
Pulgaon	45	Kamptee	45	Ramtek	45
Sevagram	45	Katol	45	Savner	45
Sindhi	45	Khapa	45	Umred	45
Nashik Region					
District Ahemadnagar		*Dhule*	*43*	**District Nandurbar**	
Ahemadnagar	*43*	Shirpur-Warawade	43	Nandurbar	43
Belapur	43	**District Jalgaon**		Nawapur	45
Deolali-Pravara	43	Amalner	43	Shahade	43
Kopargaon	43	Bhusawal	43	Talode	43
Newasa	43	Chalisgaon	43	**District Nashik**	
Pathardi	43	Chopda	45	Bhagur	45
Rahata Pimplas	43	Dharangaon	43	Igatpuri	45
Rahuri	43	Erandol	43	Manmad	43
Sangamner	43	Faizpur	43	Nandgaon	43
Shevgaon	43	*Jalgaon*	*45*	*Nashik*	*43*
Shirdi	43	Pachora	45	Saptashrungigad	43
Shrigonda	43	Parola	43	Satana	43
Shrirampur	43	Raver	43	Sinnar	43
District Dhule		Sawda	43	Tryambakeshwar	50
Dondaicha-Warawade	43	Yawal	43	Yeola	43
Pune Region					
District Kolhapur		Satara	56	*Pune*	*43*
Gadhinglaj	50	Wai	54	*Pimpri-Chinchwad*	*43*
Ichalkaranji	43	**District Sangli**		Saswad	49
Jaysingpur	43	Ashta	43	Shirur	43
Kagal	49	Islampur	43	Talegaon-Dabhade	50
Kolhapur	*45*	*Sangli-Miraj-Kupwad*	*43*	**District Solapur**	
Kurundwad	43	Tasgaon	43	Akkalkot	43
Malkapur	45	Vita	49	Akluj	43
Murgud	45	**District Pune**		Barshi	49
Vadgaon Kasba	49	Alandi	43	Dudhani	43
District Satara		Baramati	43	Karmala	43
Karad	49	Bhor	49	Kurduwadi	43
Koregaon	49	Daund	43	Maindargi	43
Lonand	43	Indapur	43	Mangalwedhe	43
Mhaswad	43	Jejuri	49	Pandharpur	43
Phaltan	43	Junnar	43	Sangole	43
Rahimatpur	49	Loni-Kalbhor	43	*Solapur*	*43*

APPENDIX 3: ALGORITHM TRANSLATED FROM PORTUGUESE

Encontro Nacional de Tecnologia do Ambiente Construido	National Meeting of Technology for Built Environment
Em 2008, em sua 12ª edição, foi realizado em Fortaleza, Ceará, de 07 a 10 de outubro, tendo como tema a "Geração de Valor no Ambiente Construído: Inovação e Sustentabilidade".	In 2008, the 12th edition of this national meeting was held in Fortaleza, Ceará, between 07-10 October on the subject of " Value Generation in Built Environment: Innovation and Sustainability ".

Estimativas De Valores Horários De Temperaturas E Umidades Do Ar Em Função De Normais Climatológicas

Maurício Roriz

Estimation of Hourly Air Temperature and Relative Humidity values as function of Climatological Normals

Mauricio Roriz

ABSTRACT

Detailed analyses of thermal and energy performance of buildings demand the knowledge of hourly values from some climatic elements. However, the only available climatic information for countless places are them denominated Climatological Normals, constituted by statistical averages and extreme values of data obtained along 30 years of observation. This paper presents the development of a method that allows to estimate the hourly oscillation of air temperatures and humidities, for any latitudes and times of the year, as function of the Climatological Normals of each place. In that sense, statistical analyses were applied to the hourly data of typical climatic years of 120 cities, being obtained regression equations for the studied variables. Including 51 countries, latitudes from 64° north to 53° south and elevations from the sea level the more than 4000 m, this database is representative of wide geographical and climatic diversity. The application of the method provided quite satisfactory results for the typical climates of June and December of the 120 places, with correlation coefficients of 0.99 for the hourly temperature and 0.98 for the one of relative humidity.

Keywords: Hourly values of air temperature and humidity. Applied climatology.

I. INTRODUCTION

1.1. Daily cycle of air temperature oscillation

Typical hourly fluctuations in air temperature derived from the daily cycle of sunlight and darkness, due to the relative motion between the earth and the sun. The Earth absorbs solar radiation from sunrise to sunset (Fig. 1) and, on the other hand, constantly emits radiation the upper atmosphere. At every moment, the surface temperature of the soil is a function of its heat specific and thermal balance between the energy received and issued. The higher the surface temperature, the greater is the heat loss rates. Under normal conditions, the radiation Solar received is maximum at noon, but the surface of the planet is still warming up to the time of sunset. Atmosphere being virtually transparent to solar radiation, its main process of heat exchange is by convection to the soil. Thus, the minimum air temperatures occur approximately at the time sun rises, while the maximum air temperatures occur in mid-afternoon, when the radiation emitted by the Earth exceeds the absorbed.

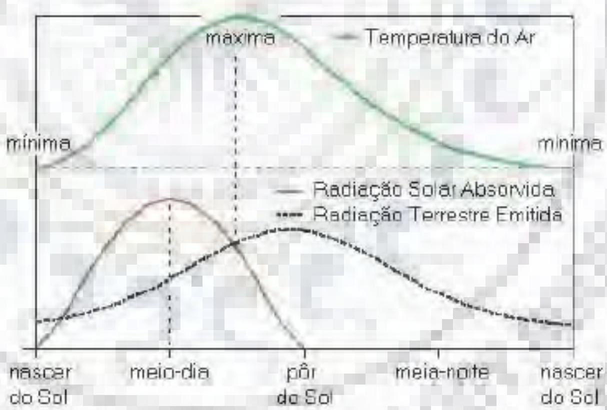


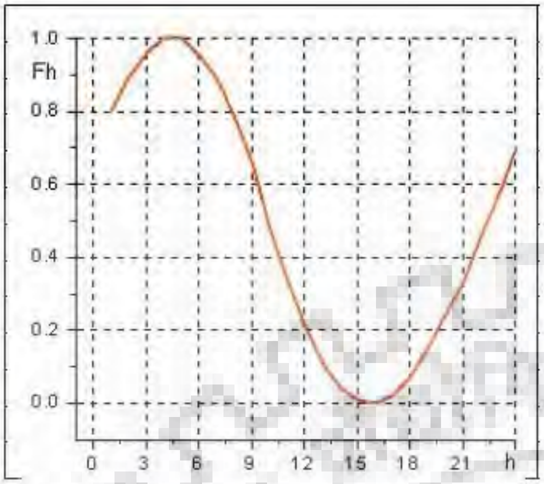
Figure. 1. Air temperature, a function of the thermal balance between the Earth and the Sun

1.2. PRECEDENTS

Several methods have been proposed for estimating the typical course of air temperature over a day. The first, summarized in tabulated values of a time factor to be applied on the maximum and minimum temperatures, obtained in Climatological normals. For example, over forty years ago, Berthier and Anquez (1964) mentioned the "Deplanches method", described as follows:

$$Th = Tmax - Fh\,(Tmax - Tmin) \qquad \text{Eq. [1]}$$

Where:
Th = Air temperature at the time "h" of the solar system time
Fh = temperatures calculation factor in time "h", as shown in Figure 2.
Tmin and Tmax = Monthly averages of the minimum and maximum air temperatures, respectively.



Solar time	Fh	Solar time	Fh
1	0.80	13	0.11
2	0.89	14	0.04
3	0.96	15	0.01
4	1.00	16	0.00
5	1.00	17	0.02
6	0.95	18	0.07
7	0.89	19	0.15
8	0.78	20	0.24
9	0.66	21	0.33
10	0.49	22	0.45
11	0.34	23	0.57
12	0.22	24	0.70

Figure. 2. Factor Fh proposed by Deplanches, cited in Berthier and Anquez (1964)

Later, Serra (1975) adapted the Deplanches table to compare estimated temperature schedules with observed temperatures in Brazilian cities. The curve suggested by Serra was adopted by Roriz and Basso (1989) in computer program Arquitrop.

Other studies have been conducted in search of typical daily curves of specific cities. Based on the analysis of hourly data measured over 20 years, for example, Roriz (1996) formulated a curve (Figure 3) for estimating typical air temperature oscillations in the city of Paulo. This curve was divided into two parts, one for the first twelve hours after the occurrence of minimum temperature (Equation 3) and another for remainder of the day (Equation 4):

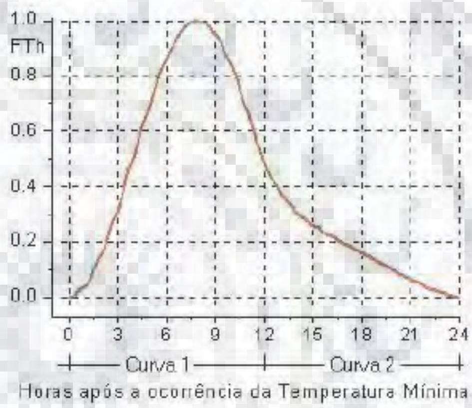


Figure. 3. Factor Regression equations FTh (Roriz, 1996)

$$Th = T\,min + FTh\,(Tmax - Tmin) \quad \text{Eq. [2]}$$

$$\text{Curve 1: } FTh = \left[1 + sen\left(\frac{-\pi}{2} + \frac{\pi \cdot h}{8}\right)\right]/2 \quad \text{Eq. [3]}$$

$$\text{Curve 2: } FTh = B0 + B1 \cdot h + B2 \cdot h^2 + B3 \cdot h^3 + B4 \cdot h^4 + B5 \cdot h^5 \quad \text{Eq. [4]}$$

Where:

FTh = air temperature calculation factor at time h

h = hours after the occurrence of the minimum temperature

π = number "Pi" (π = 3.141593)

B0 = 20.52074   B1 = -5021   B2 = 0.4984   B3 = -0.02462   B4 = 0.0006   B5 = -0.000006

Without limiting to a specific city, Tejeda-Martinez (1991) suggests the following for the calculation of hourly values of air temperature:

$$Th = T\,min + Fh\,(Tmax - Tmin) \quad \text{Eq. [5]}$$

$$Fh = A \cdot T^B \cdot Exp(C \cdot T) \quad \text{Eq. [6]}$$

Where:

Th = Air temperature at the time "h"

Fh = temperature factor calculation time "h"

Tmin = Monthly average minimum temperature

Tmax = Monthly average maximum temperature

T = h-HNS (for h> = HNS)

T = h + 24-HNS (for h <HNS)

HNS = time of sunrise

A, B and C = parameters, weather function (Table 1).

Table 1 PARAMETERS OF EQUATION 6, PROPOSED TO MEXICAN CITIES (Tejeda-Martinez, 1991)

Months	Latitude	A	B	C
March to October	Greater than or equal to 23.5	0.026	3.190	-0.375
November to February		0.023	3.436	-0.421
All	Less than 23.5	0.096	2.422	-0.339

It is observed that all these calculation methods have limitations and can not be applied to any location. The Tejeda-Martinez equation, albeit wider than before, also depends on specific parameters for each place.

2. DEVELOPMENT OF A NEW ALGORITHM

We tried to then develop a calculation model for the typical hourly values of temperature and humidity that would apply to any latitudes and times of the year and depended only on data available in the climatological normal tables for each place. The first stage of the study only focused on the air temperature and was based on measured data from 64 cities in different continents (Roriz, 2006). In continuation of the study, the database was expanded and the analysis has also included relative humidity. In this sense, statistical analyzes were applied to the data schedules typical weather year 120 cities from 51 countries (Figure 4 and Tables 2a and 2b), constituting a representative sample of large geographic and climatic diversity, with latitudes from 64° north to 53° south and altitude from sea level to over 4000 m.

Typical weather year (TMY, or "Typical Meteorological Year") of these locations were obtained in the software database Energy-Plus (DOE, 2005). Tables 2a and 2b, countries are indicated by the abbreviations adopted by the World Meteorological Organization (WMO).

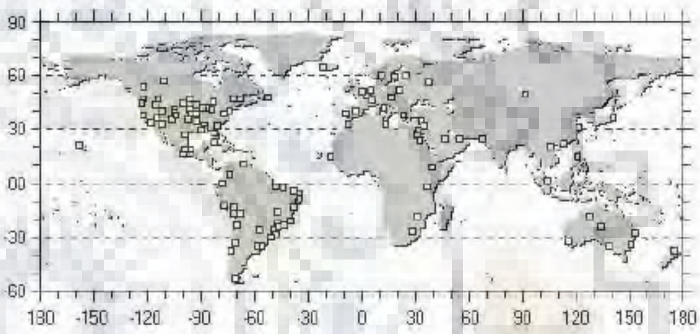


Figure. 4. Figure 4: Location of the 120 cities

Table 2 A: LOCALITIES CONSIDERED IN THE ANALYSIS OF HOURLY VALUES OF TEMPERATURE AND MOISTURE LEVELS

S.N.	Nation	Place	Lat	Alt
1	AR	Buenos Aires	-34.8	20
2	AU	Adelaide	-34.9	48
3	AU	Alice Springs	-23.8	547
4	AU	Brisbane	-27.4	10
5	AU	Halls Creek	-18.2	424
6	AU	Perth	-31.9	29
7	AU	Sydney	-33.9	40
8	BO	La Paz	-16.5	4042
9	BR	Belém	-1.4	16
10	BR	Brasília	-15.9	1060
11	BR	Curitiba	-25.5	910
12	BR	Florianópolis	-27.7	7
13	BR	Fortaleza	-3.8	25
14	BR	Maceió	-9.5	115
15	BR	Natal	-5.9	49
16	BR	Porto Alegre	-30	4

S.N.	Nation	Place	Lat	Alt
61	OS	Vienna	48.1	190
62	PE	Arequipa	-16.3	2520
63	PE	Cuzco	-13.6	3249
64	PE	Lima	-12	13
65	PH	Manila	14.5	21
66	PK	Karachi	24.9	22
67	PL	Warsaw	52.2	107
68	PO	Lisboa	38.7	71
69	PY	Asunción	-25.3	101
70	RA	Moscow	55.8	156
71	SD	Riyadh	24.7	612
72	SG	Dakar	14.7	24
73	SN	Stockholm	59.7	61
74	SP	Madrid	40.5	582
75	SR	Singapore	1.4	16
76	SW	Geneva	46.3	416

S.N.	Nation	Place	Lat	Alt
17	BR	Recife	-8.1	11
18	BR	Rio de Janeiro	-22.8	5
19	BR	Salvador	-12.9	13
20	BR	São Carlos	-22	854
21	BR	São Luis	-2.6	53
22	BR	São Paulo	-23.6	802
23	BR	Vitória	-20.3	5
24	BX	Brussels	50.9	58
25	CI	Shanghai	31.4	5.5
26	CL	Antofagasta	-23.4	120
27	CL	Concepción	-36.8	16
28	CL	Punta Arenas	-53	37
29	CL	Santiago	-33.4	476
30	CN	Fort McMurray	56.7	369
31	CN	Prince George	53.9	691
32	CN	Quebec	46.8	73
33	CN	St John's	47.6	140
34	CO	Bogotá	4.7	2548
35	CU	Havana	23	59
36	CY	Larnaca	34.9	2
37	EC	Quito	-0.2	2812
38	EG	Al Minya	28.1	40
39	EG	Aswan	24	194
40	EG	Asyut	27.1	70
41	EG	Cairo	30.1	74
42	ER	Abu Dhabi	24.4	27
43	ET	Addis Ababa	9	2355
44	FI	Helsinki	60.3	56
45	FR	Paris	48.7	96
46	GR	Athens	37.9	15
47	IL	Reykjavik	64.1	61
48	IS	Jerusalem	31.8	782
49	IY	Roma	41.8	3
50	JP	Tokyo	36.2	35
51	KN	Nairobi	-1.3	1798
52	LY	Tripoli	32.7	81
53	MC	Casablanca	33.4	206
54	MO	Ulaangom	49.9	936
55	MX	Acapulco	16.8	5
56	MX	México	19.4	2234
57	MX	Veracruz	19.2	14
58	NL	Amsterdam	52.3	2
59	NO	Oslo	59.9	17
60	NZ	Auckland	-37	6

S.N.	Nation	Place	Lat	Alt
77	UK	London	51.2	62
78	UM	Macau	22.2	86
79	US	Alpena	45.1	210
80	US	Boise	43.6	874
81	US	Boulder	40	1634
82	US	Caribou	46.9	190
83	US	Cheyenne	41.2	1872
84	US	Chicago	41.8	190
85	US	Columbia	38.8	270
86	US	Denver	39.8	1611
87	US	Fargo	46.9	274
88	US	Honolulu	21.3	5
89	US	Laredo	27.5	152
90	US	Las Vegas	36.1	664
91	US	Little Rock	34.7	81
92	US	Los Alamos	35.9	2179
93	US	Los Angeles	33.9	32
94	US	Meridian	32.3	94
95	US	Missoula	46.9	972
96	US	Mobile	30.7	67
97	US	New Orleans	30	3
98	US	New York	40.8	57
99	US	Oklahoma	35.4	397
100	US	Olympia	47	61
101	US	Omaha	41.4	404
102	US	Pasadena	34.2	263
103	US	Phoenix	33.4	339
104	US	Pierre	44.4	526
105	US	Pueblo	38.3	1439
106	US	Rochester	43.9	402
107	US	Rockford	42.2	221
108	US	Salem	44.9	61
109	US	Salt Lake	40.8	1288
110	US	San Francisco	37.6	5
111	US	Savannah	32.1	16
112	US	Sterling	39	82
113	US	Tampa	28	3
114	US	Toledo	41.6	211
115	US	Topeka	39.1	270
116	UY	Montevideo	-34.8	32
117	VE	Caracas	10.6	48
118	VS	Hanoi	21	6
119	ZA	Johannesburg	-26.1	1700
120	ZW	Harare	-17.9	1503

2.1. *Daily fluctuation of Air Temperature value*

Statistical analysis of data from 120 cities resulted in the following equations for the typical hourly values of air temperature:

$$Th = T\,min + FTh\,(Tmax - Tmin) \quad \text{Eq. [7]}$$

$$FTh = B0[1 + Sen(Z)] \quad \text{Eq. [8]}$$

$$Z = (1.5 \cdot \pi) + [(A - Hns - B1) \cdot (\pi/B2)] \quad \text{Eq. [9]}$$

Th = air temperature solar time "h" (°C)

Tmin = Monthly average of the minimum air temperatures, obtained from Standard Climatological (°C)

Tmax = Monthly average maximum temperature of the air, obtained from Standard Climatological (°C)

FTH = temperature calculation factor in solar time "h" (dimensionless)

Hns = Time of sunrise on the day considered (see Equation 10)

π = number "Pi" (π = 3.141593)

Table 3 TABLE 3: PARAMETERS FOR THE EQUATIONS 8;09

Values of A and H1	For less than or equal to H1	For higher than H1
A = h (para h >= Hns)	B0 = 0.5	B0 = 1.57865
A = h + 24 (para h <Hns)	B1 = 0	B1 = 24
H1 = 18 - (Hns / 4)	B2 = 13 - 0.75 Hns	B2 = π (7.24167 + 0.8225 Hns)

The equations 10 and 11 (Szokolay, 1983) provide the time of sunrise (HNS):

$$Hns = 12 - \{ArcCos[-Tan(Lat) \cdot Tan(Dec)]/15\} \quad \text{Eq. [10]}$$

$$Dec = 23.45 \cdot sen[(360/365) \cdot (284 + Nda)] \quad \text{Eq. [11]}$$

Lat = Latitude of the place (angle in degrees), negative for the southern hemisphere

Dec = average declination of the sun on the day considered (angle in degrees)

Nda = day number of the year, counted sequentially from 1 (January 1) to 365 (31 December)

Figure 5 shows the hourly values of the fth factor resulting from the application of Equation 8 for three different times of sunrise, respectively at 4, 6 and 8 hours. The influences of date and latitude on the time of sunrise (Equation 10) are shown in Figure 6.

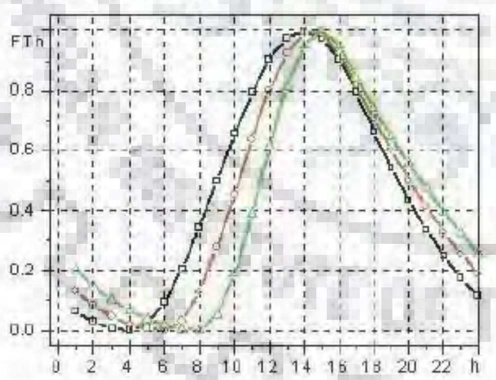


Figure. 5. Variation of Fh factor for three hours sunrise: 4, 6 and 8 hours, according to equation 4

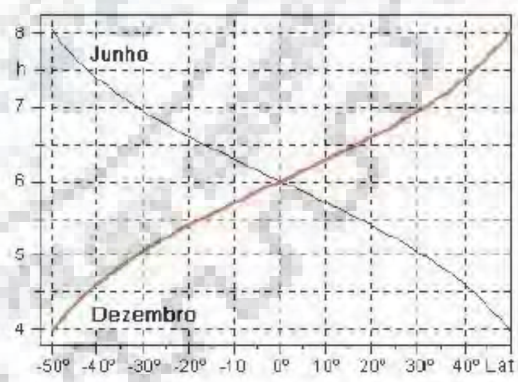


Figure. 6. Times of sunrise, on June 15 and December 15 to latitudes between South 50o and 50o North

In the absence of more precise information, it is customary to consider the average daily temperature (Tmed) as arithmetic mean between the extremes of air temperature (Tmin and Tmax). This procedure, however, adds an error to the results of the calculations, since this average should be calculated on the basis of 24-hour values of the air temperature. A data regression analysis of several cities indicated the following relationship between the two modes of calculation, with 0.999 correlation coefficient and standard deviation 0.33:

$$Tmed = (1.0037 \cdot Tmed1) - 0.33935 \qquad \text{Eq. | 12 |}$$

Tmed = Average daily air temperature, calculated as arithmetic mean of 24 hourly values

Tmed1 = Average daily air temperature, calculated as the arithmetic mean between Tmax and Tmin

2.2. Daily fluctuation of Relative Humidity value

Relative humidity (RH in%) is the ratio of the molar fraction of water vapor (X_W) of an moist air sample and the mole fraction of water vapor (X_{WS}) of a sample of saturated air, under same conditions of temperature and barometric pressure (ASHRAE, 2001).

$$UR = X_W/X_{WS} \qquad \text{Eq. | 13 |}$$

While depending on the temperature and moisture content of the air in typical weather days Relative humidity is maximum when the temperature is minimal, and vice versa. Thus, the regression equations adopt parameters reflecting this dependency:

$$URmin = 8.70479 + 0.58603\,X + 0.00428\,X^2 \qquad \text{Eq. | 14 |}$$

$$X = 16.98691 + 0.76312\,URmed + 1.73888\,Tmin - 1.7868\,Tmax \qquad \text{Eq. | 15 |}$$

$$URmax = -27.99722 + 1.80618\,Z - 0.00553\,Z^2 \qquad \text{Eq. | 16 |}$$

$$Z = -9.75203 + 1.11188\,URmed - 1.50944\,Tmin + 1.606\,Tmax \qquad \text{Eq. | 17 |}$$

Where,

URmin = Daily relative humidity simultaneously with the maximum temperature Minimum (%)

URmax = Daily Maximum humidity of the air, simultaneously with the minimum temperature (%)

URmed = Monthly average relative humidity, obtained from Standard Climatological (%)

Tmin = Minimum daily air temperature, obtained from Standard Climatological (°C)

Tmax = Maximum daily air temperature, obtained from Standard Climatological (°C)

Figure 7 shows the correlations resulting from the application of the equations 14:16 for the months of June and December of 120 cities.

