# A Bioclimatic Approach to the Integrated Design of Transit Stations and their Immediate Surroundings

by

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## ABSTRACT

This thesis identifies and illustrates the potential contributions of good climate-responsive design to a rapid-transit rail system under construction in San Juan, Puerto Rico. It focuses on the application of bioclimatic design guidelines to the design of stations and their immediate surroundings. The objective of doing so is to maximize the benefits to the operator and users of Tren Urbano, a 12 mile-long rapid transit rail system.

First, I seek to introduce and contextualize the notion and methodologies of bioclimatic design. An analysis is presented of climatic conditions that have direct implications for design. In order to see the impact of differing climates on design, San Juan's climate is compared to that of another location, Mexico City.

Then, the possible variations in conditions, microclimatic and site/station-specific, that may be found along the Tren Urbano alignment are identified and related to design. Following this, design guidelines for every stage of the design process are identified for both locations. One station along the system is chosen to exemplify the application of the guidelines in a specific site and to illustrate how the guidelines would differ if the location were Mexico City.

I conclude by discussing the possible constraints, obstacles and conflicts, both internal to the guidelines and institutional, that may arise in applying and implementing these recommendations. My intention is that the guidelines be published for general dissemination to the design community and applied in future stages of Tren Urbano and any other infrastructure project. The guidelines present ample opportunities for application, yet many hurdles must be overcome to make them reality.

Thesis Supervisor: John deMonchaux
Title: Professor of Architecture and Urban Planning

# 1. ACKNOWLEDGMENTS

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## Table of Contents

# 1. INTRODUCTION

The introduction states the objectives for carrying out this research and the organization of the thesis. The thesis focuses on the use of climate as a critical input to the transit station design process. It is intended to provide guidance on how to design stations and their surroundings in order to improve acceptability of the system and economy in use of resources.

## 1.1. Objectives

My motivations in carrying forward this research are many.

First, application of bioclimatic design guidelines will make the system more comfortable. Greater comfort will yield more riders. More riders will come in part from auto drivers and as a result energy can be saved. Moreover, some trips that may have been foregone before will be made if the appropriate environment to sustain those trips is provided. A recent study by R. Cervero[1] identifies the importance of urban design in increasing ridership and concludes that substantial reduction in auto trips and increased walking to stations results from more pedestrian-oriented streets. Pedestrian friendly streets refers to many of the concepts that bioclimatic design deals with: comfortable, inviting walking environment that respond to the conditions in which they are located, making the arrival to transit stations by foot possible.

Second, my motivation has economic implications. Through the application of the design guidelines it is possible, indirectly, to reduce dependence on private automobiles and to considerably reduce energy consumption. Puerto Rico imports all of its cars and energy sources. Experimental evaluations of climate-responsively-designed buildings have shown energy consumption reductions of over 20%. Car ownership figures are amongst the highest in the United States. In 1997, there was 1 automobile for every 1.8 persons in Puerto Rico. This is despite the fact that average annual incomes are lower than those of the poorest US State, Mississippi. A study by the Tren Urbano Office reports that Puerto Ricans spend up to 40% of their disposable income in the use and maintenance of cars.

My third goal is educational: to disseminate and make accessible and understandable to architects, engineers and planners how to design with the climate rather than against it. This is a concern that is relatively unfamiliar and unexplored in the design community in Puerto Rico. A tour of the newer developments in San Juan illustrates the lack of consideration for some very basic considerations regarding the interaction of buildings and climate. All facades in buildings are treated equally, glass curtain walls are used extensively, regardless of orientation. Even more critical is the lack of attention given to making outdoor spaces comfortable, further deepening reliance on automobiles for access to anywhere.