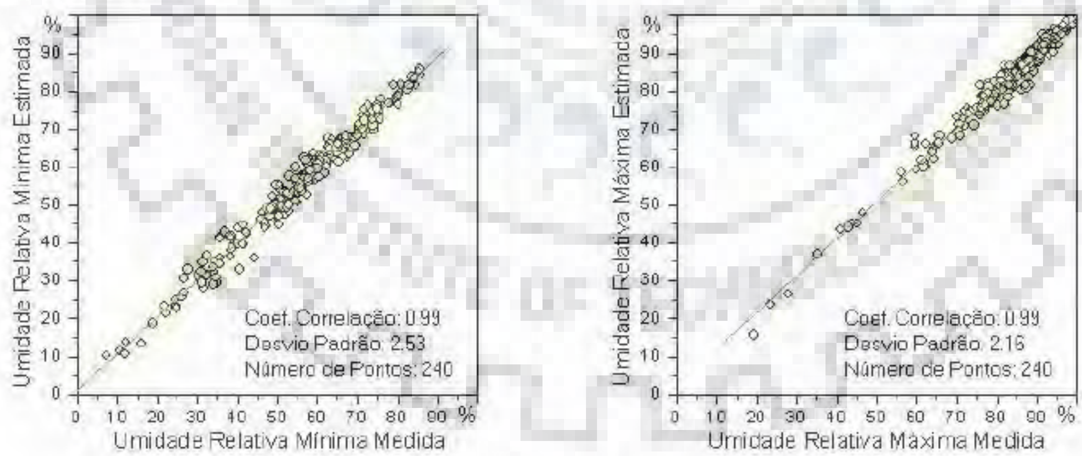


Figure. 7. Relations between estimated and measured values of daily minimum and maximum relative humidities

Hourly values Relative humidity is given by Equation 18:

$$URh = URmin + fUR\,(URmax - URmin) \qquad \text{Eq. [18]}$$

$$FUh = B0 + (B1 \cdot FTh) + (B2 \cdot FTh^2) + (B3 \cdot FTh^3) \qquad \text{Eq. [19]}$$

Where,

URh = Relative humidity in solar time "h" (%)

Fuh = humidity calculation factor on the solar time "h" (dimensionless)

FTH = temperature calculation factor in solar time "h" (dimensionless, given by Equation 8)

B0, B1, B2 and B3 = calculation parameters, as shown in Table 4

Table 4 PARAMETERS IN THE EQUATION 19

Schedules	B0	B1	B2	B3
For h less than Hmin or greater than Hmax	1.0011	-0.58994	-0.80439	0.39796
For h between Hmin and Hmax	1.00062	-1.00745	0	0

Hmin = occurrence time of daily minimum temperature, according to the results of Equation 7

Hmax = occurrence time of daily maximum temperature, according to the results of Equation 7

3. ANALYSIS OF RESULTS

To assess the accuracy of the model presented here, time values calculated TBS (Equation 7) and RH (Equation 18) were compared with mean monthly days of data for each of the 120 locations. Temperatures and humidities each time these average days were considered as arithmetic averages between those recorded at the same time every day of the same month in the typical weather year. Figure 8 indicates that the application of the model provided strong correlation between the estimates and the average hourly measures, to 34560 (24x12x120) considered data. This result, however, occurs in relation to medium days and should not be expected when applying the method to actual days of a specific place. It should be noted that any inaccuracy in estimating temperatures causes also inaccuracies in the calculation of relative humidities, as these are estimated on the basis of those. Depending on the respective standard deviations presented to the air temperature, each location was classified into one of four groups shown in Table 5.

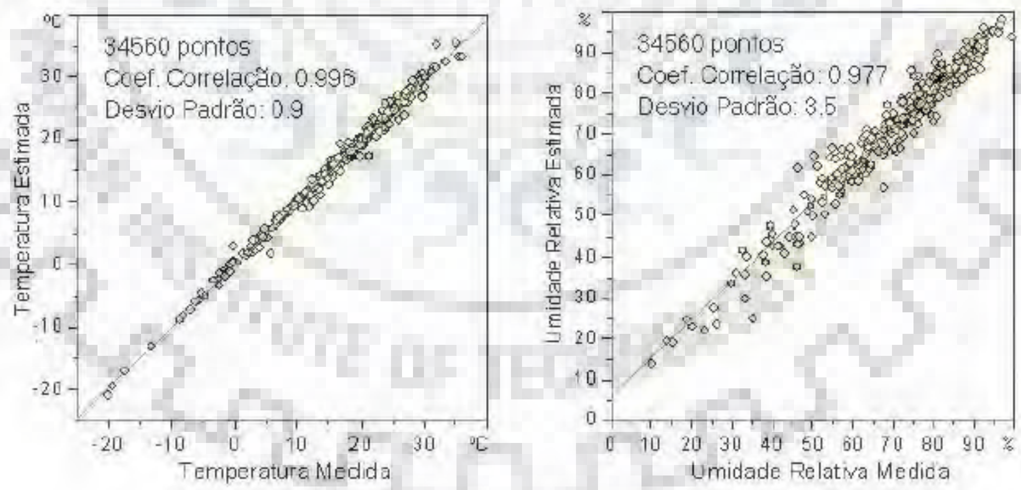


Figure. 8. Relations between estimated and measured values of temperature and humidity Time

Table 5 CLASSIFICATION OF THE RESULTS OF APPLYING THE MODEL

Group	No of cities	Std. Dev. Temperature (DpT)		Std. Dev. Moisture levels (DpU)	
		Minimum	Maximum	Minimum	Maximum
1	40	0.17	0.49	0.93	3.05
2	44	0.5	0.73	1.79	5.75
3	16	0.75	0.97	1.67	4.69
4	20	1.03	1.82	2.5	7.17

Figures 9 to 16 compare temperatures and humidities obtained by hourly averages of the measured values (dotted lines), with the curves resulting from the calculation algorithm (solid lines) of the various cities, for the average days of June and December.

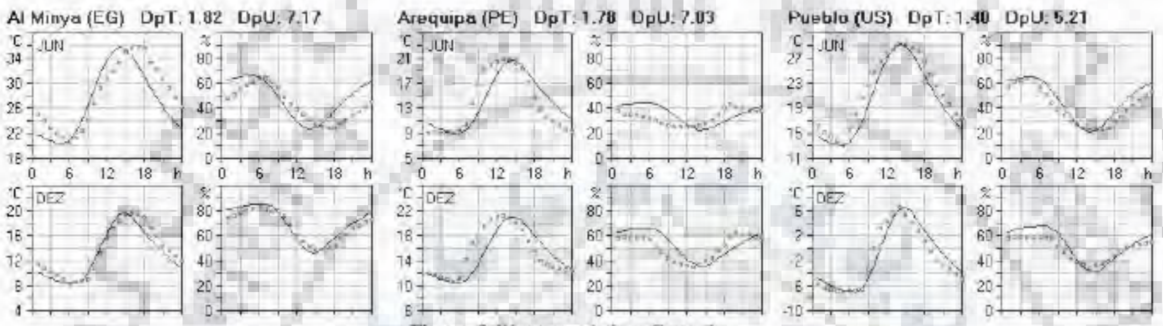


Figure. 9. Worst correlations Group 4

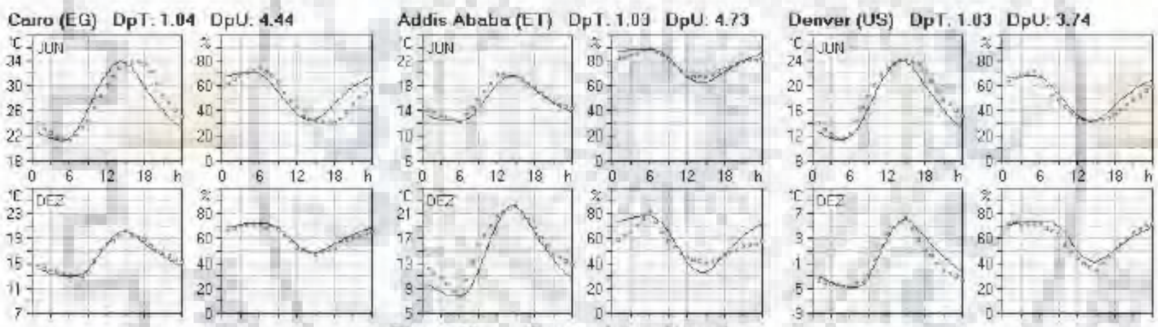


Figure. 10. Top correlations Group 4

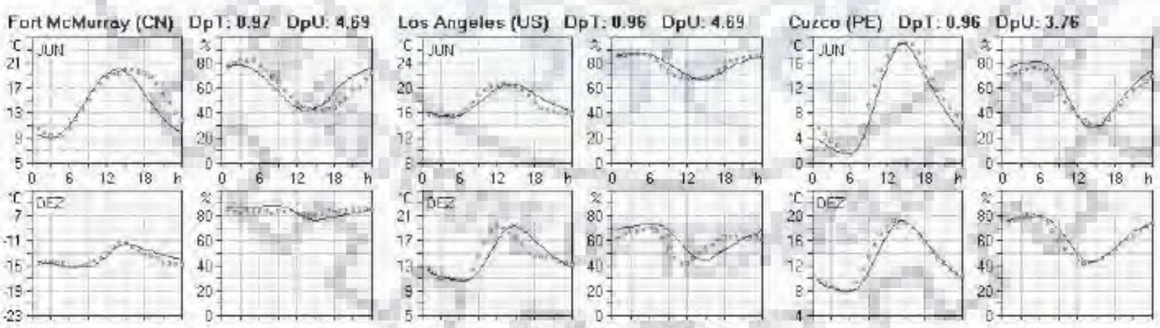


Figure. 11. Worst 3 Group correlations

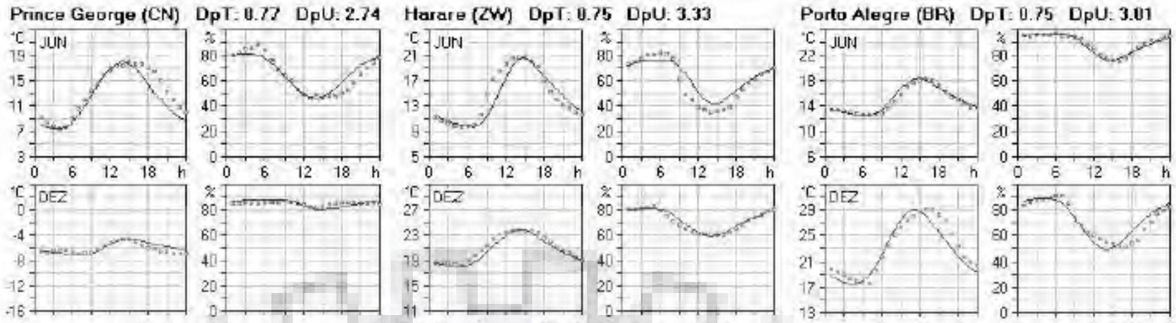


Figure. 12. Top 3 Group correlations

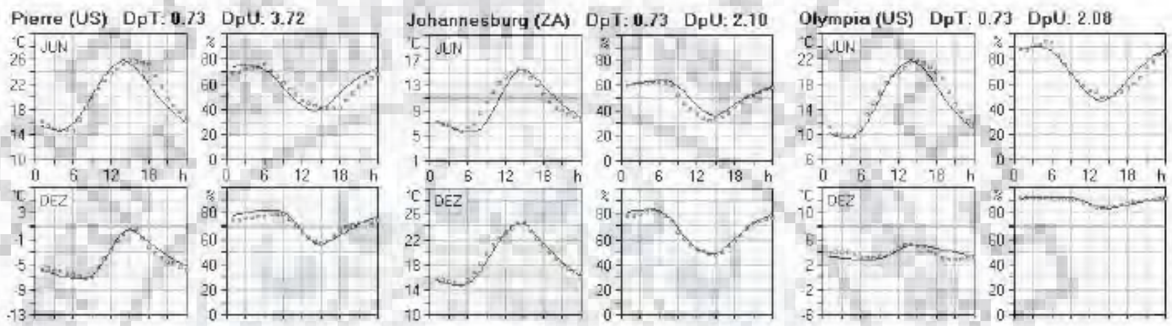


Figure. 13. Worst correlations Group 2

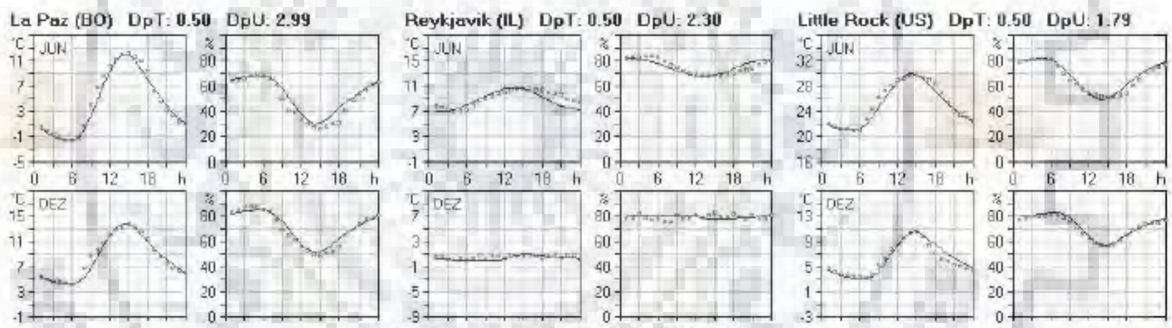


Figure. 14. Top correlations Group 2

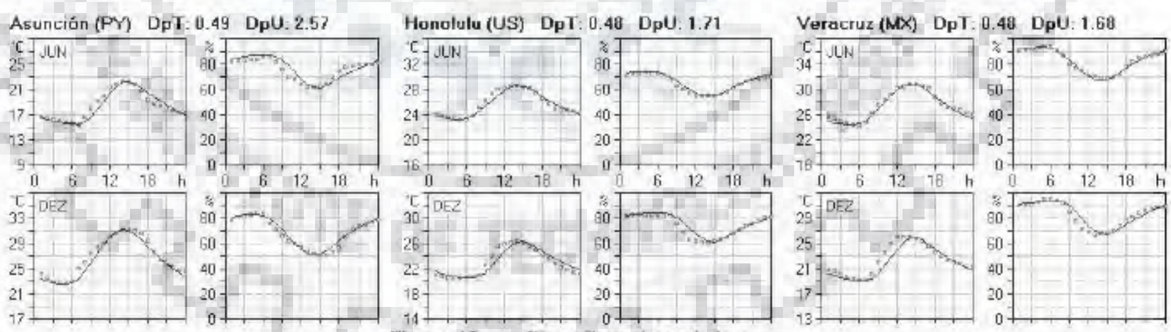


Figure. 15. Worst Group 1 correlations

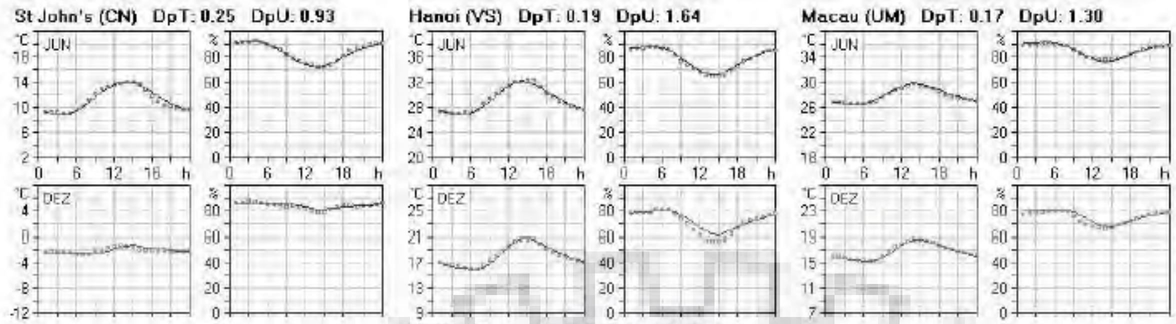


Figure. 16. Top Group 1 correlations

4. CONCLUSIONS

A method for estimating time values of air temperatures and humidity from Climatological normal is presented. To assess the accuracy of the algorithms, they were applied to normal for the months of June and December of 120 cities, representing wide geographical and climatic diversity. The predicted results were close to the measured values with correlation coefficient of 0.99 for air temperature and 0.98 for the moisture relative.

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PAPER 1

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Thermal Comfort Design Zone Delineation for India Using GIS

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Thermal comfort design zone delineation for India using GIS

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A B S T R A C T

This paper describes a procedure devised using Geographical Information System (GIS) to delineate boundaries of zones, where any change in thermal comfort requirement indicates corresponding change in responsive building design strategies. Very high resolution interpolated climatic data subset for India has been used in this analysis so as to distinctly represent the variety of climates experienced in India. The raster datasets of climatic parameters have been analyzed in GIS to get derived and classified parameters required in the Mahoney Tables method for computation of six climatic indicators. These six indicators have been used in the selection of suitable climate-responsive building strategies from 8 strategy groups for the whole dataset. The selected strategies in 8 groups are superimposed together to identify 62 Thermal Comfort Design Zones with unique combination of building design strategies. The proposed zones can be useful in the legislative tools for implementation of energy conservation measures and sustainable building practices.

1. Introduction

In response to the phenomena of global warming and urban heat island effect, researchers have been recently trying to address the envisaged variation in thermal stresses governing the design of built environment. Li et al. [1] iterate that climate plays a vital role in the way our built environment is designed, constructed as well as the way it consumes energy. Corroborating the need for detailed thermal comfort analysis in the selection of appropriate bioclimatic strategies, Chesné et al. [2] have defined indicators for the assessment of climate specific environmental resources and their utilization potential not only at global (yearly whole building) scale but also at dynamic (monthly building element) scale.

1.1. Thermally comfortable built environment

The urban built environment has become a preferred habitat for humans, due to the socio-economic prospects on offer therein. Globally the urban population had grown by 45% since 1992 and reached 3.5 billion in 2011 [3]. Three of the top 10 megacities of the world are Indian [4]. Fifty-three urban agglomerations in India have a population of over 1 million [5]. It is predicted that this trend in urban population growth will continue, though at a slower rate. The growing size of urban agglomeration as a result of increasing urban population has resulted in deterioration of urban built environment. All aspects of the environment including biosphere, hydrosphere and atmosphere are affected by urbanization. Replacement of natural surfaces with extensive impervious built mass, reduces bio-habitat, increases run-off and absorbs more insolation [6]. Re-radiation of absorbed insolation acts as a secondary source of energy, increasing energy gain of atmosphere, while depleted bio-habitat and increased run-off deplete atmospheric humidity. These are few factors which combine together to cause urban heat island (UHI) effect which increases thermal discomfort. Other causes of UHI are increased pollution from automobiles and industries causing anthropogenic heat gain as well as hindrance to radiation energy loss to sky.

To improve productivity even in unfavorable climatic conditions, mankind has been resorting to active mechanical technology, rather than giving a chance to passive refinement of built environment through energy (resource) conserving strategy. The atmospheric conditions in outdoor built environment have further deteriorated in pursuit of indoor thermal comfort due to waste heat generated by deployment of active technologies. Architects need to plan for a climate-responsive built environment keeping in view atmospheric conditions resulting from expansion of urban

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agglomeration. However, they seem to lack constitutional support to implement the building design strategies at their disposal. Appropriate design strategies to counter the thermal stress expected in a region depend on its climatic characteristics. Mass housing in particular completely relies upon the initiative of architect, builder & developer when it comes to implementation of climate-responsive approach.

1.2. Climate zones for legislative provisions

Kumar [7] reports that, experts hope the upcoming code provisions [8] and the implementation of Energy Conservation Building Code (ECBC) will provide constitutional support for the design and construction of climate-responsive buildings. ECBC was developed by the Bureau of Energy Efficiency (BEE) established by the Government of India under the Energy Conservation Act 2001. A strong legislative tool will ensure that urbanites will not have to spend extra resources for achievement of thermal comfort. To implement this, thermal properties of building components and products need to be designed, evaluated and rated based on site specific thermal comfort requirements [9]. Maps delineating extents of various thermal comfort requirements of a region may be called Architectural Climate Zones, Building Climate Regions, or Bioclimatic Zones. These maps and zoning criteria are published in many climatically diverse countries including but not limited to India [10], China [11], USA [12,13], Brazil [14,15]. Studies suggesting need for revision of existing Indian [16,17] as well as other [18–20] building climate zoning, based on geographical as well as bioclimatic variation, have been published. In this research India has been regionalized into zones based on the climatic data analysis sequence given by Mahoney [21], using adaptive thermal comfort criteria. It builds on the method developed earlier in Nigeria [22] for identifying zones with unique combination of applicable climate-responsive building strategies derived from Mahoney tables. It also benefits from usefulness of interpolated climatic parameters – in achieving climate classification objectively sensitive to geographical features – demonstrated by Peel et al. [23] and Roriz et al. [15]. Available datasets of spatially contiguous climatic parameters have been analyzed in GIS application. Place-value notation codes have been innovatively devised to delineate the boundaries where change in regional climate causes change in thermal stress and reflects in requirement of a changed building form or changed building element. The aspects of climate study which help in gaining understanding of factors considered in the synoptic climate classification for thermal comfort have been discussed in Section 2.

2. Background

2.1. Climate

McGuffie and Henderson-Sellers [24] broadly defined Climate as 'all of the statistics describing the atmosphere and ocean determined over an agreed time interval – seasons, decades or longer – computed for the globe or possibly for a selected region'. While resolving the complexity of issues comprising climate study, they gave the analogy of a 3 × 3 Rubik's Cube. They (arbitrarily) divided the 3 axes representing 3 domains of climate study namely time, space and human perception, into 3 levels of detail namely fine, intermediate and coarse. As shown in Fig. 1, they divided the domain of time into, a year, decade and millennia, while, the domain of space into, local, regional and global; whereas, the domain of human perception into, synthesis of observations, personal observations and model prediction. They observe here, that generally a discipline deals with a single cell from the cube.

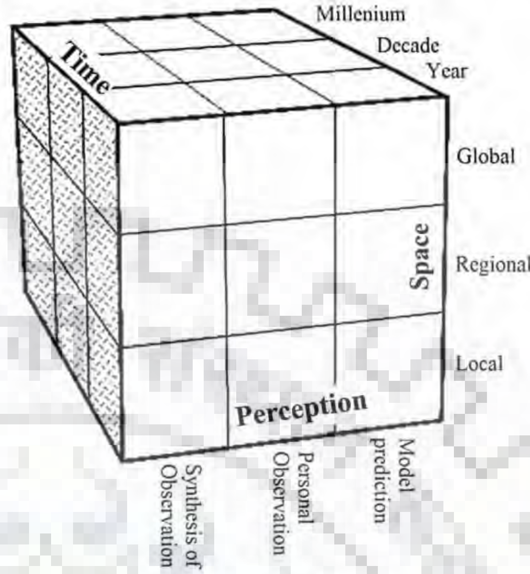

Fig. 1. The Climate Cube: Source [24].

This might have been a reason why the advances in climate data collection network or modeling did not easily percolate to other disciplines. There are few recent examples where Li et al. [1] use not only interpolated data based on historical climate records, but also future climatic scenario predicted based on general circulation models; in the computation and comparison of human comfort index across 20th and 21st century. Here they also discuss effects of the observed variation in human comfort conditions on the energy consumption in future. Considering application of climatology to the built environment in particular, there seems to be segregation between the researchers dealing with climatic classification and those dealing with passive design strategies.

Researchers have delineated climate zones either directly or indirectly based on long term meteorological data. Fovell et al. [25] performed direct climatic delineation based on means of long term temperature and precipitation data using '*Hierarchical Cluster Analysis*' to classify Climate Zones for conterminous United States. Peel et al. [23] interpolated data from all available weather stations over tension spline with a fine grid resolution of 0.1° by 0.1°, to perform indirect climatic delineation based on the predetermined criteria of Köppen-Geiger System; first introduced in the year 1900 to understand global distribution of vegetation cover.

2.2. Indian geographical context

A variety of geographical features participate as drivers in the creation of India's plethora of climates. India spans between 8°4′N – 37°6′N latitude and 68°7′E – 97°25′E longitude, while occupying major part of the south Asian realm. It is girdled by the Himalayan mountain chain on its NW, N and NE and washed by the foundered basins of the Bay of Bengal, the Indian Ocean, and the Arabian Sea on SE, S and SW respectively [26].

Based on stratigraphic and tectonic history and relief, along with erosion process, geographers distinguish four macro regions of India viz., the northern mountains, the Great Plains, the peninsular uplands, and the Indian coasts and islands. A variety of regional/

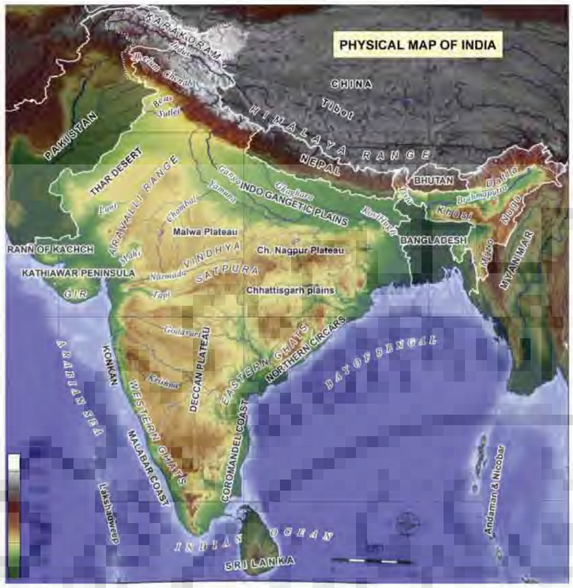

Fig. 2. Physical map of India: after [27].

meso-climates result from various mountains and rivers flanking and dividing these four macro regions as seen in Fig. 2.

The geographical variety of India is evident in the Agro-climatic zoning of India, delineated under National Agricultural Research Project (NARP) [28]. The 15 Resource Development Regions have been subdivided into 127 zones, using an indirect method based on soil type, climate (temperature), rainfall and other agro meteorological characteristics, in order to appropriately plan agricultural activities in each zone. However same variety is not evident in climate zones of India available for architectural design.

2.3. Indian climate design zones

In 1993 Ali et al. [29] classified five 'Climatic Zones for Building Design for India' based on mean monthly maximum temperature and mean monthly relative humidity of 225 stations. Each of the 12 monthly data recorded at all 225 weather stations is classified into one of the four seasons viz., 'hot-dry', 'warm-humid', 'temperate' and 'cold', based on temperature and humidity criteria given with 'Climatic Zone Map' in Fig. 3. If one particular season is prevalent for 6 or more months at a given station, then it is classified under a climate zone named after that season. However, if no season is prevalent for 6 or more months at the given station, then it is classified under 'Composite' climate zone. Currently this climatic zone criterion is adopted by National Building Code of India (NBC) and used by ECBC for stipulating energy conservation requirements for building components [30]. Fig. 3 shows the climatic zone map published by NBC [10].

In 1995 Bansal et al. [31–33] delineated India into six climatic zones based on statistical analysis of 38 years of meteorological data including sunshine, global & diffuse solar radiation, wind speed, rainfall, relative humidity, mean maximum and mean minimum temperature from 233 weather stations. The method used for spatial delineation of climatic zones from classified weather stations, has not been elaborated in the respective Indian building design climate zone publications. Rawal et al. [9] reviewed 4 climate classification methodologies and their application, to 33

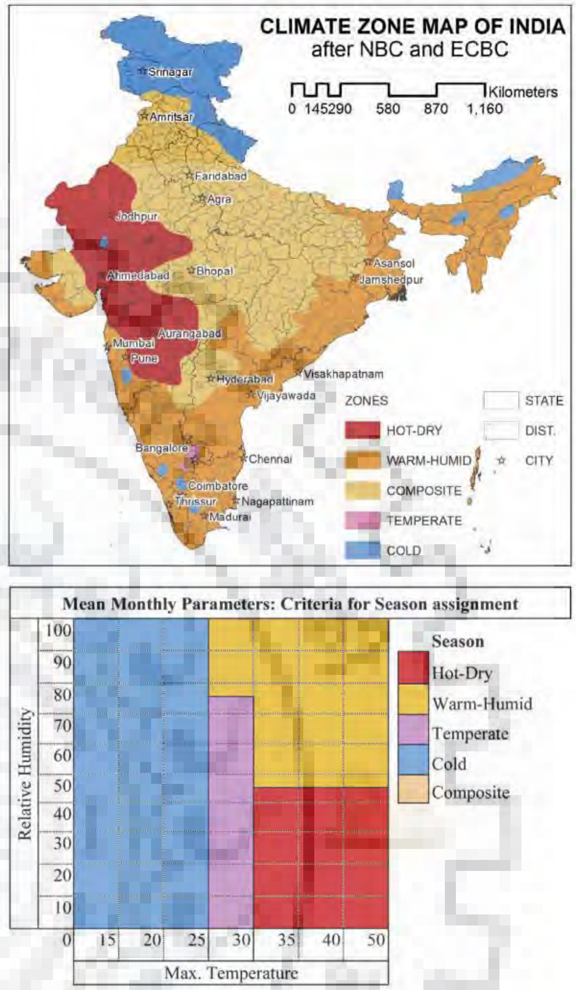

Fig. 3. Climate zone map of India: after [10,30].

weather stations in urban local body (ULB) areas of Maharashtra State of India. The goal of this review was to arrive at a delineation of climate zones to help in implementation of ECBC. Three of the methodologies applied viz., ASHRAE climate classification, International Energy Agency climate classification & CEU climate classification, gave a sketchy picture of climate zones. The studied samples were classified into only one or two zones. Application of criteria given by Bansal and Minke [31] classified climatic data of 24 ULBs into Moderate zone and 9 ULBs into Composite zone; however this reclassification was not similar to that delineated in the original research [9].

There are a few deficiencies in the Indian climate design zones seen so far. Firstly, the climatic data analyzed is point data from a particular weather station and hence the zone variation between the classified points, had to be based on the intuitive knowledge of geographical regions. Secondly, the delineated climate zone information is general and an architect has to perform further city specific bioclimatic analysis to ascertain the exact thermal stress and comfort requirements, before actually selecting climate-responsive design strategies.

2.4. International climate design zones

The criteria used for thermal comfort zoning vary from country to country and even for specific regions. In USA, 'Building America Climate Regions' [12] classifies counties on the criteria of *heating degree days* and *cooling degree days* [34], whereas 'California Energy Commission' [13] classifies geographic areas with similar climate characteristics that dictate the implementation of particular energy efficiency requirements [35]. In China [11], thermal climatic zoning is based on analysis of weather station data for average temperature of the hottest and coldest months of the year and the count of days with average temperatures <5 °C and >25 °C. The Brazilian territory was divided into 6500 grid cells for interpolating available climatic data from 330 cells to perform bioclimatic zoning analysis using the Givoni and Mahoney Tables methods to determine climate-responsive building strategies [15].

The Brazilian bioclimatic zones suggest only few climate-responsive building design strategies and their analysis grid was wide and interpolation method adopted did not factor for altitude variation. Ogunsote et al. [22] suggest an exhaustive list of climate-responsive strategies combinations in Nigerian 'Architectural climatic zones' but the zoning is based on weather station data and reflects use of intuitive knowledge of geographical variation. They corroborate the need for spatially contiguous climatic data for climate design zoning. Some of the classification [23,1] based on high resolution interpolated data reflect geographical variation but the classification criteria do not help in determining climate-responsive strategies. The basis for delineation of zones using such data has depended upon the respective disciplines of the experts.

2.5. Use of Mahoney tables for climatic zoning

Mahoney Tables method had been used in the past for; evaluating the fulfillment of thermal comfort requirements in traditional buildings [36], identifying the thermal comfort requirements of new buildings [37], as well as delineation of thermal comfort design zones [15,22] especially in tropical climates. In 1968 Mahoney proposed a climate analysis sequence consisting of four steps carried out by filing up 4 tables. Mahoney Table 1 dealt with recording basic and widely available monthly climatic data of temperature, humidity and rainfall [38]. Mahoney Table 2 part I dealt with diagnosing adaptive comfort limits, based on annual mean temperature and monthly average humidity.

Mahoney conducted surveys in different regions of Nigeria to ascertain the months of the year which were considered most comfortable [38]. The answers were useful in deciding distinct daytime and nighttime comfort limits corresponding to the distinction in expected physical activities and varying with annual mean temperature and relative humidity group as shown in Table 1.

Table 1
Humidity group-wise adaptive comfort limits: Humidity group criteria: <30% = 1, 30% to 50% = 2, 50% to 70% = 3, >70% = 4.

Annual Mean Temp.(Group)	<15 °C (1)				15 to 20 °C (2)				>20 °C (3)			
Humidity Group	1	2	3	4	1	2	3	4	1	2	3	4
Day Comfort Upper Limit	30	27	28	24	32	30	28	25	34	31	29	27
Day Comfort Lower Limit	21	20	19	18	23	22	21	20	26	25	23	22
Night Comfort Upper Limit	21	20	19	18	23	22	21	20	25	24	23	21
Night Comfort Lower Limit	12	12	12	12	14	14	14	14	17	17	17	17

Source 'Mahoney Table 2 - part I' [21][38]

Evans originally proposed the use of temperature range, as a factor to choose appropriate bioclimatic design strategies, which was put to use in the Mahoney Table 2 part II [39]. As shown in Table 2 here the severity and duration of prevalence of various conditions of climate parameters including mean monthly temperature range were used to assign monthly status to a series of six climatic indicators [21]. Mahoney Tables 3 and 4 help in the selection of design recommendations for the sketch design and detail design stage respectively [21]. As seen from Table 3 here, yearly totals of the six climatic indicators translate into recommended design strategies out of multiple options in each of the strategy groups related to orientation, spacing, wind movement, opening sizing and construction type of walls and roofs [22].

Ogunsote et al. [22] divided all the alternative building strategies of 'Mahoney Tables 3 and 4' into 10 'Strategy groups' and gave them alphabetical IDs from 'a' to 'j'. They systematically delineate climate zones for building design in Nigeria based on Hosni's classification of selected locations in Egypt. Hosni [40] considered procedures of Olgyay [41], Givoni [42] and Mahoney [43], before following the Mahoney method to identify a set of possible alternate architectural responses corresponding to a defined set of climatic conditions existing in the selected locations of Egypt using Sommerhof's [44,45] Adaptive Systems model.

Ogunsote et al. [22] arrived at combinations of building design strategies recommended using Mahoney Tables method, in order to define climatic zones for architectural design. He concluded in this study that, though the locations lying in different climatic zones were being identified, limited data did not allow the establishment of zone boundaries.

2.6. Spatially contiguous interpolated climatic datasets

The inaccessibility of large geographic areas due to sparse population or difficult terrain results in inconsistent spacing between weather stations. Incidentally difficult terrains like series of mountain ranges are also a cause of meso climatic variation. State of the art in climate modeling has enabled estimation of climatic conditions at locations for which observed data is either available for a short period of time or is not at all available. The climatic datasets modeled by interpolating climatic parameters observed at various weather stations across the globe are useful for objective delineation of climate zones at synoptic level [23]. Since 1997, Thornton, Daly and New used weather station datasets from multiple sources to improve creation of spatially and temporally integrated continuous datasets for the whole world [46–48].

Table 2
Factor codes (Parameter values) with respect to indicators.

Meaning→ / *Applicable when ↓*	*Air movement essential*		*Air movement desirable*	*Rain protection necessary*	*Thermal capacity necessary*	*Outdoor sleeping desirable*		*Protection from cold*
Indicator→	**H1**	**H1**	**H2**	**H3**	**A1**	**A2**	**A2**	**A3**
PAT				>200 (2)				
TMMR_mm		<10° (1)			>10° (2)		>10° (2)	
RHG_mm	4	2, 3	4		1, 2, 3	1, 2	1, 2	
MSN_m						H (3)	O (2)	
MSD_m	H (3)	H (3)	O (2)				H (3)	C (1)

after Notes at bottom of 'Mahoney Table 2- part II' [21]

Table 3
Building Design Strategies w.r.t. Indicator Totals as per Mahoney Tables 3 and 4 modified after [22].

INDICATORS						BUILDING STRATEGY GROUPS	
H1	***H2***	***H3***	***A1***	***A2***	***A3***	***ID***	***Building Strategy***
							a: LAYOUT OF BUILDING
			0-10			*a1*	Orientation N&S (long axis east -
			11,12		5-12	*a1*	west)
			11,12		0-4	*a2*	Compact Courtyard Planning
							b: SPACING BETW^N BUILDINGS
11,12						*b1*	Open spacing for breeze penetration
2-10						*b2*	Open spacing for breeze penetration, protect from H&C wind
0,1						*b3*	Compact Layout of Estates
							c: AIR MOVEMENT
3-12						*c1*	Single banked Rooms, permanent
1,2			0-5			*c1*	provision for air movement
1,2			6-12			*c2*	Double banked Rooms with
0	2-12					*c2*	temporary provision for air movement
0	0,1					*c3*	No air movement required
							d: SIZE OF OPENING
			0,1		0	*d1*	Large openings, 40-80% of wall area
			0,1		1-12	*d2*	Medim Openings, 25-40% of wall
			2-5			*d2*	area
			11,12		4-12	*d3*	Composite Openings, 20-35% of wall area
			6-10			*d4*	Small openings, 15-25% of wall area
			11,12		0-3	*d5*	Very small openings, 10-20% of wall area
							e: POSITION OF OPENING
3-12						*e1*	Openings in N&S walls at body
1-2			0-5			*e1*	height on windward side
1-2			6-12			*e2*	Openings in N&S walls at body
0	2-12					*e2*	height on windward side as well as in internal walls
						e3	Has no climate related value
							f: PROTECTION OF OPENING
		0,1			3-12	*f1*	No special protection necessary
					0-2	*f2*	Exclude direct sunlignt
		2-12			0-2	*f3*	Protection from rain & direct sunlight
		2-12				*f4*	Provide protection from rain
							g: WALL AND FLOOR
			0-2			*g1*	Light walls, short time-lag
			3-12			*g2*	Heavy external & internal walls, over 8 hour time-lag
							h: ROOF
10-12			0-2			*h1*	Roof Light, reflective surface, cavity
10-12			3-12			*h2*	Light well insulated roofs
0-9			0-5			*h2*	
0-9			6-12			*h3*	Heavy roofs, over 8 h time-lag
							i: OUTDOOR SLEEPING
				0		*i1*	No space for out-door sleeping
				1-12		*i2*	Space for out-door sleeping
							j: RAIN PROTECTION
		2-12				*j1*	Protection form heavy rain needed
		0,1				j2	No Protection form heavy rain needed

In 2005, Hijmans et al. [49] used data compiled under various international cooperation projects like GHCN – Global Historical Climate Network of weather stations across the world for the period 1950–2000 to prepare interpolated *raster datasets*. They used 'Digital Elevation Model' (DEM) obtained from the Shuttle Radar Topography Mission SRTM for interpolating the climatic parameters to factor in the effect of altitude. They interpolated the data for the entire land surface of the world (except Antarctica). They have provided individual parameter datasets as tiles of 30°Latitude × 30°Longitude arranged in 5 rows and 12 columns covering the whole world as shown in Fig. 4 [50].

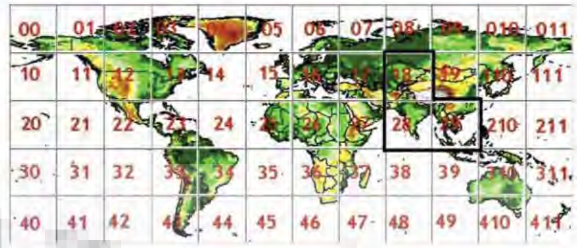

Fig. 4. Tiles 18, 28 & 29 in Index of Raster Dataset; which have been pieced together & subset taken as input data [50].

SEWRA and UNEP [51] used NASA's Surface meteorology and Solar Energy database for the period 1983–2005 to compile data of monthly relative humidity at 10 m above surface. Regional averages of 1°Latitude × 1°Longitude were available online [51] in designated field in attribute table of polygon features. Total of 360 × 180 polygons covering the whole world were available in a single shape file named 'RH10M_NASA_low' [52].

3. Materials and method

3.1. Subset of interpolated climatic dataset

Air temperature, relative humidity and precipitation are the parameters required in the analysis of thermal comfort [21], modeled climatic datasets of these parameters have been obtained from two different sources discussed in Section 2.6 for use in this research.

For climatic parameters namely, Monthly Precipitation, Monthly Maximum & Minimum Temperature and Annual Mean Temperature, *raster datasets* of resolution 30″(second) Latitude × 30″(second) Longitude available from 'WorldClim' [50] in Grid format described in Section 2.6 have been selected.

For Monthly average relative humidity, a GIS vector dataset of the whole world at 1° Latitude × 1° Longitude resolution, available from 'Open Energy Information' [51] has been selected.

The polygon for India administrative boundary subdivided into three hierarchical levels available from 'Global Administrative Areas' [53] has been used to subset the selected raw data.

The features and datasets of downloaded input climatic parameters, derived and classified factors (humidity group, temperature range group, comfort limits, indicators) have been described in various steps of the present research using abbreviations (for complete list see Appendix: Table 9).

3.2. GIS tools & workflow

ArcMap 10 has been chosen for use in this research as license has been available with the Institute Computer Center at I. I. T. Roorkee. The tools used in analysis of selected data, have been discussed in Appendix: (Explanatory GIS Notes) at the end of this paper. The workflow involves step by step implementation of 'Mahoney Table 1–4' on a subset of 30″ Latitude × Longitude resolution gridded climate dataset discussed above. The goal here is to ascertain boundaries where any change in thermal stresses necessitates corresponding change in building design strategies. Conceptual model of workflow comprising 11 Steps grouped under 5 Stages has been presented in Fig. 5.

3.3. Stage I: Data Recording

Stage I called 'Data Recording' is completed in 4 Steps namely, 1A, 1B, 1C & 1D. This stage corresponds to 'Mahoney Table 1' where the climatic data of air temperature, humidity and rainfall has been assembled.

In Step 1A raw data has been used to create a yearly input parameter 'Annual Mean Temperature' (AMT_Bio01) and the monthly input parameters 'Precipitation' (PREC_mm). (See Fig. 9-A for GIS procedure).

In *Step 1B* raw data has been used to create the monthly inputs of air temperature 'maxima' (TMAX_mm) and 'minima' (TMIN_mm). These inputs are used to calculate the derived parameter 'Temperature Monthly Mean Range' (TMMR_mm), which is then used to create the classified parameter 'Temperature Monthly Range Class' (TMRC_mm). Fig. 9-B details this classification process of coding parameter values using following criteria:

<10 deg C = 1 and >10 deg C = 2.

In *Steps 1C and 1D* the vector raw data at 1° Lat × Long has been converted to raster data at 30″ Lat × Long and used to create monthly input 'Relative Humidity' (RH30S_mm). Fig. 9-C depicts the process of curtailing the world wide vector data using 1° buffer around AOI. Fig. 9-D depicts the process of conversion of vector data to raster data.

3.4. Stage II: Data Diagnosis

Stage II called 'Data Diagnosis' corresponding to 'Mahoney Table 2 first part' has been executed in 3 steps namely 2A, 2B and 2C.

In *Step 2A* first input AMT_Bio01 from Step 1A has been used to create the classified parameter called 'Annual Mean Temperature Group' (AMTG), wherein the input values have been coded as follows:

<15 °C = 1, 15 °C to 20 °C = 2, & >20 °C = 3

Then the AMTG is used to create 13 derived parameters called 'Humidity group-wise Adaptive Comfort Limits' corresponding to the values listed in Table 1. (See Fig. 10-A for GIS procedure).

In *Step 2B* first input RH30S_mm from Step1D has been used to create the classified monthly parameter 'Relative Humidity Group' (RHG_mm), wherein input values have been coded as follows:

<30% = 1, 30 to 50% = 2, 50 to 70% = 3, & >70% = 4

Then, RHG_mm and the 'Humidity group-wise Adaptive Comfort Limits' available from Step 2A have been used for creating the 4 derived parameters 'Monthly Comfort Limits' (MDCUL, MDCLL, MNCUL, MNCLL). Fig. 10-B also details the GIS process.

In *Step 2C* the monthly input TMAX_mm and derived parameters 'Monthly Day Comfort Upper Limit' (MDCUL) & 'Monthly Day Comfort Lower Limit' (MDCLL) have been used to create the classified parameter 'Monthly Daytime Stress' (MSD_mm).

The criteria used to determine the values of classified parameter MSD_mm is as follows:

Cold (1) if, TMAX_mm < MDCLL;
Ordinary (2) if, TMAX_mm within MDCLL & MDCUL;
& Hot (3) if TMAX_mm > MDCUL.

Similar criterion has been used for the classified parameter 'Monthly Nighttime Stress' (MSN_mm) (See Fig. 10-C).

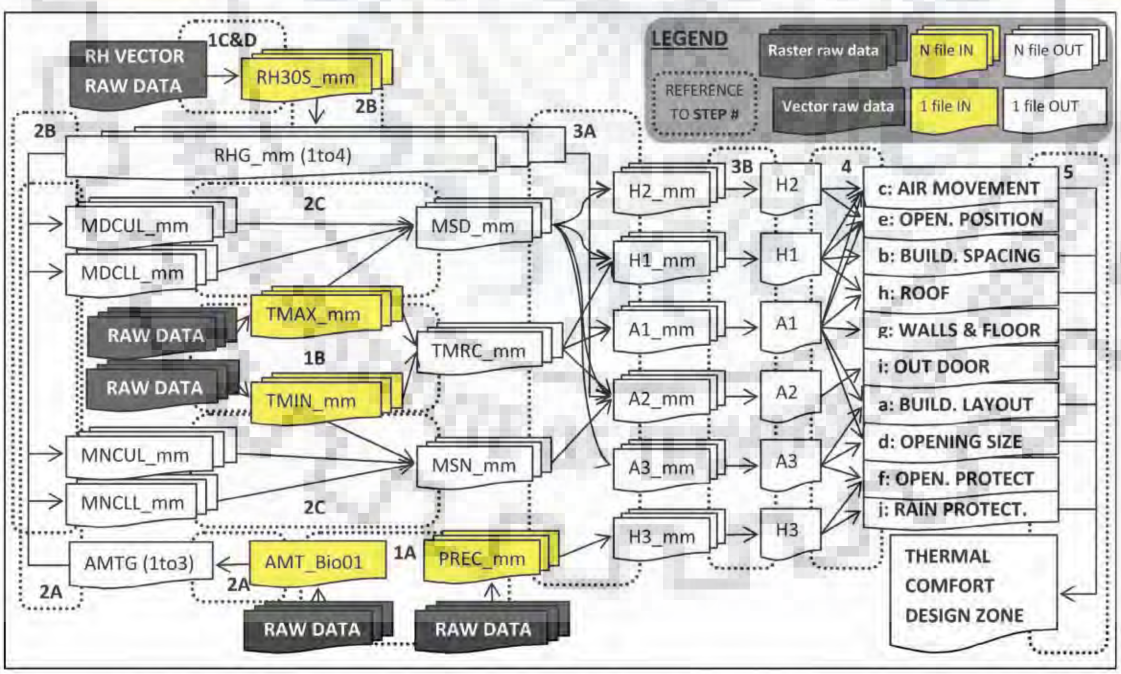

Fig. 5. Conceptual model of GIS procedure devised to analyze interpolated climatic data based on Mahoney Tables method for delineation of Thermal Comfort Design Zone (TCDZ).

3.5. Stage III: Climatic Indicators

Stage III called 'Climatic indicators' corresponding to 'Mahoney Table 2 second part' is executed in 2 steps. Three 'Humid Indicators' (H1, H2, H3) and 3 'Arid Indicators' (A1, A2, A3) have been created at this stage based on; nature of thermal stress, some climate characteristics and the duration of both [21].

In *Step 3A* six 'Monthly Indicators' (H1_mm, H2_mm, H3_mm, A1_mm, A2_mm, A3_mm) have been created using monthly variables of input (PREC_mm) from Step 1A, and the classified parameters (RHG_mm, TMRC_mm, and MSD_mm & MSN_mm) from Steps 1B, 2B and 2C respectively. These monthly indicators are binary records of pixel-wise True-False analysis of indicator definitions. Table 2 shows the parameter values defining respective indicator, represented as factor codes.

Table 4 shows values from a place-value notation created by adding the weighted code values from two or more factors contributing to respective indicator definitions. Values representing only isolated factors from an indicator definition have been highlighted as colored infill or bold font in color; while the values at collation of factors corresponding to the indicator definition are highlighted as ***bold + italics + underlined.*** (See Fig. 11 for GIS procedure).

In *Step 3B* 'Monthly Indicators' from previous step have been used to create the six 'indicator (yearly) totals' (H1, H2, H3, A1, A2, and A3). The values for each of the Indicator Totals are calculated by summing up the binary (yes/no i.e. 1/0) values from the respective monthly indicators.

3.6. Stage IV: Design Strategy Checking

At Stage IV termed as 'Design Strategy Checking' the group wise 'Strategy Codes' are delineated across Indian territory based on the co-existence of suitable conditions in all contributory indicators. This Stage corresponds to the culminating 'Mahoney Tables 3 and 4'. Distinct indicator totals designated for the selection of specific design strategy from each group ('a' to 'j') are listed in Table 3. The selection of strategies from a group dependant only on one indicator (group 'b', group 'i' and group 'j') has been done using reclassification. The indicator values suitable to different strategies have been coded and weighted before they are used to create the place-value notation codes. Table 5 shows the strategy group-wise place-value codes for respective strategies in all groups dependant on more than one indicator. All indicator conditions in groups' c & e exactly match; while the indicator conditions of H3 are identical in groups' f & j, hence the place-value notation codes for the respective groups are same. (See Fig. 12 for detailed procedure followed to create the 'Strategy Codes').

Table 4
Place-value notation of factor codes corresponding to monthly indicators.