Not negligible is the critical environmental situation in which the San Juan Metropolitan Region finds itself. The predominance of cars and the considerable lack of public transportation has placed the city in a cycle whereby meeting increasing travel demand requires deforestation for capacity expansion. Capacity expansion, it has been shown, generates demand. Heat island effects due to increased impervious surfaces (asphalt) modify the climate (figures 1.1, 1.2). Deforestation

[1]Robert Cervero, *Transit Villages in the 21st. Century*, 1997.

produces climatic changes that feed a cycle whereby higher levels of air conditioning are required. There are also examples from which to draw lessons in the San Juan area, mostly in the older part of Old San Juan (figures 1.3 and 1.4).

**Figure 1.1. Hato Rey Centro area. Vast impervious surfaces create adverse microclimates**

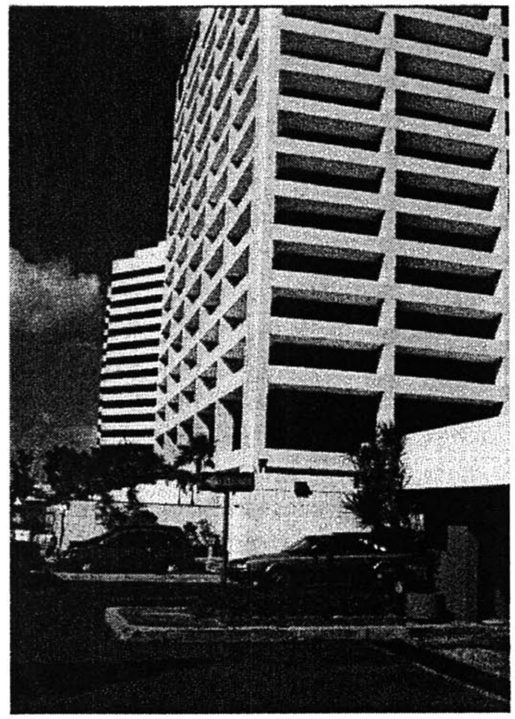

**Figure 1.2. Hato Rey Centro area. No differentiation between facades.**

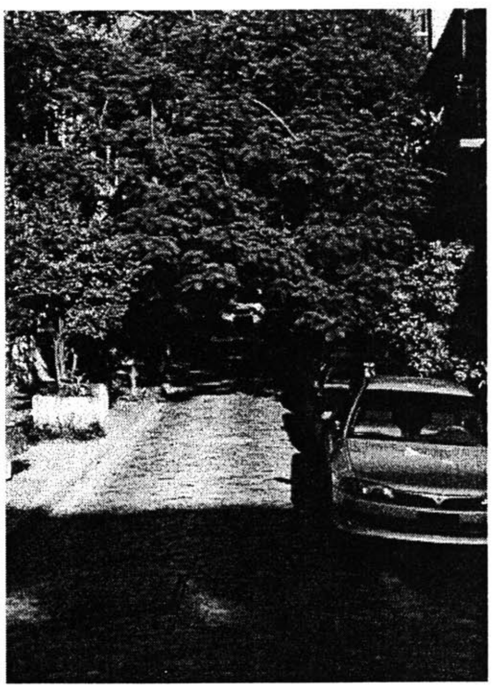

**Figure 1.3. Street in Old San Juan. Use of vegetation for shade and glare reduction.**

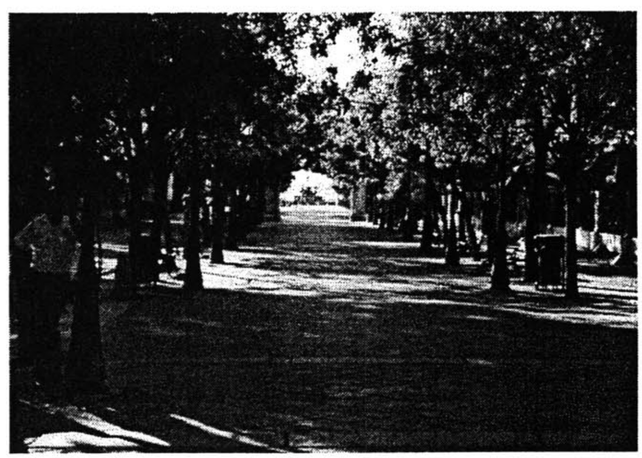

**Figure 1.4. Paseo de la Princesa, Old San Juan. Use of vegetation provides comfortable outdoor conditions.**

Ultimately, a simplified version in a design manual format that summarizes my findings and recommendations should be produced to be distributed by and to the Puerto Rico Association of Architects, the University of Puerto Rico, Chamber of Construction and other institutions related to design disciplines. The literature on climate-responsive design is enormous and can be complex.

This manual will summarize the main concepts, methods and techniques for architects in an accessible and user-friendly manner.

A further motivation for this thesis is the opportunity cost of not maximizing the benefits of this major transportation investment for the San Juan Metropolitan Region (SJMR) and Puerto Rico as a whole. Public transportation in San Juan urgently needs improvements, of which the first phase of Tren Urbano represents a first step. If design considerations and integration of stations into the urban fabric are not given due importance in creating inviting, safe and efficient system stations and surroundings, much of the potential benefits of the system, in terms of capturing ridership, may be lost and the damage to perception of public transportation given a further final blow.

As a last and more personal motivation is my appreciation of architecture that relates and responds to its context, one that seeks to discover natural rules that exist to be revealed and respected rather than imposing a set of rational, artificial rules. There are numerous examples I will draw upon where this concept is visibly behind design decisions. Even within pre-established rational design rules, some cultures have found ways to adapt to local topographic and climatic conditions as can be seen in parts of Old San Juan. It is also my belief that good climate-responsive design can be a source of re-identification with cultural roots, not a secondary issue in Puerto Rico.