Place-Value Notation for A2

TMRC(2)	RHG (4)	MSN (3)	1000	1000	1000	2000	2000	2000	3000	3000	3000
		MSD (3)	100	200	300	100	200	300	100	200	300
10	1		1111	1211	1311	2111	2211	2311	***3111***	***3211***	***3311***
10	2		1112	1212	1312	2112	2212	2312	***3112***	***3212***	***3312***
10	3		1113	1213	1313	2113	2213	2313	3113	3213	3313
10	4		1114	1214	1314	2114	2214	2314	3114	3214	3314
20	1		1121	1221	1321	2121	2221	***2321***	***3121***	***3221***	***3321***
20	2		1122	1222	1322	2122	2222	***2322***	***3122***	***3222***	***3322***
20	3		1123	1223	1323	2123	2223	2323	3123	3223	3323
20	4		1124	1224	1324	2124	2224	2324	3124	3224	3324

Place-Value Notation for H2

MSD (3)		100	200	300
RHG (4)				
1		101	**201**	301
2		102	**202**	302
3		103	**203**	303
4		104	***204***	304

Place-Value Notation for H1

TMRC (2)	RHG (4)	MSD (3)	100	200	300
10	1		111	211	**311**
10	2		112	212	***312***
10	3		113	213	***313***
10	4		114	214	***314***
20	1		121	221	**321**
20	2		122	222	**322**
20	3		123	223	**323**
20	4		124	224	***324***

Place-Value Notation for A1

TMRC (2)→		10	20
↓ RHG (4)			
1		11	***21***
2		12	***22***
3		13	***23***
4		14	**24**

3.7. Stage V: Zone Delineation

The last Stage V is called 'Zone Delineation' because here the 8 'Strategy Codes' from previous stage have been used to delineate the extents of 'Thermal Comfort Design Zone' (TCDZ) with unique combination of climate-responsive design strategies. To incorporate the place-value notation system, all the Strategy Codes have been weighted as per Table 6 and then 'combined' by summation.

4. Results: Thermal Comfort Design Zones (TCDZ)

A total of 86 distinct Zones Code values have been identified at the end of this process. The histogram of zone-wise pixel count (See Fig. 13-A) shows that some zones had a pixel count of as low as 1×10^1 pixels (10 sq. km. area); whereas, the largest zone has about 1.1×10^6 pixels (11,00,000 sq. km. area).

4.1. Zone Generalization

Zone Generalization has been aimed at removing zones with insignificant pixel counts. Zones with less than 100 contiguous pixels have been generalized after trying four incremental sizes of *zone islands* for merger into the surrounding zones.

Fig. 6 shows results of the four iterations of generalization (carried out as per procedure in Fig. 13-B). It can be seen that as the

Table 5
Strategy group wise place-value notation codes obtained from sum of weighted yearly indicator totals.

Group a	A3	0_4	5_12
A1		1	2
0_10	10	11	12
11_12	20	21	22

Group c&e		H1	0	1_2	3_12
H2	A1		1	2	3
0_1	0_5	110	111	112	113
0_1	6_12	120	121	122	123
2_12	0_5	210	211	212	213
2_12	6_12	220	221	222	223

Color	Strategy ↓Code
	1
	2
	3
	4
	5

Group f&j	A3	0_2	3_12
H3		1	2
0_1	10	11	12
2_12	20	21	22

Group d	A3	0	1_3	4_12
A1		1	2	3
0_1	10	11	12	13
2_5	20	21	22	23
6_10	30	31	32	33
11_12	40	41	42	43

Gr. h	H1	0_9	10_12
A1		1	2
0_2	10	11	12
3_5	20	21	22
6_12	30	31	32

Table 6
Correlation between combined strategies.

Unique Values	*Code Weight*	*Strategy Group*	*d*	*h*	*g*	*c*	*b*	*a*	*f*	*i*
5	10000000	d	1.00							
3	1000000	h	0.92	1.00						
2	100000	g	0.58	0.60	1.00					
3	10000	c	0.38	0.44	0.32	1.00				
3	1000	b	0.11	0.21	0.26	0.57	1.00			
2	100	a	0.05	0.21	0.12	0.32	0.17	1.00		
4	10	f	-.06	-.07	-.08	-.13	-.08	-.07	1.00	
2	1	i	0.24	0.30	0.30	0.08	0.03	0.10	-.04	1.00

zone island size called 'nibble region' increases from 25 to 100 pixels, the total number of zones reduce significantly, while the zone boundaries are still fluid. However when the nibble region has been increased significantly to 525 the reduction of number of zones is little while the zone boundaries become hard. Sixty-two values of Zone Code remaining after generalization process have been mapped and overlapped with boundaries of Climate Zone Map of India as per NBC for comparison in Fig. 7.

4.2. TCD zones compared with NBC zones

Detailed visual analysis shows that the 5 NBC zones span over varying number of TCD Zones. Some TCD Zones also span across one or more NBC Zones. The IDs of TCD zones delineated within NBC Zones have been listed in Table 7. Maximum numbers (27) of TCD Zones have been delineated within Warm-Humid Zone, while only two TCD Zone are delineated over Temperate zone. High numbers of TCD Zones have also been delineated within Cold Zone (21) while relatively less number of zones has been delineated within Hot-Dry and Composite Zones (7 and 8 respectively).

Some of the TCD zones delineated over small isolated areas exclusively within one NBC Zone only have been highlighted as **BOLD**. Three of the TCD zones have been delineated in sporadic hilly areas across multiple NBC zones. A comparison of NBC Zones with TCDZ along with unique combinations of Passive Design Strategies for 21 cities has been presented in Table 8.

4.3. Validation

In the present research a process has been developed using GIS where, the raw data of climatic parameters is processed, classified and analyzed in a step by step analysis based on Mahoney Tables. Validation has been done to check whether, the conversion of climatic parameters to derived parameters to classified parameters to indicators to design strategies is error free. The climate-responsive design strategies for 21 highly populated cities (point locations listed in Table 8), in various zones delineated through the developed process; have been compared with those obtained through a semi automated process in MS Excel.

To start with, the list of 53 cities [5] with population more than 1 million has been sorted by delineated zone code and then by city

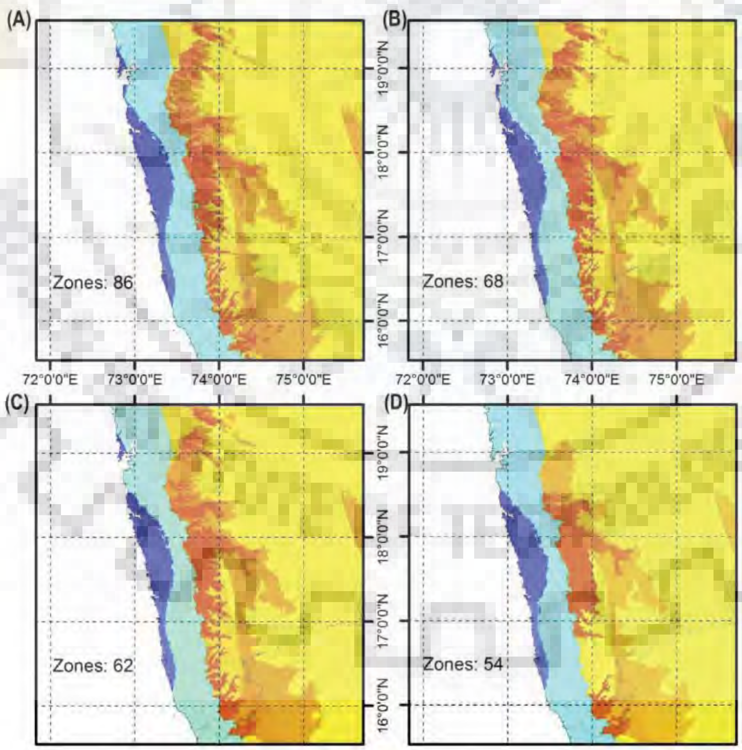

Fig. 6. Comparison of generalizations obtained by varying zone island pixel count: (A) base case (B) count <25 (C) count <100 (D) count <525.

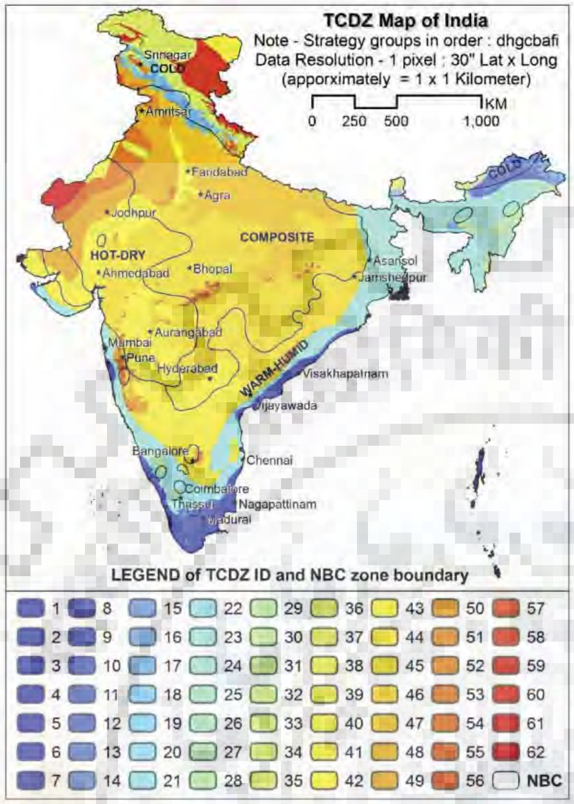

Fig. 7. Thermal Comfort Design Zone (TCDZ) map of India overlapped with NBC zone boundary (**BOLD CAPS**).

name, to select the first city in each zone for comparison. The required climatic parameters were extracted from the respective raster datasets using '*Extract Multi Values to Point*' tool from 'Spatial Analyst Toolbox'. These parameters were then linked into a MS Excel Template created to automate the city wise 'Mahoney Table' analysis of climate-responsive design strategies. Strategies for all selected cities obtained by both GIS and MS Excel methods match 100%.

5. Discussion

Zone delineation of group-wise strategies has been shown in the eight parts of Fig. 8. It can be seen here that only the building design strategies in group'd' and 'h' are somewhat similar, as they share the indicator A1 in their definition. All other strategies follow independent boundaries purely based on climatic parameters and indicators governing their selection. Such an exhaustive selection of strategies was only possible due to the analyses of available high resolution interpolated data as per Mahoney Tables using overlay analysis tools in GIS.

Table 7
All TCD Zone ID's sorted as per NBC Zones.

NBC Zone	TCDZ ID	Count
Hot-Dry	39, (43), (45), 49, 53, 54, 62	5(2)
Warm-Humid	1-10, 13, 15, 21-24, **25**, **29**, **30**, **31**, **33**, **34**, 42-45, 55	27
Composite	12, 38, 41, (45), 47, 48, 51, (53)	6(2)
Temperate	(43), (33)	0(2)
Cold	11, 14, 16-20, **26**, 27, **28**, 32, 35, **36**, 37, **40**, 46, 52, 57, **59**, 60, 61	21
Hilly (in multiple)	*50, 56, 58*	*3*
Total		***62***

TCDZ ID's counted in other NBC Zone indicated in ()

As seen from the comparison of proposed TCD zones with existing climate zones given by NBC in Table 8, the selection of design strategies varies within one climate zone as well as across climate zones. For example TCDZ 2, 5, 7, 8 all fall in the NBC zone Warm-Humid; while TCDZ 43 has been assigned to the cities Pune, Aurangabad, Hyderabad, Bangalore which fall under NBC zones Warm-Humid, Hot-Dry, Composite, Temperate respectively. This situation creates ambiguity in the effective implementation of design strategies. The proposed Thermal Climate Design Zone can directly specify the unique combination of all applicable climate-responsive strategies as it has been identified using the extents of strategies on all groups. If the TCD zone map is approved and adopted by legislative bodies, Architects can directly know the bioclimatic strategies at the outset of any project, just by locating their site on the map. The developed procedure can be implemented for any tropical region with diverse geographical conditions where Mahoney Tables are useful.

It is possible to objectively delineate any new design strategy selection criteria as and when they are developed. As pointed out by Li et al. [54] the interpolated data available is based on historical records, and should be periodically updated. The zone delineation can be repeated as and when more complete or dense data is made available by Climatologists.

5.1. Conclusion

Meteorological observations of three decades synthesized by interpolation at regional scale have been used for the synoptic climate classification of thermal comfort design zones. The variety of climatic conditions experienced in India due to its geographical diversity, is not depicted in the existing Building Design Climate Zones. A very high resolution climatic dataset has been used to delineate geographical extents having common recommended climate design strategies based on similar thermal stress and climate characteristics. GIS based procedure has been developed to analyze the climatic data as per Mahoney Tables by processing and creating raster datasets as follows:

- Data Recording by collection & completion of climatic parameters & bioclimatic factors.
- Data Diagnosis to determine adaptive & monthly comfort limits, so as to ascertain monthly thermal Stress.
- Suitability of building design strategies are analyzed based on duration of experienced thermal stress and specific climate characteristics categorized as climatic indicators.
- For carrying out these multi criteria analyses, place-value notation codes have been setup to represent various combinations of factors for reclassification of raster datasets.
- Thermal Comfort Design Zone(s) have been delineated based on unique combinations of recommended building design strategies.
- The 86 TCD Zones delineated in base case have been generalized into 62 zones by merging zones and islands having contiguous area less than 100 sq. km. The 53 Urban Agglomerations having population more than 1 million fall in one of the 15 TCD Zones identified for validation.

Table 8
Comparison of NBC Zone with Thermal Comfort Design Zone (TCDZ) and applicable group-wise strategy codes (Indicated as 'Y').

SN	City Name	NBC Zone	TCDZ	Group→	d					h			g		c			b			a		f				i	
			ID	Code ↓→	1	2	3	4	5	1	2	3	1	2	1	2	3	1	2	3	1	2	1	2	3	4	1	2
1	Nagappattinam	WARM-HUMID	2	11111138	Y					Y			Y		Y			Y			Y				Y		Y	
2	Visakhapatnam	WARM-HUMID	5	12112128	Y						Y		Y		Y				Y		Y			Y			Y	
3	Thrissur	WARM-HUMID	7	21112138		Y				Y			Y		Y				Y		Y				Y		Y	
4	Madurai	WARM-HUMID	8	22112128		Y					Y		Y		Y				Y		Y			Y			Y	
5	Mumbai	WARM-HUMID	23	22112138		Y					Y		Y		Y				Y		Y				Y		Y	
6	Coimbatore	WARM-HUMID	21	22212128		Y					Y			Y	Y				Y		Y			Y			Y	
7	Chennai	WARM-HUMID	23	22212138		Y					Y			Y	Y				Y		Y				Y		Y	
8	Asansol	WARM-HUMID	24	22212139		Y					Y			Y	Y				Y		Y				Y			Y
9	**Faridabad**	**COMPOSITE**	**41**	**43212119**				Y				Y		Y	Y				Y		Y		Y					Y
10	Vijayawada	WARM-HUMID	42	43212128				Y				Y		Y	Y				Y		Y			Y			Y	
11	Pune	WARM-HUMID	43	43212129				Y				Y		Y	Y				Y		Y			Y				Y
12	*Aurangabad*	*HOT-DRY*	*43*	*43212129*				Y				Y		Y	Y				Y		Y			Y				Y
13	**Hyderabad**	**COMPOSITE**	**43**	**43212129**				Y				Y		Y	Y				Y		Y			Y				Y
14	***Bangalore***	***TEMPERATE***	***43***	***43212129***				Y				Y		Y	Y				Y		Y			Y				Y
15	Jamshedpur	WARM-HUMID	45	43212139				Y				Y		Y	Y				Y		Y				Y			Y
16	**Bhopal**	**COMPOSITE**	**45**	**43212139**				Y				Y		Y	Y				Y		Y				Y			Y
17	*Ahmedabad*	*HOT-DRY*	*45*	*43212139*				Y				Y		Y	Y				Y		Y				Y			Y
18	**Agra**	**COMPOSITE**	**47**	**43212149**				Y				Y		Y	Y				Y		Y					Y		Y
19	**Amritsar**	**COMPOSITE**	**48**	**43222119**				Y				Y		Y		Y			Y		Y		Y					Y
20	*Jodhpur*	*HOT-DRY*	*49*	*43222129*				Y				Y		Y		Y			Y		Y			Y				Y
21	Srinagar	COLD	53	43223119				Y				Y		Y		Y				Y	Y		Y					Y

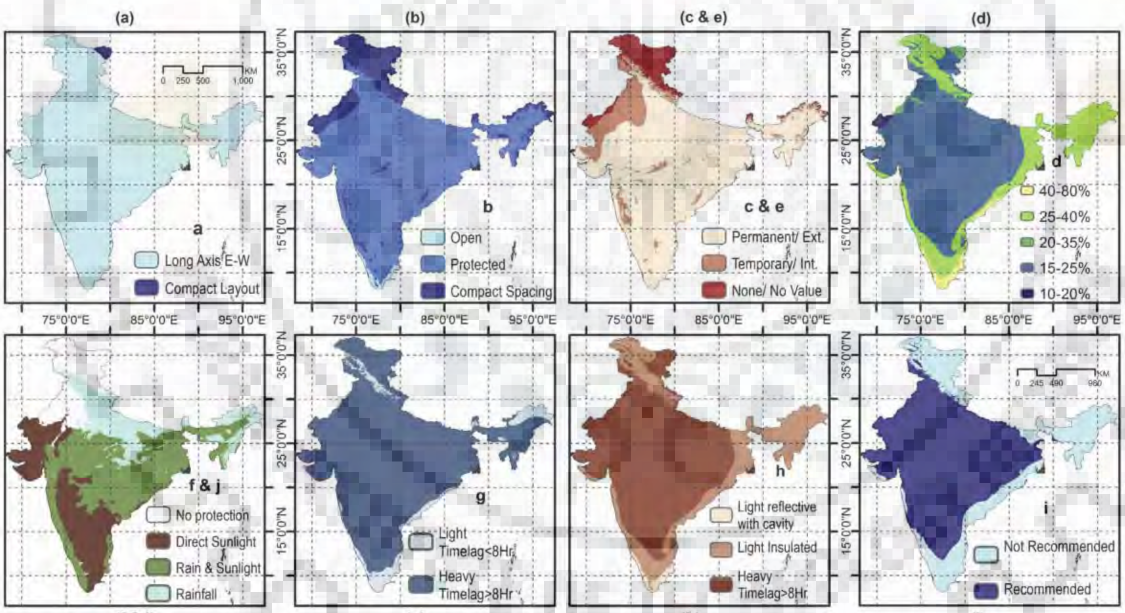

Fig. 8. Group-wise strategy codes: (a) Layout of building (b) Spacing between buildings (c & e) Air movement & Opening position (d) Opening size in %age of wall area (f & j) Protection required from? (g) Wall and floor type (h) Roof type (i) Outdoor sleeping space requirement.

- As has been demonstrated, the delineated TCD Zones can now be used in the formulation of zone specific constitutional measures for implementation of climate-responsive building design and construction.

The procedure adopted for spatial delineation of thermal comfort requirements in India and suitable climate-responsive building design strategies thereof can also be applied to other tropical regions experiencing diverse climatic regimes.

Acknowledgment

NNRMS-ISRO sponsored training course at Indian Institute of Remote Sensing Dehradun has benefited ASP immensely in acquiring platform knowledge crucial to this research. The authors thank the reviewers for their insightful comments, which were useful for improving this paper.

Appendix. Explanatory GIS Notes

To prepare input parameters from raw data, create derived parameters and to classify the two for delineating climate-responsive design strategies (listed in Table 9) various GIS tools have been used. *Model Builder tool* has been used to execute, document and represent the various tools in process flow charts. Some tools have to be reiterated multiple times, for e.g. applying one particular clip boundary (see Fig. 9-B) or reclassification criteria (see Fig. 9-C) to 12 raster datasets of 12 months. Batch processing of such parametric tools (PT) has been devised using 'Model Builder'.

Analysis Toolbox

'Buffer' tool has been used to create a clip feature of 1° buffer around the AOI polygon to be used in *'Clip' tool*, while extracting polygon features from vector dataset as described in Fig. 9-C.

Conversion Toolbox

As described in Fig. 9-D, *'Polygon to Raster' tool* has been used to convert the extracted polygon features to raster datasets. *'Raster to Point' tool* has been used to convert these raster datasets to point features.

Spatial Analyst Toolbox

'Spline' tool has been used to interpolate high resolution raster surface through point features at low resolution as described in Fig. 9-D.

Table 9
Glossary of abbrevations used to describe features and datasets of input climatic parameters, derived parameters and classified factors.

Abbreviation	Parameter/Factor
Data Recording (mm=01-12)	
TMAX_mm	Temperature Mean Maximum_month
TMIN_mm	Temperature Mean Minimum_month
AMT (Bio01)	Annual Mean Temperature (Yearly Raster)
PREC_mm	Precipitation Total_month
RH10M_NASA	*Regional Avg. Relative Humidity (Full)*
India_All	*Administrative Boundary of India (AOI)*
India_Buffer	*Buffer of 1° around AOI*
TMMR_mm	Temp. Monthly Mean Range_month
TMRC_mm	Temp. Mean Range Class_month
RH10M_Clip	*Regional Avg. Relative Humidity (AOI)*
RH1D_mm	Relative Humidity 1° Cell value_month
RH1Dpt_mm	*Relative Humidity 1° point value_month*
RH30SUC_m	Relative Humidity 30″ Unclipped_month
RH30S_mm	Relative Humidity 30″ Cell value_month
RHG_mm	Relative Humidity Group_month
Data Diagnosis: Adaptive Comfort (Gr = Group 1/2/3/4)	
AMTG	Annual Mean Temperature Group
DCUL_HGr	R.H. Group-wise Day Comfort Upper Limit
DCLL_HGr	R.H. Group-wise Day Comfort Lower Limit
NCUL_HGr	R.H. Group-wise Night Comfort Upper Limit
NCLL_HGa	Night Comfort Lower Limit (all R.H. Groups)
Data Diagnosis: Monthly Comfort	
MDCUL_mm	Monthly Day comfort Upper limit_month
MDCLL_mm	Monthly Day comfort Lower limit_month
MNCUL_mm	Monthly Night comfort Upper limit_month
MNCLL_mm	Monthly Night comfort Lower limit_month
Data Diagnosis: Monthly Stress	
MSD_mm	Monthly Stress Daytime _month
MSN_mm	Monthly Stress Nighttime _month
Indicator Checking & Totaling	
Wt_A1_mm, Wt_A2_mm, Wt_H1_mm, Wt_H2_mm	Place-value notation of factor codes corresponding to monthly indicators A1, A2, H1, H2 respectively
A1_mm, A2_mm, A3_mm, H1_mm, H2_mm, H3_mm	Monthly status of indicator A1, A2, A3, H1, H2, H3 respectively
A1, A2, A3, H1, H2, H3	Yearly totals of indicators A1, A2, A3, H1, H2, H3 respectively
Strategy Checking	
A1a, A1ce, A1d, A1h; A3a, A3d, A3f; H1ce, H1f; H2ce, H3f	Strategy group-wise place-value notation codes obtained from sum of weighted yearly totals of indicators A1; A3; H1; H2 & H3 respectively
au, cu, du, eu, fu, hu	Weighted Sum Code Strategy Group Raster Datasets
a, b, c, d, e, f, g, h, i, j	Delineated Strategy Group Raster Datasets

(Abbreviations of vector features denoted in Italics).

Data Management Toolbox

The tools *'Create Mosaic Dataset'* and *'Add Rasters to Mosaic Dataset'* have been used to piece together raster datasets as described in Fig. 9-A. *'Clip'* tool is employed to create a subset of this mosaic dataset for spatial extent of AOI.

As seen in Fig. 9-B, using *'Minus' tool* values of Monthly Mean Range 'TMMR_mm' raster datasets have been calculated as the difference between the value of 'TMIN_mm' and 'TMAX_mm' on a cell by cell basis. These monthly datasets have been classified into two classes 'TMRC_mm' using 'Con' tool.

The geo-processing tool 'Con' as part of expression in '*Raster Calculator' tool* has been used to perform conditional if/else evaluation of individual cell of the derived parameter 'TMMR_mm' as well as to obtain classified parameter 'RHG' from input 'RH30S_mm'.

These tools have been sequentially used to complete the remaining steps in the analysis. In Section 3.7 the use of '*Combine' tool* has been discussed. In Section 4.1 the use of tools, '*Raster Group*', '*Nibble*' and '*SetNull*' has been discussed. In Section 4.3 the use of '*Extract Multi Values to Point*' tool has been discussed.

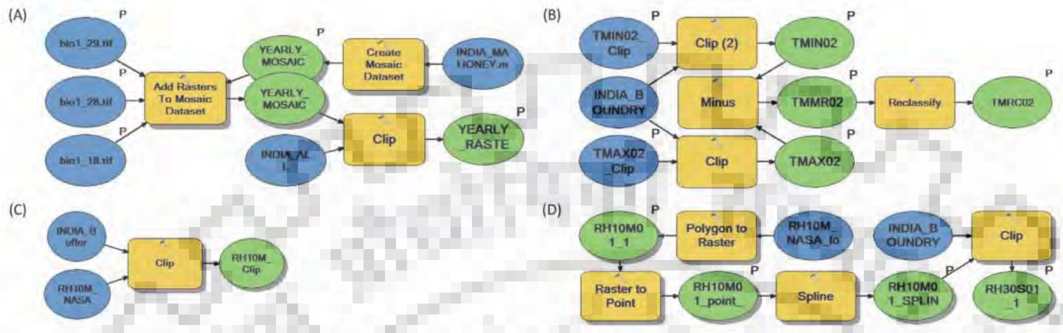

Fig. 9. Model builder tools for data recording (A) Parametric tool – PT – for raster data collection (B) PT for data completion: monthly temperature range and its class (C) Tool for vector data collection (D) PT for data completion: monthly relative humidity.

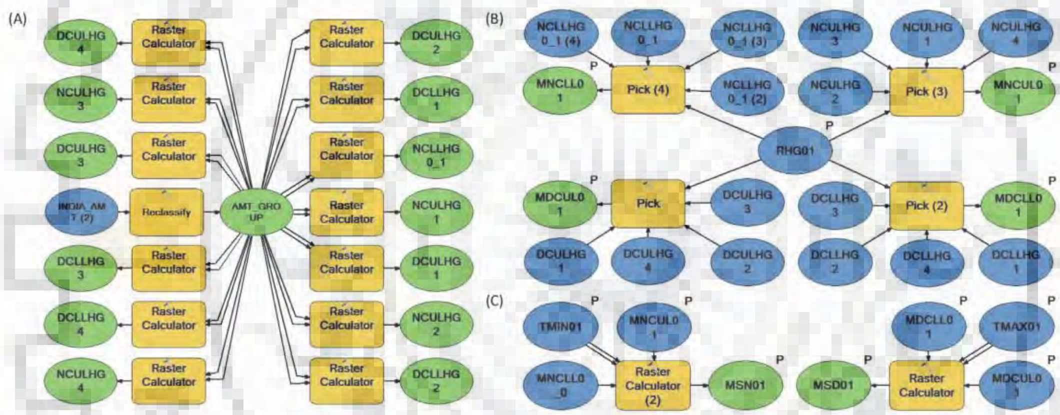

Fig. 10. Model builder tools for data diagnosis (A) Tool for adaptive comfort limits (B) PT for monthly comfort limit (C) PT for monthly stress.

'*Reclassify' tool* has been used to classify values in a raster, like in the instance in Fig. 10-A, where the values in input raster Annual Mean Temperature Value 'AMT' have been classified into one of three values in output raster Annual Mean Temperature Group 'AMTG'.

Table 4 describes a place-value notation of factor codes devised to represent, combinations of factors corresponding to the indicator definition. The number of places in the code is equal to the number of factors contributing to the indicator. As described in Fig. 11, '*Weighted Sum' tool* has been used to overlay the values of, multiple factors contributing to the output Monthly Indicator raster datasets. The *Reclassify Tool* has been especially useful when the aforementioned place value notation of factor codes had to be put into specific binary class to ascertain the applicability of respective monthly indicators.

As shown in Fig. 10-B, Monthly Humidity Group raster(s) 'RHG_mm' with 4 possible values have been used as position raster in '*Pick' tool* to determine from which input *Adaptive Comfort* raster e.g. 'DCULH1'/2'/3'/4' the cell value for output *Monthly Comfort* raster e.g. 'MDUL_mm' will be obtained.

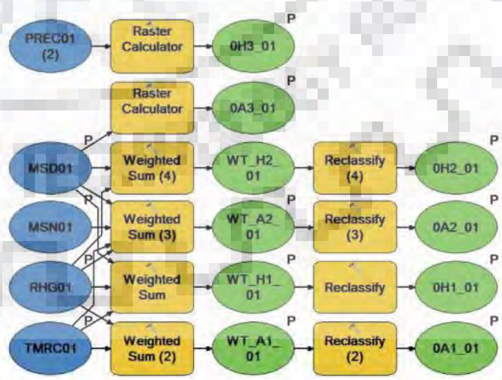

Fig. 11. Parametric model builder tool for monthly indicator checking.

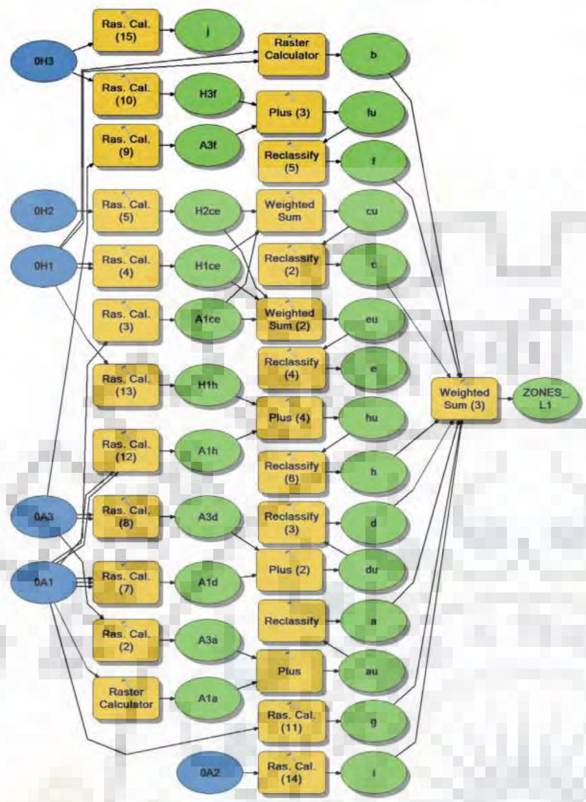

Fig. 12. Model builder tool for strategy checking.

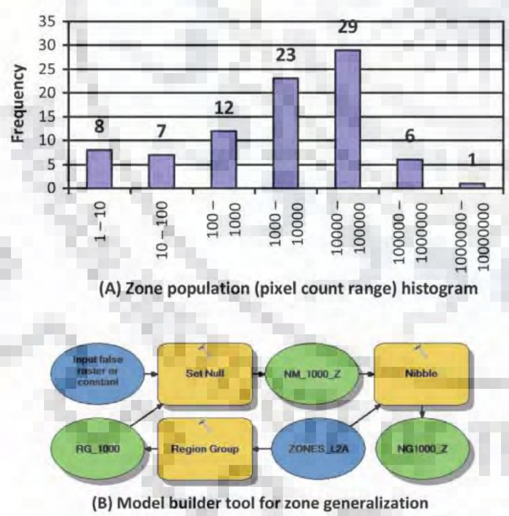

Fig. 13. Statistics and tools for zone generalization.

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PAPER 2

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Assessing Thermal Behaviour of LULC from Micro-Meteorological Measurements

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Abstract—**Methods adopted in the investigation of Urban Heat Island (UHI) depend upon the spatial extent of study area and the factors considered in the assessment. The choice of equipment, tools and techniques used in the study, depends upon the method adopted. This paper reports the assessment of thermal behavior of various land use / land cover (LULC) pockets in an educational campus. Documentation of land cover in terms of Built-up: Paved: Vegetation (B:P:V) area ratio for 10 selected sites is carried out; before conducting a mobile (instantaneous) survey through predetermined route and diurnal (as well as seasonal) surveys at each site to record meteorological measurements. A causal relationship has been established between climatic parameters and land use/land cover type. The 3d structure of land cover is observed to be as much responsible for the thermal behavior as its B: P: V proportion.**

Keywords*- *Thermal Environment, Educational Campus, UHI, Micro-Meteorological Measurements, Field Surveys

I. Urban Heat Islands in Educational Campuses

Increase in population and urbanization is leading to the setting up of new educational institutions as well as increase in intake capacity of existing institutional campuses in India. Some of the existing institutional campuses are as old as 150 years, for example IIT Roorkee (formerly University of Roorkee). Few historical heritage buildings are still in use in these campuses, others have been demolished for accommodating new facilities (often taller structure than the buildings they replaced) required for facilitating quality education to the increased population it is supposed to cater. Re-densification is a common strategy available in these campuses.

The open spaces are also under pressure for conversion into built-up areas, apart from the aforementioned redevelopment of old buildings. The institutional population and buildings to house them are growing, whereas land owned by these institutions is not, reason being the dense development they have already attracted all around their periphery.

The choice between redevelopment (brown field development) and conversion of green open spaces (green field development) within the campus is also having a bearing on the ambient thermal environment. Open green spaces including ground cover and trees are being replaced by not only buildings but also impervious surfaces like asphalt and concrete paving. Reason for this transformation is increase in users of motorized vehicles, which in turn leads to increased parking space and metal-road width. Potential higher aesthetic value without need for cleaning & maintenance are also leading decision makers to opt for hardscape surfaces.

Firstly, the surface transformation causes retention of heat gained from solar radiation during the day, which is reradiated during the night further delaying reduction in ambient thermal stress [1].

Secondly, the surface transformation causes quick water runoff leading to reduction in retention capacity and ground water recharge. The reduced ground water further decreases the life of naturally growing vegetation ground cover in the vicinity. The prolonged moisture content even in bare soil would have otherwise helped by conversion of sensible heat gained by solar radiation into latent heat [2].

Studies have shown that nearly half of the operational energy in institutional buildings is consumed to achieve thermal comfort [3]. Due to the aforementioned delayed recuperation from heat gain, as well as a tendency to avoid un-shaded harsh outdoor environment, the energy requirement for achieving indoor thermal comfort seems to have increased. This can be summarized as a creation of urban microclimate.

II. Assessment Methods

Sahu et al. [4] enumerate the following objectives of UHI investigations: examining existence of UHI, determining intensity of UHI and establishing relationship of land use/land cover with UHI intensity. They observe that the methodologies employed in various investigations since 1810 have been dependant on the objective and have evolved with resource availability. The investigation methods can be broadly classified into following three categories; Comparison between Meteorological data from rural and urban weather stations [5] [6] [7] [8] [9] [10] [11], Field Measurements at various LULC stations [9] [12] [13] [14] and transects [7] [15] [16] [13] within study area, and Remote Sensing Measurements of larger areas [13] [17] [18] [19].

In the earliest reported UHI investigations only air temperature measurements from two or more meteorological stations located few kilometers apart were compared. The field survey investigation used to compare either diurnal & seasonal variation in meteorological observation at discrete LULC pockets; or instantaneous variation in meteorological observations taken at specific time interval along a short travel route (within 1 to 1.5 hour) passing through various LULC pockets. The availability of medium and high resolution, multispectral-thermal and panchromatic satellite data respectively has enabled recent investigations over large contiguous areas. The techniques of delineating LULC as well as surface temperatures using remote sensing images are being regularly used in UHI investigations. Use of more than one methodology has been reported in various investigations from validation and causal relationships point of view. Some studies also use Sky View Factor (SVF) to resolve the thermal behavior of various LULC [14] [11].

This paper reports the UHI investigations carried out to assimilate the influence of important aspects of surface-plant-air interaction, using the methodologies in predetermined sequence. The data collection has been divided into several sub-areas of study in order to provide focused efforts as follows:

- Step 1 – Identify & document observation sites in select land use with select land cover & sky view factor
- Step 2 – Mobile instantaneous field survey for analysis of variation in air temperature w.r.t. LULC
- Step 3 – Diurnal and seasonal field survey for trend analysis interpretation of results according to the LULC & SVF

The reported field survey is initiated though a post graduate dissertation as part of a funded project wherein repeat surveys are planned to corroborate the research findings.

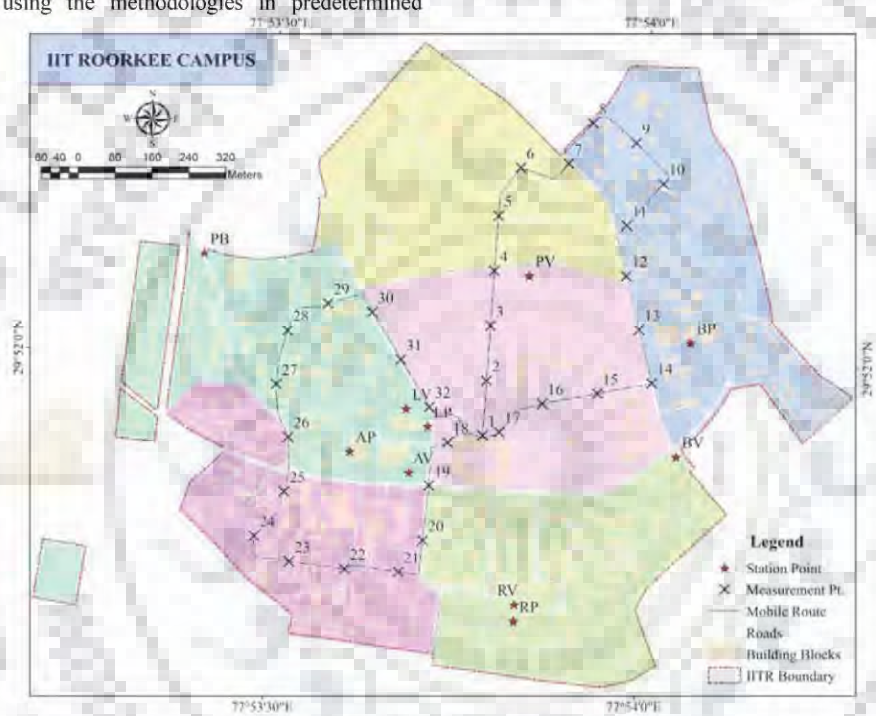


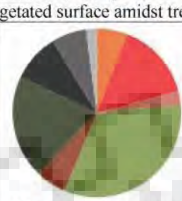
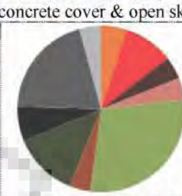
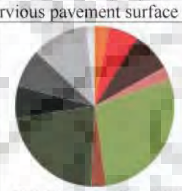
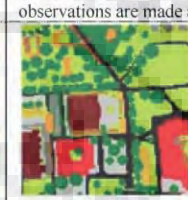
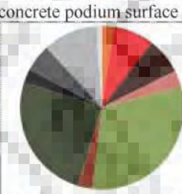
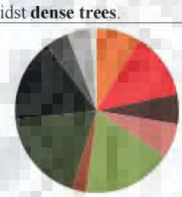
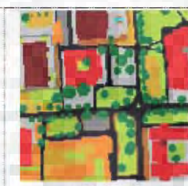
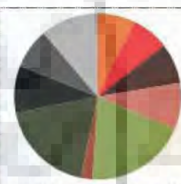
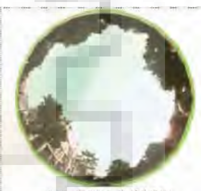
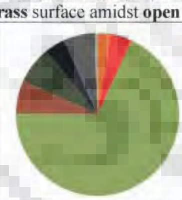
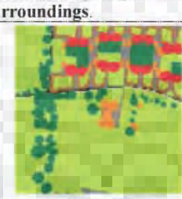
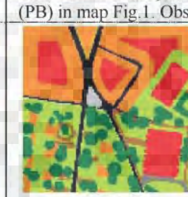
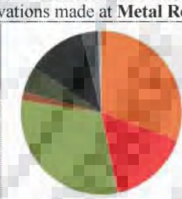
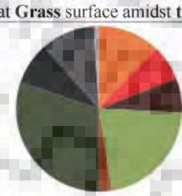
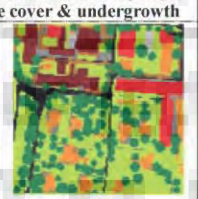
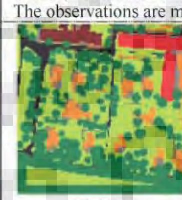
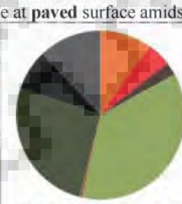
Figure 1. Locatoin Plan of Mobile Survey Route and Observation Sites

III. Identification and Documentation of Observation Stations

State of the art review of literature has identified field survey as mainstay research method for the spatial-temporal analysis of UHI. Identifying study area is crucial to carry out meaningful research. IIT Roorkee is adopted as case study area due to easy proximity and identification of pockets for study. This decision has also provided an opportunity to the research team to revisit site location easily. Also there have been significant surface transformations in the recent years, within the Indian Institute of Technology Roorkee campus. This justifies the selection of the IITR Campus as a representative of the many Indian campuses undergoing densification. Recently various impervious surfaces are added extensively at the newly constructed sites. However, as landscaped pockets are rather common in the Campus, both surface typologies (urban & rural) are available till date.

In this research, 10 locations have been identified for comparing the effects of newly installed impervious surfaces & taller buildings vis-a-vis the existing soft-landscaped surfaces & vegetation on the ambient thermal environment. Spatial data of LULC apart from micro-meteorological measurements has been collected from the 10 sites. The stations identified for diurnal and seasonal meteorological measurements are shown in Figure 1 as two-letter alphabetical abbreviated names. Table I lists the dates of diurnal and seasonal survey along with details of individual observation station, documented using LULC Maps, B: P: V ratio and fish eye photographs.

TABLE I. DOCUMENTATION OF OBSERVATION SITES AFTER [20]

NAME OF RURAL SITE [Autumn Dates] [Winter Dates] [Summer Dates]			NAME OF URBAN SITE [Autumn Dates] [Winter Dates] [Summer Dates]		
Sky View Factor (Photo)	***B: P: V Ratio***	***Use & Land Cover Map***	***Use & Land Cover Map***	***B: P: V Ratio***	***Sky View Factor (Photo)***
Jawahar Bhawan (BV) [26 & 27/09/13] [4 & 5/01/2014] [2 & 3/05/2014] Jawahar Bhavan site is described as (BV) in location map Fig.1. The observations are made at vegetated surface amidst tree cover.			**Kasturba Bhawan (BP) [26 & 27/09/13] [4 & 5/01/2014] [2 & 3/05/2014]** Kasturba Bhaven site is described as (BP) in location map Fig.1. The observations are made at concrete cover & open sky. Ref. ULC map and SVF		
					
BV_SVF _0.4545	B:P:V = 1 : 0.86 : 2.94	BV_ULC	BP_ULC	B:P:V = 1 : 1.64 : 2.63	BP_SVF _0.7991
MGCL Parking (LV) [27 & 28/09/13] [5 & 6/01/2014] [3 & 4/05/2014] MGCL Parking site is described as (LV) in location map Fig.1. The observations are made at pervious pavement surface amidst tree cover .			**MGCL Podium (LP) [27 & 28/09/13] [5 & 6/01/2014] [3 & 4/05/2014]** MGCL Podium site is described as (LP) in location map Fig.1. The observations are made at concrete podium surface under open sky near glazing.		
					
LV_SVF _0.1776	B:P:V = 1 : 1.62 : 3.29	LV_ULC	LP_ULC	B:P:V = 1 : 1.12 : 3.54	LP_SVF _0.6800
DOMS Front Lawn (AV) [28 & 29/09/13] [7 & 8/01/2014] [5 & 6/05/2014] DOMS Lawn site is described as AV in location map Fig.1. The observations are made at **grass cover** amidst **dense trees**.			**LHC Parking (AP) [28 & 29/09/13] [7 & 8/01/2014] [5 & 6/05/2014]** _site is described as () in location map Fig.1. The observations are made at surface amidst _		
					
AV_SVF _0.2795	B:P:V = 1 : 0.96 : 1.65	AV_ULC	AP_ULC	B:P:V = 1 : 1.25 : 2.20	AP_SVF_0.8227
Saraswati Temple (PV) [29 & 30/09/13] [8 & 9/01/2014] [6 & 7/05/2014] 'Saraswati Temple' site is described as (PV) in location map Fig.1. The observations are made at **Grass** surface amidst **open surroundings**.			**Century Gate (PB) [29 & 30/09/13] [8 & 9/01/2014] [6 & 7/05/2014]** This site is a campus entrance towards off-campus development described as (PB) in map Fig.1. Observations made at **Metal Road** amidst **sparse trees**.		
					
PV_SVF _0.6538	B:P:V = 1 : 1.58 : 12.01	PV_ULC	PB_ULC	B:P:V = 1 : 0.33 : 0.81	PB_SVF _0.3353
Resi. Front Lawn (RV) [30/09 & 1/10/13] [9 & 10/01/2014] [7 & 8/05/2014] 'Faculty Residance front lawn' site is described as (RV) in location map Fig.1. The observations are made at **Grass** surface amidst **tree cover & undergrowth**			**Resi. Rear Court (RP) [30/09 & 1/10/13] [9 & 10/01/2014] [7 & 8/05/2014]** 'Faculty Residance rear court' site is described as (RP) in location map Fig.1. The observations are made at **paved** surface amidst **tree cover**		
					
RV_SVF _0.4716	B:P:V = 1 : 0.76 : 2.11	RV_ULC	RP_ULC	B:P:V = 1 : 1.16 : 3.71	RP_SVF _0.3660

Legend ■ Low Rise buildings ■ Mid Rise Buildings ■ High Rise Buildings ■ Barren Land ■ Grass Cover ■ Shrubs ■ Trees ■ Metal Road ■ Concrete Cover ■ Impervious Pavments ■ Semi-Pervious Pavements ■ Water

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A. (Land) Use and Land Cover

The selected locations include various land use types viz. Academic, Public, Single family (faculty) residential, Multi-unit residential (hostel), Transport (entrance portal), Religious and Recreational. Care has also been taken to include variety of land cover types available in the institute. The ratio of proportions between land cover classes in the source area of a observation station determine the local energy balance and thus the measured parameters [21]. According to Stewart, I., & Oke, T. [22] an area of 250 × 250 meters surrounding the instrument location is considered as effective source area for a weather station. Accordingly, individual land cover (ULC) maps measuring 250 × 250 meters around the selected observation stations are documented based on visual survey. A plan with a 2.5 × 2.5 meters resolution grid overlay is used to classify the LULC using color code on a hardcopy template during physical site visit. Table II lists typical surfaces grouped under three classes viz. Build-up, Pavement and Vegetation.

TABLE II. LIST OF SURFACES DOCUMENTED AND CLASSIFIED FOR CALCULATION OF B: P: V PROPORTIONS

Built-up Surfaces	Paved Surfaces	Vegetated Surfaces
Low Rise buildings	Metal Road	Barren Land
Mid Rise Buildings	Concrete Cover	Grass Cover
High Rise Buildings	Impervious Pavements	Shrubs
	Semi-Pervious Pavements	Trees
		Water

B. Calculation of B:P:V ratio and Land Cover Index

Using the individual station ULC maps, area for each surface type is tabulated separately and class wise sum is used to calculate B: P: V ratio. Wong et al [16] had used B:P:V to represent the proportionate area of paved and vegetated space against the Built-up area represented as 1; within individual zones identified within the NUS Kent Ridge Campus. Land Cover Index represents the same areas as proportionate shares of unit area.

In this research the calculations for 'B: P: V' ratio and LC index of individual station source area have been done using AutoCAD and MS Excel.

C. Sky View Factor

Exposure of the observation station to and its radiation exchange with the sky plays a vital role in the energy flux as demonstrated in various studies [14] [11] [23]. It was necessary to document the 3d land cover structure of the observation stations while comparing the observed meteorological parameters. Sky View Factor (SVF) is a dimensionless indicator describing proportionate area of visible sky without the area covered by surrounding urban structures. Souza et al [24] proposed a method for automated calculation of SVF to reduce the time required using other methods for instance, mathematical models, fisheye-lens photographs analysis, image processing, diagrams or graphical determination. In this research fisheye-lens photographs taken from 1m above ground have been used to calculate SVF for comparison. These photographs have been taken using the Plant Canopy Imager CI110 (CID Bioscience make), to document 3D structure of LULC of individual observation stations.