### 1.2. Methodology and Organization

This research is conceived as a client based thesis. Three parties are the potential targets of this research: the Tren Urbano Office, the Siemens Transit Team, and the design professions represented by its interest associations and academic institutions.

Chapter 2 reviews some of the salient contributions to the literature on bioclimatic design. Definitions of the main concepts used throughout the thesis are presented. Literature on bioclimatic design is very extensive and I then point to the relevance of the main sources to the discipline. Following this is a brief review of the history and evolution of the discipline of environmental/climate-responsive design and the general policy climate, for lack of a better word, that permitted or obstructed it. The chapter ends with a description of the Tren Urbano project.

Chapter 3 describes methods and graphical tools to visualize and analyze climatic indicators of a location. The first part of the chapter discusses the concept of comfort, the factors that affect its measurement and its relation to building design. This is followed by a classification of tropical climates. The main part of the chapter is a step by step comparative analysis of the climate of two locations, San Juan and Mexico City. This is done in order to illustrate the meaning of climatic indicators and how they shape design decisions. The chapter ends by identifying the appropriate bioclimatic strategies and their limit of applicability for each climate.

Chapter 4 introduces the geometric relationships that govern the relationship between buildings and climate. A discussion of the relevant properties of building materials is also presented. The properties of air movement, noise and daylight/glare and their impact on buildings and vice versa are also discussed. Lastly, methods for easy verification of design proposals in terms of heat gain, insolation, wind protection/capture and protection of openings are presented.

Chapter 5 identifies the possible microclimatic and site and station-specific variations to be found at different station sites along the alignment of phase one and the possible extensions of Tren Urbano. A discussion of the specific features of transit stations is presented. The variations are identified in order to adapt, refine and customize the guidelines to microclimatic and station-specific conditions of a site and make them of system-wide applicability.

Chapter 6 describes how the strategies that emerged from the climatic analysis are translated into design guidelines. This is again done comparatively for both climates to contrast the design guidelines and make them more understandable. Three scales of guidelines are presented: site-planning, building design, and building component considerations. The second part of the chapter synthesizes all the information by illustrating, step by step, the application of the guidelines using one station in Tren Urbano for both San Juan and Mexico City in order to show the differences in design that result from the guidelines.