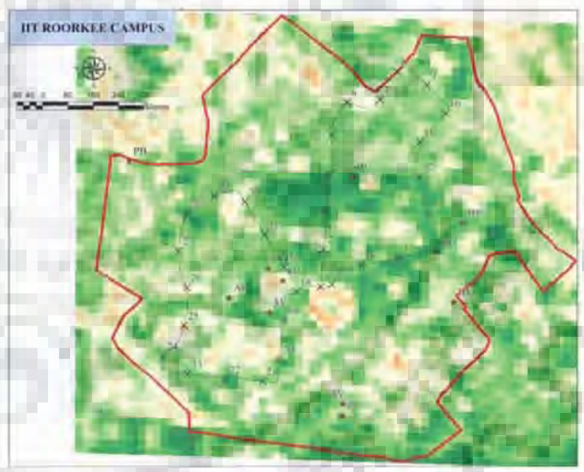
D. Normalized Differential Vegetative Index

Various researchers [13] [17] [18] [19] have used Normalized Difference Vegetation Index (NDVI) in the study of temporal growth of urbanization resulting in depletion of vegetation cover and variation in Land Surface Temperatures (LST). To differentiate between intensity of vegetated & built-up pockets in the study area, NDVI has been calculated for the IITR campus using LISS III image procured on 5th May 2012. NDVI is derived from multispectral remote sensing images, by calculating the ratio between the reflectance measured in the red and near infrared bands using the following formula [18]:

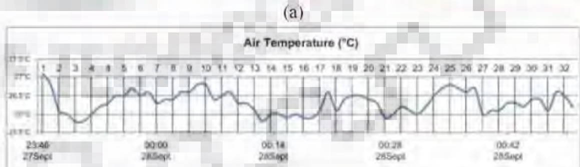
$$NDVI = (R_{NIR} - R_{red}) \div (R_{NIR} + R_{red})$$

IV. MOBILE INSTANTANEOUS SURVEY

Studies say that nocturnal UHI intensity is independent of solar irradiation and hence clearly dependent on the Land Use Land Cover characteristics [25]. Accordingly, mobile survey has been conducted in autumn season on a calm night around midnight of 27/09/2013. The mobile survey route is shown as dotted line superimposed on the NDVI map of IIT Roorkee Campus in Figure 2 (a). Serially numbered points are also marked on this route at 2 minute intervals for comparison with the trend of recorded T_a shown in Figure 2 (b). The route is, identified in two closed loops so as to cover most land use land covers in the campus.



(a)



(b)

Figure 2. Mobile Survey (a) Route super imposed on NDVI map (b) Air Temperature potted against points at 2 minuites interval After [20]

A. Parameters and Instruments used in Mobile Survey

As listed in Table III, air temperature (T_a) and relative humidity (RH) are recorded during the Mobile survey using calibrated instruments.

TABLE III. PARAMETERS MEASURED IN MOBILE SURVEY

Instrument Used	Parameter Measured	Accuracy
Digital Thermo hygrometer: Sika Make Model: MH-3350 (Made in Germany)	*Air Temperature (Ta)*	*±0.5 ° C*
	Relative Humidity	*±2% RH linearity, ±1% RH hysteresis*

B. Discussion of Temperature Trend with LULC

A temperature difference of 1.5 deg C has been recorded during the mobile survey ranging from a minimum of 25.6°C to a maximum of 27°C. Point wise comparison of Figure 2 (a) and (b) shows that the NDVI is in higher range (green) between points 3 &4 which lie in the heart of recreational open space; the T_a observed between these points is also the lowest. Point No. 25 lies amidst high-rise residential buildings, which is why the NDVI is in a lower range (orange); T_a trend at this point is on the higher side.

V. DIURNAL AND SEASONAL FIELD SURVEY

The diurnal field survey has been conducted in three seasons; dates on which observations are recorded at a particular station are listed besides name of Rural/Urban station in Table 1. The meteorological parameters have been recorded at every 30 min interval, for 24 hours at each station. For instance at the first station, recording started at 10:00 hrs on Day 1 and stopping at 9:30 hrs on Day 2. While at the consequent station, recording started around 10:30 hrs on Day 2 and stopping around 10:00 hrs on Day 3. Sometimes, there has been a gap between the readings, due to time lost in transport of instruments between stations.

A. Parameters and Instruments used in diurnal survey

Two sets of Portable Weather Data loggers have been used to cover 10 stations of diurnal field survey. Two sites each in the 5 land use groups have been observed on 5 consecutive days in three seasons viz. autumn, winter and summer.

TABLE IV. PARAMETERS MEASURED IN DIURNAL SURVEY

Instrument Used	Parameter Measured	Accuracy
Portable Weather Data logger (PWS) Nova Lynx make Model No. WS100 (Made in USA)	*Air Temperature (Ta)*	*±0.5 ° F*
	Relative Humidity	*±3% (10-90%)*
	Wind Speed (WS)	*±1mph*
	Direction (WD)	*±3%*
	Solar Radiation (SR)	*±5%*

All five sensors listed in Table IV, are connected to a data logger for recording the measurements; which are then downloaded after every seasonal survey, to a Desktop PC at Climatology Laboratory for analysis in MS Excel.

B. Reference Boundary Layer Conditions for diurnal survey

The measurements from both the portable weather stations are plotted along with measurement of Boundary Layer condition obtained from Automatic Weather Station (AWS) located on the edge of the study area at National Institute of Hydrology Roorkee.

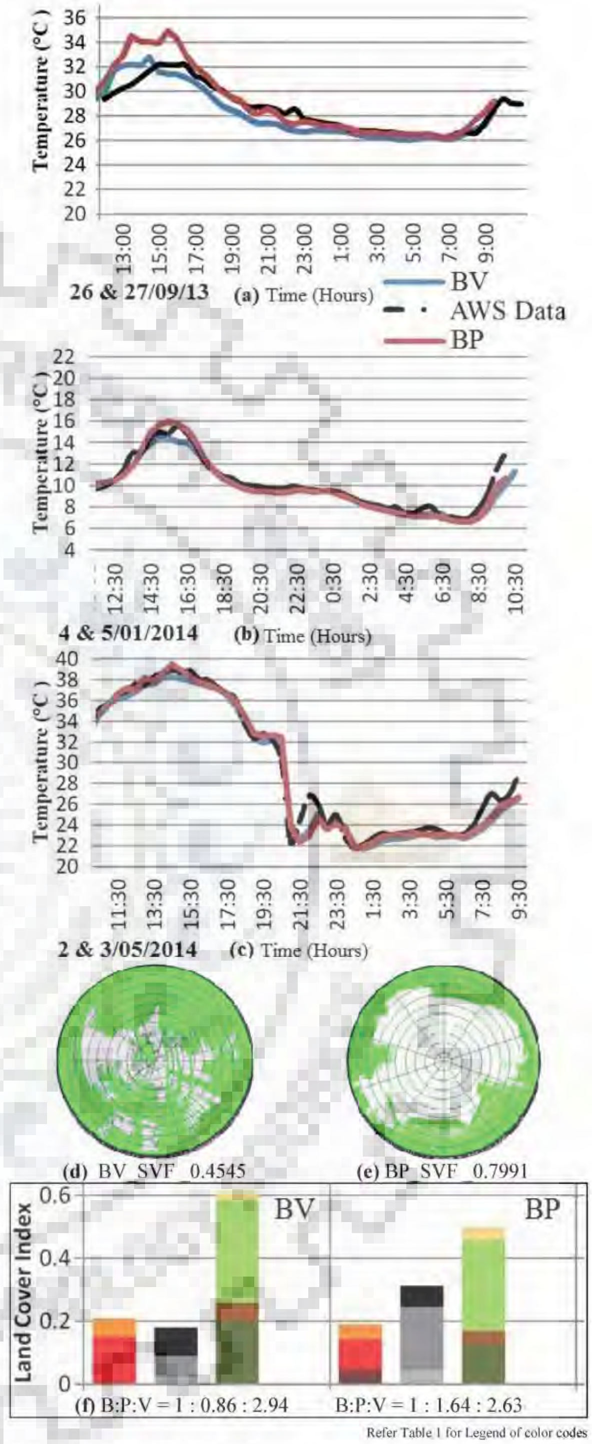


Figure 3. Land Use Group1 Comparative: (a) T_a Autumn, (b) T_a Winter, (c) T_a Summer, (d) SVF of BV, (e) SVF of BP (f) B: P: V graphs.

C. Discusson of Diurnal & Seasonal trend of Temperarture and humidity across LULC

Sahu [20] has compared diurnal trends of Ta, RH and SR recorded using two PWS (located at 5 stations each) and one AWS, season wise across all sites. In this paper the comparison of diurnal trends of Ta recorded by the three aforementioned instruments is presented, land use group wise (pair of stations) across seasons, in relation to the variation in SVF.

1) Land Use Group 1 – Residential (Hostel): Jawahar Bhavan (BV) and Kasturba Bhavan (BP)

Stations BV and BP are located besides hostels for boys and girls respectively, which represent the multi-unit residential land use. The land cover at station BV is grass cover under sparse trees, where as that for BP is open to sky concrete cover. Figure 3(a), 3(b) and 3(c) show the T_a trends for autumn, winter and summer respectively at land use group 1. Figure 3(d) and 3(e) show the images of SVF which is 0.4545 and 0.7991 for BV and BP respectively. Figure 3(f) shows the land cover index of areas under B:P:V respectively. As seen from Figure 3(a) in autumn, the daytime difference between T_{ar} at BV & T_{au} at BP i.e. $\Delta T_{a\,(u\text{-}r)}$ is approximately 4 deg C. However if we cross check the daytime $\Delta T_{a\,(u\text{-}r)}$ for other two seasons, we find that its magnitude as well as duration is less than half of that in autumn. The reasons for this variable thermal behavior may be attributed to seasonal variation in soil moisture and vegetation. Station BV is at a low laying area and receives a lot of surface runoff which stagnates in the grass cover here during and after rainy season. However, in contrast station BP does not retain moisture in any season. The over growth of grass cover also increases due to abundant soil moisture in the month of September (autumn season), this increases cooling from evapo-transpiration. Whereas, in the other two seasons the grass cover is less abundant due to lowering of soil moisture content.

2) Land Use Group 2 – Assembly (Library): MGCL Parking (LV) & MGCL Podium (LP)

Stations LV and LP are located in the vicinity of the MG Central Library building. LV is located in the north setback at the tree covered flowerbed besides the parking lot, while LP is located at the open to sky, stone paved podium besides the east facing glazed façade. Since both the stations are located close together, as seen from Figure 4(f) the B:P:V ratios are similar 1:1.62:3.29 & 1:1.12:3.54 respectively. As seen from Figure 4(a), 4(b) & 4(c) the daily morning $\Delta T_{a\,(u\text{-}r)}$ is around 3 deg C. This phenomenon seems to be caused due to the eastern solar radiation being reflected toward the station from the glazed façade; especially during summer the T_a trend starts increasing as early as 7 am with sunrise. Detailed analysis of Figure 4(c) also shows that T_a at LV frequently remains below the boundary layer throughout the year as it is located on the north side of the library building and has a low SVF.

Figure 4(b) shows night time $\Delta T_{a\,(u\text{-}r)}$ is approximately -1 deg C. This happens as a result of fast radiation as well as convective cooling at LP, due to its higher sky view factor of 0.6800, as compared to that of 0.1776 at LV.

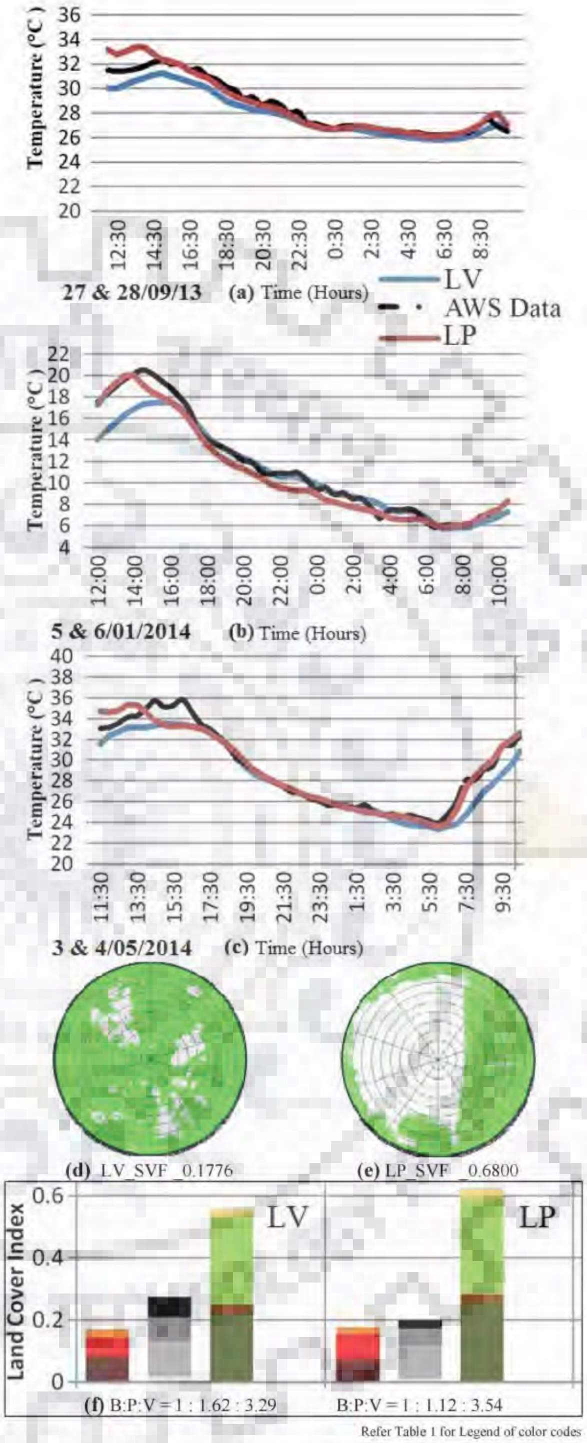


Figure 4. Land Use Group2 Comparative: (a) T_a Autumn, (b) T_a Winter, (c) T_a Summer, (d) SVF of LV, (e) SVF of LP (f) B: P: V graphs.

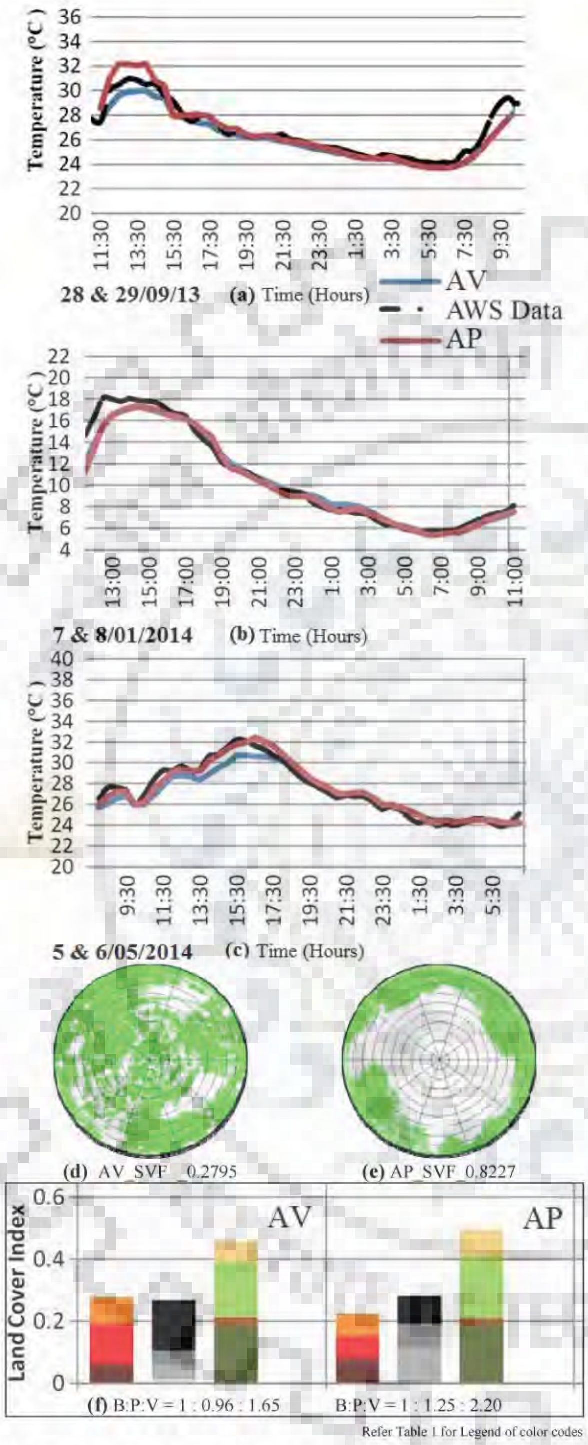


Figure 5. Land Use Group3 Comparative: (a) T_a Autumn, (b) T_a Winter, (c) T_a Summer, (d) SVF of AV, (e) SVF of AP (f) B: P: V graphs.

3) Land Use Group 3 – Academic (Department): DOMS Front Lawn (AV) & LHC Parking (AP)

Surroundings of academic departments are either landscaped or used as paved parking lots. In this land use group station AV is located at the south side lawn of Department of Management Studies (DoMS) building, under tree cover. Station AP is located at the open to sky, paved parking lot on the west side of Lecture Hall Complex (LHC). The SVF at AV is 0.2795 and that at AP is 0.8277as shown in Figure 5(d) & 5(e) respectively. Both the stations have similar B:P:V ratio and the land cover are almost equally divided between vegetation and non-vegetated spaces. Figures 5(a), 5(b) and 5(c) show T_a at both stations generally following the boundary layer trend, except for Figure 5(c) shows lower T_a at AV during late afternoon in summer due to prolonged shading.

4) Land Use Group 4 – Amenities: Saraswati Temple (PV) and Century Gate (PB)

Station PV is located on the west side of a religious building and is surrounded by recreational land use on three sides, low rise residential land use is located across the road towards the north. As seen from ULC map in Table 1 and Figure 1, station PB is located under a canopy and tree cover, besides the northwest campus entrance abutting the auditorium building and a densely built-up area. Figure 6(a), 6(b) and 6(c) show the T_a trends of three seasons at land use group 4, while Figure 6(d) and 6(e) show the LULC maps for PV and PB respectively, Figure 6(f) shows the stark contrast in the areas of land covers around stations PV and PB in terms of B:P:V ratios. PV has the highest proportion of Vegetated surface, where as PB has the highest proportion of Built-up surface among the 10 observation stations. However when we analyze the daytime difference between T_{ar} at PV & T_{au} at PB i.e. $\Delta T_{a(u-r)}$, for autumn and winter seasons, we find that its magnitude is very low. Moreover Figure 6(c) shows that in summer season, during daytime $\Delta T_{a\,(u-r)} \approx$ -2 deg C (negative), while in the night time $\Delta T_{a\,(u-r)} \approx$ +2 deg C. The Negative summer season day time $\Delta T_{a\,(u-r)}$ can be attributed to the scarcity of Tree cover at Station PV (SVF 0.6538) as compared to dense tree and canopy cover at Station PB (SVF 0.3353). Even in areas with grass cover, the absence of wind, tree cover, draught in irrigation and exposure to solar radiation from the open south can cause rise in T_a. This dependency of thermal behavior on vegetation structure has been well exploited in the Biotope Area Factor (BAF) described by Bauen [26]. Vegetation with higher leaf area and connectivity to soil provide better ecological services and hence are given higher weightage in the BAF methodology.

5) Land Use Group 5 – Residential (Single Family): Faculty Residence Front Lawn (RV) & Rear Court (RP)

Single family faculty residences are located with their own compound and the land cover within the compound varies from residence to residence and with public or private use of the space. Two such spaces were chosen in one compound. One of the stations RV was located at an overgrown garden in the front of the residence facing north. Another station RP was located at the open to sky paved rear court to the south of the residence. As shown in Figure 7(d) and 7(e) the SVF from both

The obstruction to wind movement due to tall dense vegetation and high compound walls caused a peculiar thermal behavior at this station. In Figure 7(c) the temperature range is higher than boundary layer condition. Day time T_a is higher than and night time T_a is lower than boundary layer conditions.

VI. CONCLUSION

As discussed in the previous section different reasons cause variation in $\Delta T_{a\,(u\text{-}r)}$ namely; seasonal decrease in T_{ar} due to post monsoon water-logging, complete shade from solar radiation due to excess building and tree cover, complete exposure to solar radiation due to absence of tree cover, high humidity from evapo-transpiration due to obstruction to wind movement within dense vegetation cover.

The higher proportion of unpaved vegetated and open spaces do not guarantee cooler environment. A lot is dependent on the availability of shade and soil moisture as well. For UHI studies the measurement of soil moisture, and spatial mapping of SVF is also required along with meteorological parameters and B: P: V based LULC documentation, as it will help explain observed phenomenon in detail. NDVI is a useful method for documenting various densities of greenery but it is also season specific and thus needs adaptation to account for annual variation in vegetation density. Further research to overcome these and other limitations of this project is underway.

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PAPER 3

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analysis

URBAN HEAT ISLAND INVESTIGATION: TECHNIQUES AND METHODS SO FAR

Study of Urban Heat Island is an important tool for urban designers/ planners. The methodology for the UHI study has evolved with time and very much contextual

Empathizing Urban Heat Island

Urbanization is the result of increasing population in the cities requiring more land for dwelling; causing natural land to be metamorphosed into urban areas. There is incessant use of concrete and other building materials for the construction of buildings and roads. The use of building materials with low reflectance and absence of pervious surfaces is responsible for the changing conditions. It is observed that the temperature of the region where there is more human intervention to the natural set up is more. This phenomenon in which there is a temperature difference between an urban and the surrounding rural area is called Urban Heat Island (UHI) . In other words, it can be said that transformation of the natural surface causes the rise in temperature. This rise in temperature increases with the extent of anthropogenic activities and transformation in the surface. Thereby there is a change in the weather condition of area which is more urbanized. Increase in temperature and other climatic parameters cause undesired consequences.

UHI causes increased energy consumption for artificially creating soothing environment. More energy in the form of electricity is required. Moreover, the use of electrical appliances for creating artificial comfort is actually degrading the atmosphere and causing temperature to boost up. This exploits the natural resources. It also elevates emission of air pollutants and green house gases that causes problems to human health and comfort. All this is the root cause of the upcoming issue of climate change. Increase in temperature marked by investigation of UHI is strongest significant parameter to examine the same.

UHI in the atmosphere are classified into three types depending on height of the layer in which they are found. The surface heat island refers to the warming of Surface Layer. Above this layer lies the canopy layer, warming of which is known as Canopy Layer Heat Island. There is another type which is warming up of the layer lying above the canopy layer. This type is known as Boundary Layer Heat Island. It is the canopy layer heat island which is investigated the most. This is because; the canopy layer height is the average building height. Also the major human activities take place in this layer hence it is solely for the human comfort/discomfort. Surface layer heat island has also been tested by measuring the temperature of the surface in various studies. The investigation of these various types of heat islands differs in use of techniques and instruments depending on the objectives like examining the existence of UHI, finding the intensity of UHI or to find out relation between land use/land cover and the surface temperature. The investigation of UHI has been done in many countries including India. It has been studied for various metropolitan cities like Delhi and NCR (Mohan et.al. 2011 and 2012), Chennai (Rose, L., Devdas, M., 2008), Visakhapatnam (Devi, S. 2006), Pune (Patki, P. Alange, P., 2006) etc.

Methodologies for Studying Urban Heat Island

Differing in the objectives, several methodologies have been used to study UHI. Since 1810, when UHI was first investigated, the process has evolved, improved, modified and changed according to the objective of any specific study, requirements and resource availability. In the following sections, few of the important methodologies are discussed. The description of instruments commonly used and basic requirements of the methods are also provided. From the review of studies, it has been observed that there are three basic methods to study UHI, described below:-

1. METEOROLOGICAL WEATHER STATION DATA OF RURAL AND URBAN SITES

Recapitulation of the studies show that in initial days, when UHI was a new found phenomenon, it was examined by the comparison of two meteorological weather station's data located in the nearby urban and rural sites. The selected stations used to be few kilometers apart. In this method only air temperature was the major concern of observation. This is because initially only ambient temperature was considered as a parameter for assessing UHI. Although, when used later in times, other climatic parameters were also observed. The method is rarely used now as there are more advanced technologies in the field. But there are studies which use this method in conjunction with other methods mainly for verification of the results. The method has been used to study UHI in Chicago in 1985 by Bernice Ackerman (Ackerman, B. 1985). The author has used hourly data recorded from an official weather station and a laboratory 23 km from weather station. The recording was done for 20 years and was aimed to study diurnal and seasonal variation in UHI.

2. FIELD MEASUREMENTS

a. **Stationary Field Measurements** - In this method, an area or region is selected for analyzing UHI. The area can be as large as a whole city or as small as surrounding of a single building. Few data stations are distinguished representing all types of land uses and are chosen so as to cover the whole area. Parameters identified for assessing UHI are recorded and further processed to examine the intensity. This method is also used to establish a relation between land use/land cover and ambient temperature of the area for future use in planning. It has been used to access the nature and intensity of heat island in 2006 by Suryadevara S. Devi in Visakhapatnam (Devi, S. 2006). The data was collected through field survey. Several stations were observed in the city. The results were in the form of temperature plots on city map and isothermal maps.

b. **Mobile survey** - In this type of survey, important routes covering almost all types of land uses are identified. The selected routes are travelled by a vehicle in a slow and constant speed. The survey needs to be completed in duration of about 1 or 1.5 hours such that there is not much temperature variation in the weather. The instruments are fixed on the vehicle in a covered space such that the readings are not disturbed because of vehicular movements. The method is generally used to identify temperature relationship between various areas and create a spatial distribution map for the climatic parameters. The method has been used in a study done in Singapore (Wong, N., Yu, C. 2005). Two sessions of mobile survey were conducted to study the severity of UHI and cooling impacts of green areas at macro-level. The first survey covered a single route-west to east and aimed at finding the relation between surface temperature and land use. The second survey covered four routes: west, east, center and CBD route and aimed at finding out the island vise temperature distribution. Instruments used: - Automatic Data Loggers (Figure 3 to 5),

3. Remote Sensing

Producing Land Use and Land Cover information by satellite images is the most advanced method in this field. Satellite images from satellites for specific date are acquired and processed further to achieve the surface temperature information. The method involves advanced knowledge of remote sensing technology. A study done in China used ASTER satellite image for UHI prediction (Li, K., Lin, B., Jiang, D.2012). The aim was to use remote sensing technology for urban planning approach and to finalize revision plans to be used for future projects. Two satellite images were taken, one was medium and the other was high resolution image. The purpose of medium resolution image was to deduce certain indices of underlying surface (surface temperature index and, vegetation index) to obtain characteristics and heat environment of the community. High resolution image was to analyze land use, surface classification, landform characteristics of planning and its influence upon UHI combined with results of low resolution image. Tools and techniques used in this study are remote sensing satellite images and analytical softwares.

The methods described above namely use of meteorological weather station data of rural and urban sites, field survey and remote sensing can be used individually or can be used in conjunction as per the context, requirement and objective of the study. There are studies which use two or more methods in combination for different purposes. For example, the study of UHI in Singapore in 2003 (Priyadarsini, R. et.al. 2008) uses the combination of mobile survey and remote sensing technology. The aim was to study UHI, examine key factors, possibilities of improving heat extraction rate by optimizing air flow, study

Figure 1: Automatic Weather Station

effect of geometry, material and location of air conditioners.

The data obtained from the above methods can be processed in number of ways. There are methods like comparison of climatic parameters of different study stations in order to examine the UHI intensity. There are options to analyze the data through computation and mathematical formulations. Acquired data can also be processed to be used in various modeling softwares for simulation of real world scenario into 3D models. Integration of the processed data into GIS environment is another method for producing spatial distribution maps for various climatic parameters.

Figure 2: Portable Weather Station

Instrument Details

There are some instruments commonly used by researchers to study UHI. The description and functional details of few of these are given below:

1. **AUTOMATIC WEATHER STATION (AWS)**
   The instrument is used to record data in meteorological departments and laboratories. It is fixed at a point and is used 24x7. The parameters that can be recorded are temperature, wind speed and direction, humidity, atmospheric pressure, cloud height, precipitation, solar radiation etc. The data from AWS can be downloaded in the system or can be remotely accessed via satellite. A simple automatic weather station can be seen in Figure 1. The data logger is connected to the instrument from where the data can either be downloaded online or by connecting the logger to the computer.

2. **PORTABLE WEATHER STATION**
   This instrument is used in the stationary field survey for recording data for limited number of days depending upon its battery life. Time lapse needs to be set before placing the instrument. The height of the instrument is kept according to the objective of the study. The instrument is kept in an area open to sky, sunlight and wind such that there is no obstruction to wind or heat. The data is recorded automatically via data loggers connected to the instrument which can be later downloaded through the specific softwares exclusive to the instrument manufacturers (Figure 2).

3. HANDHELD SENSORS

Hand Held Digital Thermo hygrometer

This instrument can be used for measuring air temperature, surface temperature and relative humidity. There are sensors connected to the data logger for air temperature and surface temperature separately. This instrument is generally used for the mobile survey or in the absence of Portable Weather Station. The time lapse for recording the data is set before every use (Figure 3). The sensor attached to the instrument is kept at a constant height throughout the survey.


Figure 3: Hand held Thermo hygrometer

Pyranometer

The instrument is a digital data logger (Figure 4) for recording sunshine duration and solar radiation flux density from a field view of 180 degrees. It needs to be kept perfectly horizontal to get accurate measurements.


Figure 4: Pyranometer

Digital Anemometer

The instrument is used for digital recording of wind data- Speed and direction. For sensing the direction accurately, the instrument. needs to be calibrated with North direction. Figure 5 shows a simple handheld anemometer which is used for measuring wind speed.

4. PLANT CANOPY IMAGE ANALYZER

The instrument is being used to capture wide angle plant canopy images. It also estimates Leaf Area Index (LAI) and Photosynthetically Active Radiations (PAR) which are basically a measure of ratio of area

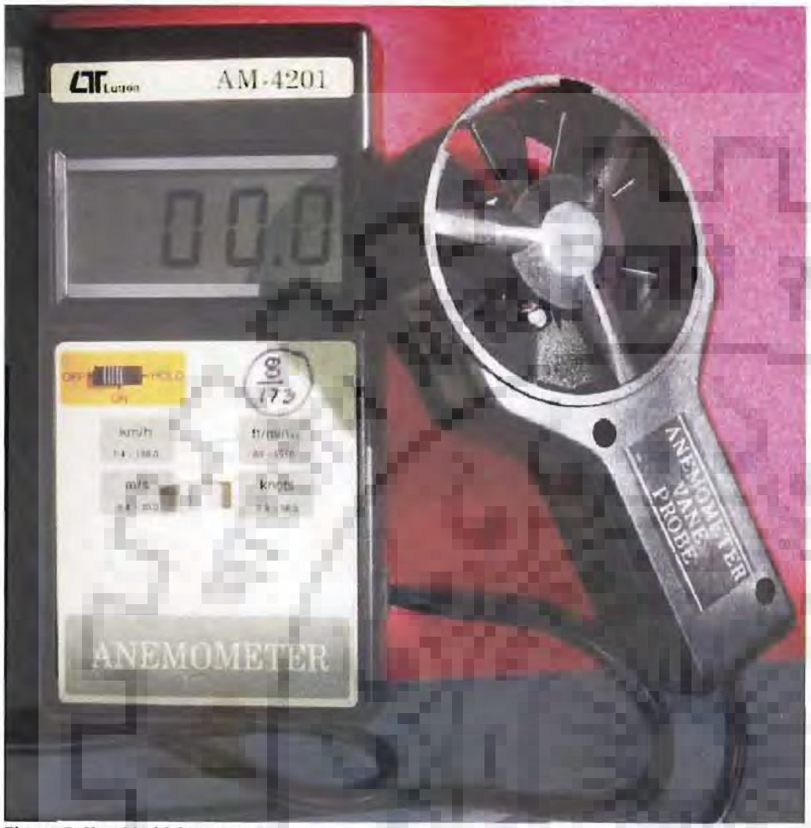

Figure 5: Hand held Anemometer

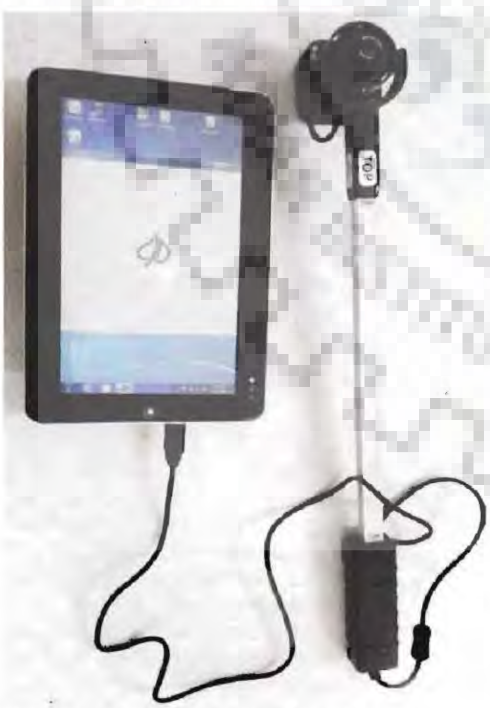

Figure 6: Fish Eye Canopy Image Analyzer

covered by leaf and sky in the present canopy. The area covered with leaf alleviates the heat island effect and hence is an important factor for mitigation of UHI. Figure 6 shows the setup of a canopy image analyzer connected to a tablet which displays the details of the canopy under observation.

Discourse

The study of UHI has been done in number of cities in India too. Cities like Delhi and NCR (Mohan et.al. 2011 and 2012), Chennai (Rose, L., Devdas, M., 2008), Visakhapatnam (Devi. S, 2006), Pune (Patki, P., Alange, P., 2006) etc have undergone the process of examining UHI by various researchers in different years. A similar study is being conducted in IIT Roorkee campus. The aim is to identify the existence and intensity of UHI. And further to find the relation between land use/land cover and ambient temperature.

Acknowledgements

The authors wish to express gratitude to Dr. Ajay Gairola, H.O.D. Centre of Excellence in Disaster Mitigation and Management. The Research Project Grant extended by Uttarakhand State Council for Science & Technology for "Surface Transformation due to Urban Dynamics in Institutional Campuses and its Environmental Impact" is thankfully acknowledged.

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Figure 7: Fish eye photograph of IIT Roorkee main building

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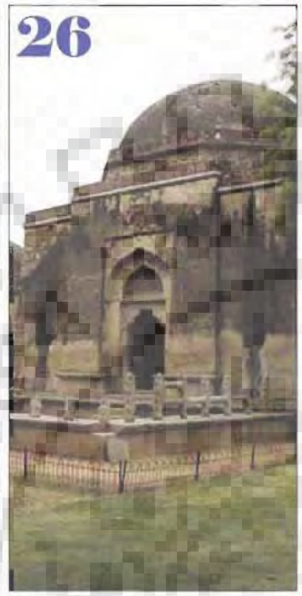

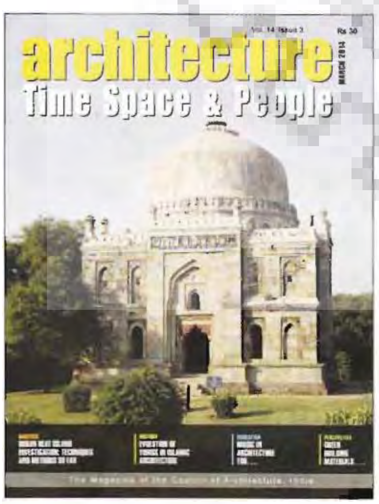

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Regulars

This issue of **Architecture Time Space & People** contains 48 pages (including the cover)

PAPER 4

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Mapping Urban Green Spaces to Identify the Potential Area for Neighbourhood Greening with Application of Urban Neighbourhood Green Index

Gaurav Vaidya, Aniruddha Subarao Pawar and Kshama Gupta

Abstract

Urban Green Spaces (UGS) have an assortment of benefits including environment benefits such as reducing city temperature during the summer months and absorbing rainwater runoff, to aesthetic benefits such as adding colour and beauty to concrete buildings. There are other social benefits like feeling of peace and happiness. An objective quantification of greenery with reference to its spatial distribution at neighbourhood level can help in identifying the critical and potential areas, which in turn can be used to identify action areas for improving the quality of green spaces since neighbourhood is an area of homogeneous characteristics and the application of greening strategies should begin from this level for effective management of UGS at city level. Hence, The Urban Neighbourhood Green Index (UNGI) was applied to 34 sectors of the New Okhla Industrial Development Authority (NOIDA), which comes under Gautam-buddha Nagar district of state of Uttar Pradesh and also part of the National Capital Region of Delhi, India. The results show an overall UNGI Average of 0.553 with a Standard Deviation of 0.17. The results of the study reveal the comparative quality & distribution of green spaces at low density and high density NH. UNGI map also assist in identifying the spatial distribution of open spaces with less or no vegetation as potential spaces for urban greening.

Keywords

Urban Green Spaces (UGS), Neighbourhood (NH), Urban Neighbourhood Green Index (UNGI), Standard Deviation (SD), Built-up density

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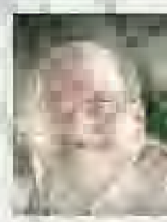

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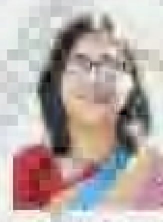

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1.0 Introduction

Post independence, India adopted a mixed economic system of development through combining socialist and capitalist approaches simultaneously with promoting development of public and private manufacturing & service sectors and because of this combine approach India exploded with rapid urbanization. Accordingly, urban areas have been recognized as engines of inclusive economic growth of country by the end of millennia and nearly 32% population of the nation started residing in urban areas (Census 2011). But rapid urbanization and developments are coming on the cost of environmental compromises due to uncontrolled and unregulated exploitation of natural resources and one of them is de-vegetation in and around the urban areas. During the initial phase of urbanization, necessity of green spaces were not considered much worthy, but with time it was realized that green spaces are an integral part of urban areas, which is essentially required for its long term sustenance.

Urban Green Spaces provides numbers of benefits including environment benefits such as reducing the impact of pollution in cities, decreasing brunt of temperature during the summer season (Baklanov et al., 2008) and increasing the infiltration of rainwater in rainy season (Arnfield, 2003), aesthetics such as adding colour and beauty to concrete buildings. The impact of UGS on the mental and physical health of the serviced population has been recorded by many researchers (Groenewegen, P.P. et al., 2006). Hence UGS is an important component of any urban area and quantity & quality of UGS is of prime concern for planners and city managers.

As per norms formulated by World Health Organization, minimum required per capita green space in urban areas should be 9.0 sq. to address the various effects of rapid urban development. But majority of the cities in India are not fulfilling this minimum requirement, apart from few cities like Gandhinagar and Chandigarh etc. In addition to amount of UGS, it is also essentially required to distribute various levels of greenness at different macro to micro settlement scales; i.e. from city to sub-city or zone to neighbourhood or community to housing block or plots (Chaudhry et al., 2011).

Neighbourhood level green spaces are coming under the primary level of vegetation for public access to UGS and hence it is essentially required to think for application of greening strategies at neighbourhood level first, before starting the large scale vegetation plan. Till date various measures and indexes are derived to determine the level of greenness like; Per Capita Green Space, Green Space to Land Ratio, Green Space Canopy Coverage Ratio, Green Index (GI), Normalized Differential Vegetation Index (NDVI), Normalized Differential Built-up Index (NDBI), Urban Neighbourhood Green Index (UNGI) etc. Most of the indices other than UNGI asses UGS primarily based on amount of UGS in an aerial unit, however UNGI developed by Gupta et al, 2012 analyses the UGS not only based on its spatial distribution but also consider vegetation as well as built up characteristics to assess the UGS. Hence, in this study the approach developed by Gupta et al, 2012 was applied to evaluate UGS in the part of NOIDA city.

2.0 Study Area

Area of interest selected for the study spans across 34 sectors (Fig-1 under Phase-I development of New Okhla Industrial Development Authority (NOIDA)) area, which is situated in Gautam Buddhanagar district of state of Uttar Pradesh, India in the Yamuna river basin between longitudes 77.29° E to 77.51° E and latitudes 28.40° N to 28.65° N. The terrain of the area is generally plain with gradual slopes varying between 0.2 to 0.1% from north-east and south-west. The maximum altitude is 204 meters above MSL, whereas most of the part of NOIDA area is below 200 m to MSL. NOIDA was constituted in the year 1976 with a view to develop an Integrated Industrial Township for the industrial growth of the area under the U.P. Industrial Area Development Act, 1976. NOIDA has now emerged as a planned, integrated, modern Industrial City, well connected to Delhi through a network of roads, national highways and the ultra - modern DND flyover, offering inter - road linkages to all parts of the country. Spread over 20,316 hectares, with many sectors fully developed, which offers a pollution free high standard of living and highly supportive industrial environment with its unique infrastructure & matchless facilities (Source: NOIDA Authority website).

NOIDA has been planned on the grid iron concept and employs state-of-the-art technology in Engineering, Urban Planning and Architecture. Significantly, it conceptualizes the needs of a fast developing city of the future. The action plan and approach compares well with international standards and is aimed at providing rapid momentum to the growth of the industrial sector both in the State of Uttar Pradesh and the Country.

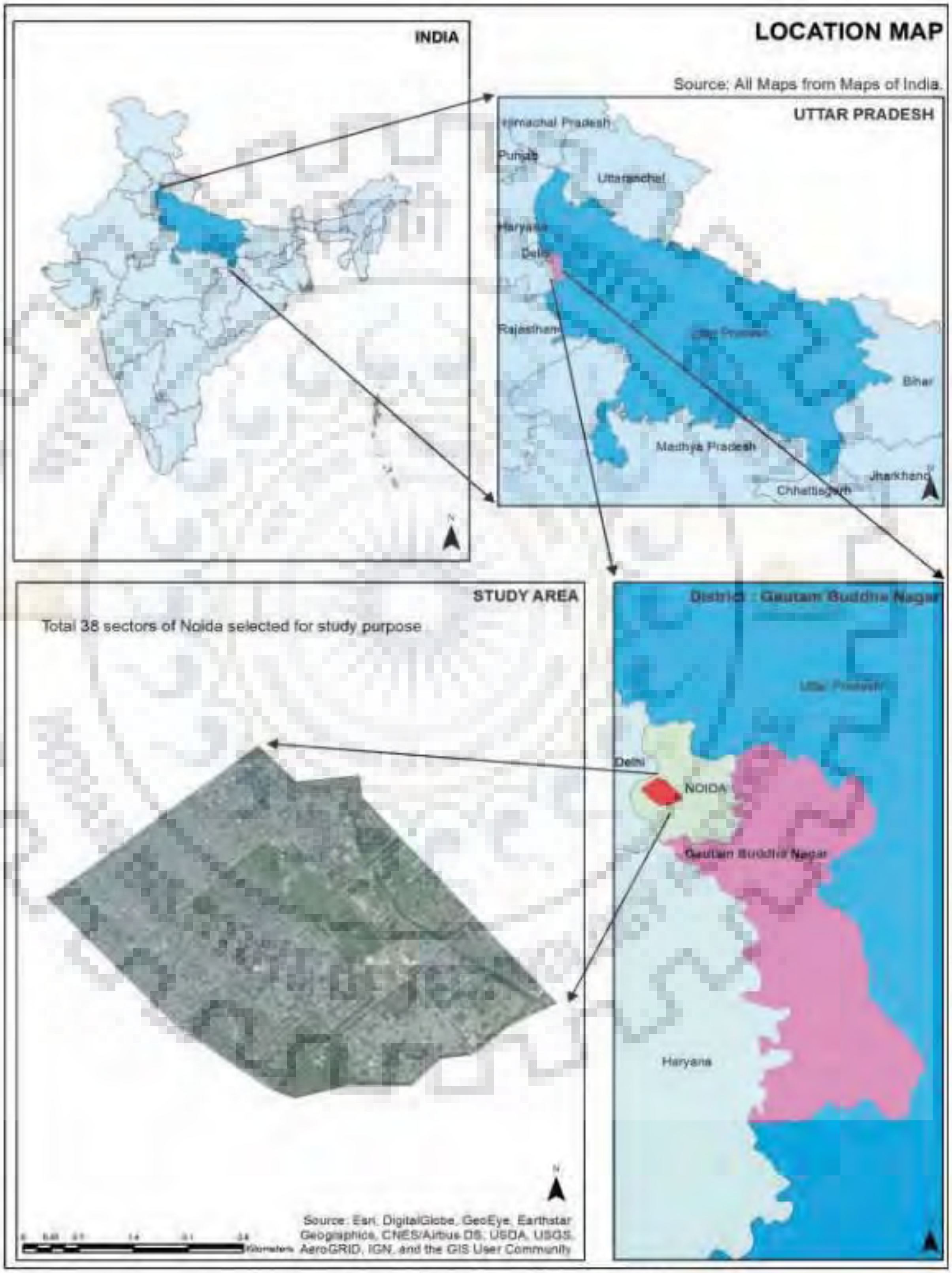

Figure 1 Location Map: Selected Sectors in NOIDA

2.1 Landuse and designated Green Spaces in Study Area

The area has two distinct types of land utilization pattern. First the planned integrated industrial township of NOIDA wherein the major industrial sectors were developed in three phases namely, Industrial Area Phase-I, Phase-II and Phase-III. The residential commercial, recreational institutional and other urban use areas have also been developed in large part of township is in the form of sectors (Figure 2). The current status of landuse distribution as per NOIDA Master Plan-2021 for Developed area (in hectares) is shown is Table-1.

Three well maintained green recreational areas have been developed, one as a recreational area along the river Yamuna, located opposite sectors 14A, 15A and 16A, another as city level green area in sector 54 and the third as the golf ground located in sector 38. Other than the above, more large recreational/ green areas are to be developed in sector 38A, one opposite sectors 28, 29, 37 & 44 and the other as sports complex is in sector 21A (Source: NOIDA Master Plan 2021). Though

Table 1 Existing and Proposed Land-use distribution as per NOIDA Master Plan-2021 (in hectares)

Land Use Distribution	As on 2011	% Share	Expected by 2021	% Share
Residential	3672	47.14	5334	38.53
Commercial	431	5.53	564	4.07
Public & Semi-public	985	12.65	1219	8.81
Industrial	1224	15.71	3001	21.68
Recreational & Green	536	6.88	1513	10.93
Transportation	941	12.08	2211	15.97
Total Developed area	7789	100	13842	100.00

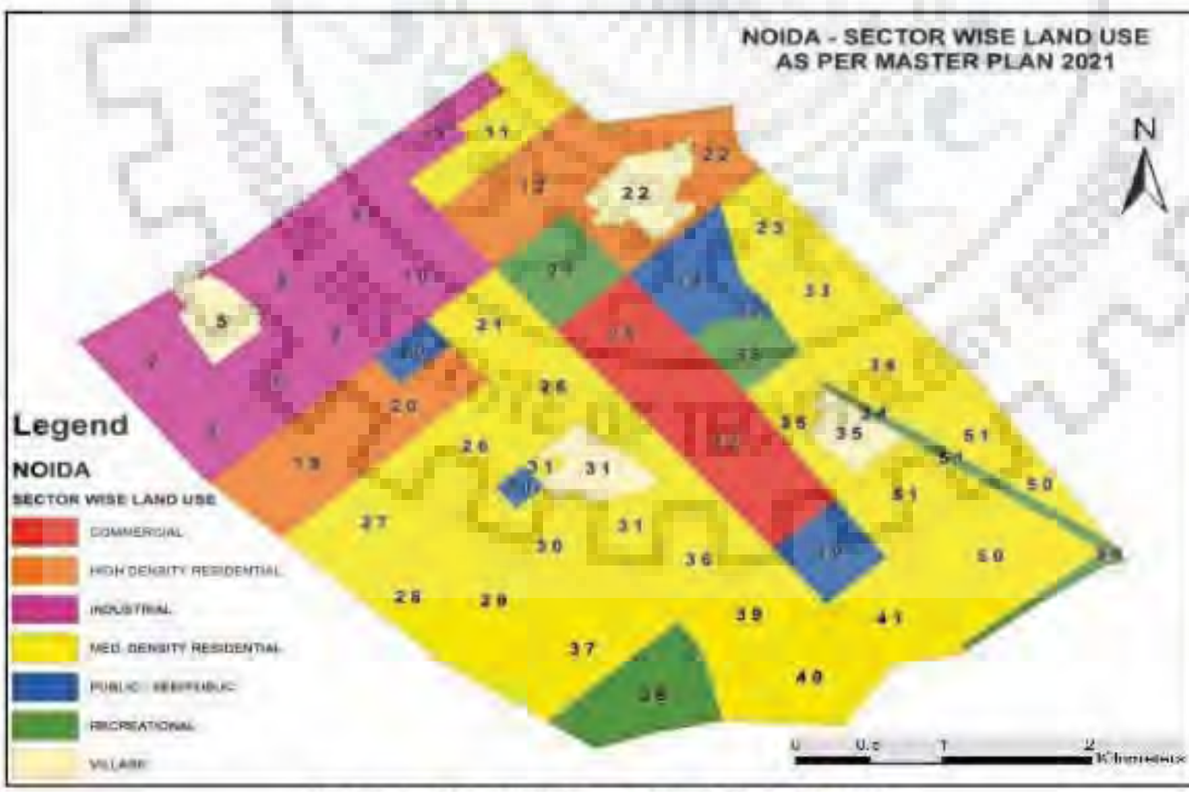

Fig. 2 Sector Map of NOIDA Source: NOIDA Master Plan 2021

NOIDA has large tracts and well developed green area, the air quality is becoming a matter of concern because suspended particle matter is increasing due to large scale construction activities in the fast developing city. However, optimum distribution of UGS is also equally important to maintain environmental and social quality of UGS. At the same time, NOIDA is located at the doorstep of Delhi, i.e. only 14 Kms. away from Connaught Place, New Delhi, which is further causes heavy impact of urbanization (Source: NOIDA Authority website). Hence, a study was taken to assess the distribution of UGS in the area.

3.0 Background

3.1 Benefits of Urban Green Spaces

Urban green spaces form an integral part of any urban area and assessment of quantity and quality of UGS is one of the important concerns for planners and city administrators. UGS comprises of parks, gardens and recreation places and other informal green spaces such as greenery at lake or river fronts, surrounding major public buildings and along transit terminals & corridors. Urban habitats such as deserted industrial sites and unkempt gardens have also been considered as UGS (Venn & Niemelä, 2004). Green areas works as a visual screen to ecology and act as noise barriers and also keep away too much spatial uniformity (Dole, 1989). UGS also provide multiple benefits to urban population by absorption of pollutants (Haughton & Hunter, 1994), provide clean air, water and soil, and refreshing city's natural urban environment (Nijkamp & Leventa, 2004). They also help individuals to recuperate from physical and mental stress and has positive impact on physical, social and cognitive development of urban children (De Vries, Verheij, Groenewegen, & Spreeuwenberg, 2003; Grahn & Stigsdotter, 2010; Groenewegen, van de Berg, De Vries, & Verheji, 2006;Dadvand et al, 2015, Gupta et al, 2016). Mcpherson (1992) assessed the environmental and health benefits of UGS are at par with monetary benefits of other capital investments required to develop and maintain UGS.

3.2 Measurement of Urban Green Spaces

Objective measurement of greenness using remote sensing images was carried out by computing percentage area of green, i.e., Green Index (GI), which is insensitive to spatial arrangement within the areal units (Gupta et al., 2012). Normalized Difference Vegetation Index (NDVI) derived from remote sensing images has been used by various researchers to quantify vegetated and non-vegetated areas (Hur, Nasar, & Bumseok, 2010; Saied, Syed, & Heshmi, 2005). Ruangrit and Sokhi (2004) has used pixel based classification for mapping urban green spaces of Jaipur city, India from remote sensing images and analyzed availability of green spaces in various administrative units based on percentage green space, green space per 1000 persons and green space/built up area ratio. Other than NDVI also, there are many indices such as Difference Vegetation Index (DVI), Transformed Vegetation Index (TVI) (Deering et al., 1975), Perpendicular Vegetation Index (PVI) (Richardson and Wiegand ,1977)and Urban Green Space Index (UGSI) (Xiaojiang et al,,2014) are applied to assess the quality of green but these indices are mainly dependent on the amount or percentage of green in a particular area and do not address the proximity or spatial distribution and type of green. Gupta et al, 2012 developed Urban Neighborhood Green Index (UNGI) by incorporating the type of green, proximity to green and height of buildings other than the percentage of green for the assessment of UGS at neighborhood level. Besides, Measuring UGS at neighbourhood level is important as the neighbourhood is considered as the primary unit of urban system and first stage application of greening strategies for a city needed to be focused at this level only. The Urban Neighbourhood Green Index (UNGI) aims to assess the greenness and can help in identifying the critical areas, which in turn can be used to identify action areas for improving the quality of green. For the application of UNGI, four parameters, i.e., Percentage of green (Green Index), Proximity to green, Built-up density and Height of structures were generated and weighted using Saaty's pair wise comparison method as described in Gupta et al, 2012. The input for UNGI is easily derivable from RS images, besides the developed method is simple, and easily comprehendible by city

Table 2 Description of Remote Sensing Images used for assessing UNGI

Input	Satellite / Sensor	Resolution	Type	Date of Acquisition
Image-1	IRS P6 LISS-IV	6 mt	Multispectral	14.06.2005
Image-2	Cartosat-2	2.5 mt	Panchromatic	05.05.2007

administrators and planners. It compared four different types of NH and found that mean GI was equal for high-rise low density and low-rise low density NH, i.e., both areas have same quality of urban green based on GI. But mean UNGI was higher for low-rise low-density NH, as compared to high-rise low-density NH, hence, area of high-rise NH requires more amounts of good quality properly distributed green as compared to low-rise NH.

4.0 Research Methodology

This research study is aimed at identifying potential sites for implementation of urban greening projects within the area of interest. , The scope is limited to analysis based on step by step methodology (Figure 3) adopted for classification of remote sensing images (Table 2) into various vegetation characteristics (dense & shallow) and built-up characteristics (built –up Density , proximity of builtup to UGS and height of built up structures.) The study was carried out for the area of interest spanning across 34 sectors of NOIDA. The results of the study would reveal the comparative levels of good quality & properly distributed green spaces among various neighbourhoods.

4.1 Step-1 – Subsetting imagery

Figure 3 Methodology Flow Chart

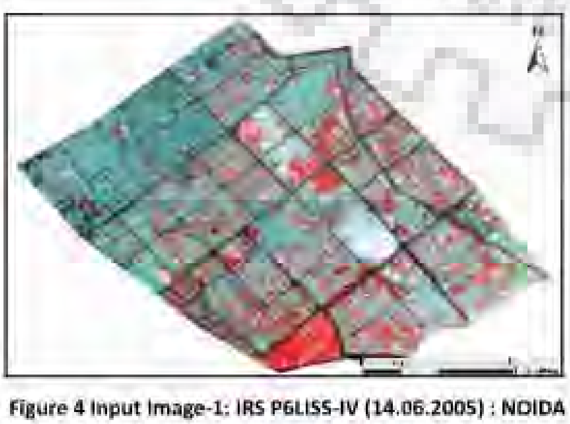

Figure 4 Input Image-1: IRS P6LISS-IV (14.06.2005) : NOIDA

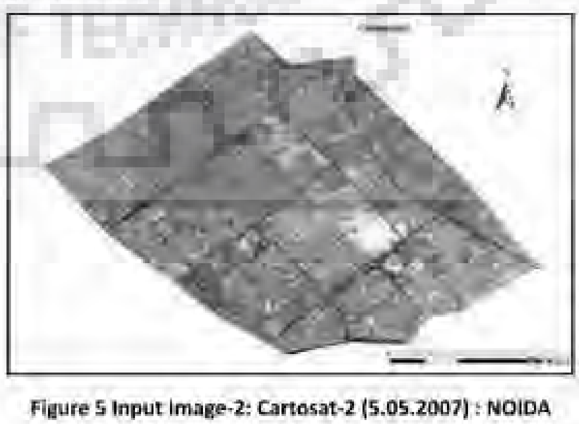

Figure 5 Input Image-2: Cartosat-2 (5.05.2007) : NOIDA

Figure 6 Steps for classifying the study area based on Percentage Green

First stage was creating subsets of the both input images for the area of interest spanning across 34 sectors of NOIDA (Figure 4 and Figure 5). The boundary map generated from Sector land use map of NOIDA was used for subsetting the mentioned images.

4.2 Step-2 – Calculating P1 – Percentage Green

Further, the subsetted multispectral IRS P6 LISS IV data was classified into vegetated and non-vegetated land covers. For this purpose NDVI was calculated using Red (R) and Near Infrared (NIR) band of LISS4 image. Then a binary classification of NDVI image into Green / Non-green was carried out. Then 20m X 20m fishnet grid was used to analyze percentage of greenery in each cell of 6 m resolution and then a value was assigned to each cell based on percentage of green in each cell (Table 3 and Figure 6)

Table 3 Criteria for Classifying Percentage Green

Percentage of Green Pixels	Parameter P1 value
>75%	1
<75% to >50%	0.75
<50% to >25%	0.5
<25%	0.25

Equation of NDVI

NDVI = [NIR – R] / [NIR + R] = [Band 4 – Band 3] / [Band 4 + Band 3]

4.3 Step-3 – Calculating P2 – Percentage Builtup area

Once the un-vegetated area was marked then the built-up area was classified on the basis of density and building height and then the classified image was further used to quantify the open area available for potential vegetation. First the LISS4 image was subjected to supervised classification using the classes shown in Table 4. Then the 20 m X 20 m fishnet grids were used to analyze percentage built-up on per cell basis (Figure 7). The output parameter P2 is classified as per Table 5.

Table 4 Classes used for Supervised Classification of LISS 4 image

Vegetation Dense	Builtup High Density
Vegetation Sparse	Builtup Medium Density
Vegetation Sparse Dry	Builtup Low Density
Water	Road
Land Bare soil	

Figure 7 Steps for classifying the study area based on Percentage Built up

Table 5 Criteria for Classifying Parameter P2

Percentage of Builtup Pixels	Parameter P2 value
<25%	1
>25% to <50%	0.75
>50% to <75%	0.5
>75%	0.25

4.4 Step-4 – Calculating P3 – Proximity to Green

The classified image created in Step-3 was also used to derive the proximity to green based on a buffer distance to determine the less connected area and un-connected areas with respect to UGS. First Keeping in mind the 20m grid cell size while classifying the zone in proximity of dense vegetation, grass/low vegetation and open spaces without vegetation into high quality, moderate quality and low quality green area, a 20 m wide buffer zone (excluding built-up area) was generated around class Dense Vegetation. Then the 20m X 20m fishnet grid was used to analyze proximity to green on per cell basis (Figure 8). While creating the fishnet - considering the minimum mapping unit of 3 pixels by 3 pixels for IRS P6 LISS IV data, which comes to approx. 18 m × 18 m - a grid cell size of 20 m × 20 m was used. The output parameter P3 was classified as per Table 6.

Table 6 Criteria for Classifying Parameter P3

%age of Buffer Pixels	Parameter P3 value
>50%	1
<50%	0.75

Table 7 Criteria for Classifying Parameter P4

%age of High-rise Pixels	Parameter P4 value
<25%	1
>25% to <50%	0.75
>50% to <75%	0.5
>75%	0.25

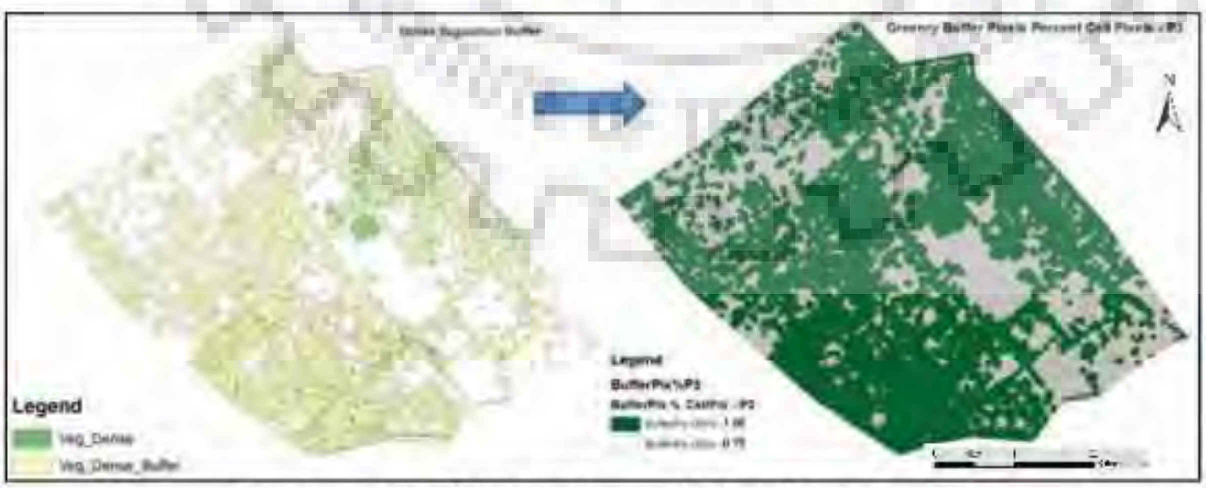

Figure 8 Steps for classifying the study area on the basis of Proximity to Green

4.5 Step-5 – Calculating P4 – Percentage Highrise Structures

Norms for basic landuse classifications under Building Byelaws & Regulations (Amendment 2010) of NOIDA were used to clarify the landuse differences and built-form issues with help of the spatial manifestation. From byelaws of NOIDA and present status of types of landuse / built form from the Cartosat-2 image, the ranges for height based analysis were classified in two categories:

1. Low-rise Buildings (Height < 10 m)
2. High-rise Buildings (Height ≥ 10 m)

Again, the 20 m X 20 m fishnet grid was used to analyze percentage high rise (P4) on per cell basis (Figure 9). The output parameter P4 was classified as per Table 7.

4.6 Step-6 – Calculating UNGI

Once above mentioned steps were accomplished and all the parameter maps were generated, multi criteria analysis was performed for estimation of UNGI value as described in Gupta et al, 2012 (Figure 10).

4.7 Step-7 – Comparison with Sector extents and designated land-use

At this stage, extents and designated landuse of various sectors encompassing the area of interest were overlaid on the UNGI map to carryout sectoral analysis. The distribution of UNGI values across the various designated land uses and sectors encompassed in the study area were mentioned in Figure 10. And finally potential sites for urban greening had been identified in each particular sector with reference to its designated landuse. For evaluating alternative interventions in a particular Sector available open area and quantum of vegetation possible on any particular site can be determined by simulating cases of proposed greening interventions. The distribution of UNGI values across the various designated land uses and sectors encompassed in the study area are mentioned in Figure 10.

5. Result and Discussion

5.1. Finding -1: Average of UNGI

In order to study the distribution of UNGI across the study area, the average UNGI was analysed in a cross table with Sector ID in rows and designated land use in columns, the range of variation in values was represented by colour coding of the cells (Table 9). It was observed that average UNGI was maximum in Sector 38 corresponding with recreational land use; where as it was minimum in Sector 8 corresponding with industrial land use.

Further detailed analysis was done using a cross table of Standard deviation in UNGI values across Sector

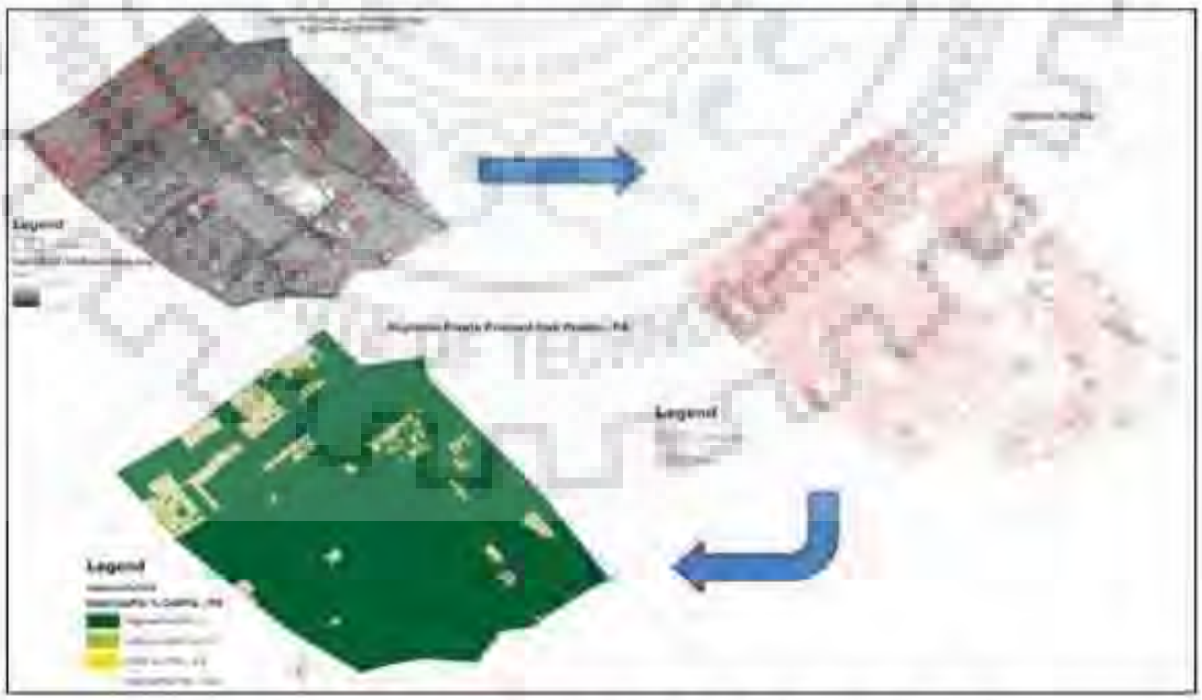

Figure 9 Steps for classifying the study area on the basis of Percentage High Rise

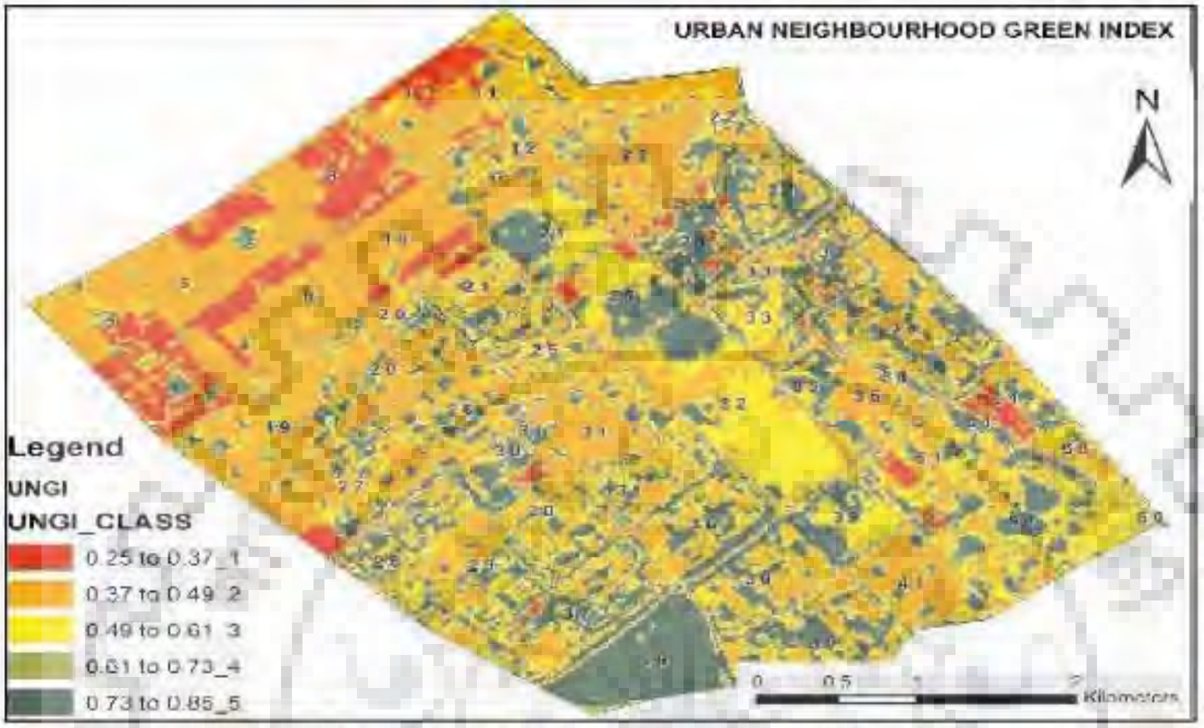

Figure 10 Outcome: Urban Neighborhood Green Index (UNGI) Map: NOIDA

extents and designated land use as shown in Table 10. It was observed that Standard deviation in UNGI Value is highest in Sector 24 corresponding to Public Semi Public land use; while it was lowest in Sector 5 corresponding to village land use.

As per zoning regulation, industrial areas should have more greenery whereas the current scenario was opposite as seen in UNGI Map for sectors 2 to 11, where vegetation level was very less hence these areas should be vegetated on priority basis as some of open lands were available for green space developments under the designated industrial sectors. At the same time it had also been seen in UNGI Map for sectors 12 to 32 that few sectors were satisfactorily green but in most of sectors equal and homogeneous distribution of greenery was not achieved, which was also not upto the sustainable development standards, therefore each sector should have distributed greenery.

5.2. Finding -2: Identifying Potential Spaces for Urban Greening

The aforementioned analysis helped us to ascertain not only the sectors lacking urban green areas but also those where there was a potential for introducing greening interventions. Various strategies may be formulated based on the need and potential of urban spaces in various sectors.

For example, though the average UNGI values for Sector 3 and Sector 9 were very close (0.411 and 0.424 respectively), the stark difference in Standard Deviation values (0.159 and 0.085 respectively) indicate the presence of different quality of green spaces. Combining the values of average and standard deviation we ascertained the following. In the case of Sector 3 the UNGI value varied between 0.411 ± 0.159 i.e. 0.57 to 0.252; where as in case of Sector 9 the UNGI value varied between 0.424 ± 0.085 i.e. 0.509 to 0.339. The result corroborated on visual inspection of the extents of Sector 3 and Sector 9 in Figure 10.

Majority of the area in the case of Sector 3 was covered under UNGI Class 1 corresponding to high rise builtup; while that in Sector 9 was covered under UNGI Class 2 corresponding to medium rise builtup. The second majority area in case of Sector 3 was covered under UNGI Class 5, whereas that in case of Sector 9, it was covered under UNGI Class 1. The presence and equitable distribution of UNGI Class 5 was feasible and desirable alongside UNGI Class 1. Further field analysis will enable verification of ground reality regarding feasibility and desirability of the combination of UNGI Classes.

Table 9 Cross table representing average UNGI across Sector extent (in rows) and Designated land use (in columns)

SECT. ID	COM	HDR	IND	MDR	PSP	RECR	VILL	ST.D.
2			0.122					0.122
3			0.159					0.159
4			0.074					0.074
5			0.119				0.061	0.105
8			0.095					0.095
9			0.085					0.085
10			0.076					0.076
11			0.120	0.134				0.141
12		0.144						0.144
19		0.121						0.121
20		0.141			0.134			0.140
21				0.154		0.155		0.159
22		0.140					0.104	0.135
23				0.161				0.161
24					0.199			0.199
25	0.176			0.134				0.159
26				0.155				0.155
27				0.161				0.161
28				0.153				0.153
29				0.146				0.146
30				0.160	0.150			0.160
31				0.150			0.107	0.149
32	0.128							0.128
33				0.176	0.159	0.134		0.162
34				0.160		0.140		0.159
35				0.166			0.117	0.167
36				0.163				0.163
37				0.157				0.157
38						0.095		0.095
39				0.162	0.139			0.154
40				0.165				0.165
41				0.146				0.146
50				0.145		0.114		0.142
51				0.165		0.148		0.168
ST.D.	0.145	0.137	0.111	0.162	0.176	0.156	0.100	0.170

Table 10 Cross table representing standard deviation in UNGI across Sector extent (in rows) and Designated land use (in columns)

SECT ID	COM	HDR	IND	MDR	PSP	RECR	VILL	AVG
2			0.429					0.429
3			0.411					0.411
4			0.395					0.395
5			0.387				0.425	0.399
8			0.359					0.359
9			0.424					0.424
10			0.386					0.386
11			0.393	0.493				0.455
12		0.535						0.535
19		0.505						0.505
20		0.530			0.505			0.525
21				0.562		0.637		0.599
22		0.530					0.445	0.502
23				0.653				0.653
24					0.652			0.652
25	0.614			0.563				0.589
26				0.571				0.571
27				0.517				0.517
28				0.622				0.622
29				0.585				0.585
30				0.598	0.661			0.603
31				0.577			0.456	0.542
32	0.572							0.572
33				0.632	0.612	0.612		0.624
34				0.624		0.602		0.623
35				0.626			0.474	0.571
36				0.618				0.618
37				0.630				0.630
38						0.813		0.813
39				0.623	0.645			0.631
40				0.630				0.630
41				0.489				0.489
50				0.593		0.606		0.595
51				0.538		0.725		0.544
AVG	0.584	0.524	0.395	0.586	0.633	0.703	0.449	0.553

6. Conclusion

Government of India has begun to develop specific types of industrial and economic policies that have led to the emergence of certain economic spaces such as Special Economic Zones (SEZs), Special Investment Regions (SIRs), National Industrial Manufacturing Zones (NIMZs), Regional Industrial Corridors and Industrial townships etc. As these new spaces of production emerge, they will encounter challenges related to governance and planning. These newer forms of economic settlements are evolved as those spaces where usual norms and legislations of urban Indian settlements are relaxed to a large degree. It is important to ensure that residents in these emerging settlements have access to all forms of public facilities, which is essentially required for human liveability and long term sustainability of settlement areas and one of them is urban green spaces.

There is a need for getting quantifiable information regarding green structures and their amount and distribution for sustainable planning (Lang et al., 2008). UNGI can act as a decision support tool to evaluate, quantify and compare various neighbourhoods in terms of amount and distribution of green structure. Rather than merely measuring the overall percentage of green, i.e., GI, the UNGI reflects the importance of distribution of green areas in specific neighbourhoods and environments (Gupta et al. 2012).

Ultimately it is concluded with this study that UNGI technique is one of the very effective decision making tool for selection and planning of potential urban green space development. It can be applied by Govt. authorities to address the need of space coverage in vegetation and level of greenery required under various types of land-uses and land utilizations at neighbourhood level as this index is easy to understand and comprehendible by planners even if they are not expert in RS techniques. UNGI can also be explored to verify the distribution of green spaces within the neighbourhoods for various forms of urban design elements under public as well as private ownerships.

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