In chapter 7, I explore the possible conflicts, challenges and obstacles in applying the recommendations gathered from chapters 5 and 6. Two levels of conflicts are relevant to this discussion. First, internal to the guidelines some may conflict with others, such as requirements for wind and protection from the sun. A compromise solution in these situations may be called for. Second, the contractual arrangement under which Tren Urbano is being built requires special attention and poses another layer of institutional challenges in order to evaluate how, for whom and by whom the recommendations may best be implemented.

Lastly, I summarize my conclusions. Transit stations are particularly apt for application of bioclimatic design guidelines in warm humid island climates, such as that of San Juan, because stations by nature are narrow, elongated buildings, at least at the platform level. Moreover, since many stations are to be elevated (which improves wind capture) and the relatively benevolence of the climatic conditions, the bioclimatic design guidelines recommended can have a big impact on the comfort of stations and their immediate surroundings. On the other hand, many obstacles must be overcome for these guidelines to be implemented, not the least of which is the particular contractual arrangement under which Tren Urbano is being procured. This calls for institutional creativity, which is beyond the scope of this thesis. Perhaps the biggest obstacle anticipated, however, is the entrenched auto-oriented, air conditioned, indoor culture so predominant in San Juan.

# 2. LITERATURE REVIEW, DEFINITIONS AND CONTEXT

This chapter introduces the definitions that will be used throughout the thesis. It also highlights the principal contributions to the literature on climate-responsive design. Following is a brief overview of the history and policy-climate that gave birth to environmental/climate-responsive design. The chapter ends with a description of the context of San Juan, its transportation network, history, and a description of the Tren Urbano project.

## 2.1. Definitions

- Sustainability: the capacity of one generation's consumption habits to be carried forward by future generations without jeopardizing that future generation's ability to do so.

- Bioclimatic design/architecture: approach to architecture centered around the comfort conditions/requirements of living organisms and the role natural climatic factors can play in providing these conditions of comfort.

- Vernacular architecture: cumulative architectural wisdom passed on from generation to generation as a result of incremental mastering of building techniques and adaptation to the natural forces of a given landscape and location.

- Microclimate: climatic conditions constrained to a small area within which conditions are homogeneous and different from regional climatic conditions due to topographical and/or location differences.

- Comfort: condition in which the human body does not need to exercise any thermo-regulatory, adaptive mechanism to react to or counteract external climatic or other environmental factors (noise, pollution, smell). Sensation of complete physical and mental well being.

- Integration: coordination of diverse components of a system to optimize its performance. In transportation systems terms, integration of various modes, schedules, information, fare, diverse riders, and architectural/urban.

- Street furniture: the sum of all street structures that provide for functional needs such as benches, trash bins, bike racks, lighting posts, shelters, water fountains, etc.

- Passive means of environmental control: Structural and/or constructional means to achieve environmental controls that compensate discomfort conditions.

- Active means of environmental control: Mechanical or energy-based means to achieve environmental controls that compensate discomfort conditions.

- Design strategy: general guiding principle/objective to be followed in the design process, not related to any particular structure but affecting all levels of design decisions. Example: solar gain, ventilation.

- Design guidelines: specific recommendations for design decisions at all levels and scale of the design process. Example: size and location of openings.

## 2.2. Bioclimatic design literature review

The literature on bioclimatic and environmental design is vast. Therefore this review will be limited to the salient theoretical contributions in the field of bioclimatic design. My review has been intentionally oriented to making the guidelines as easily understood as possible for the eventual users of the guidelines, the architects, designers and engineers. Moreover, in undertaking my research I have intentionally avoided texts, which analyze extremely technology-intensive and high-maintenance complex solutions, because I considered they are of limited applicability in the context of Puerto Rico, at least in the initial stages of operations of Tren Urbano.

I have concentrated the review on tropical climates. However, the general conceptual framework and methodology for arriving at bioclimatic design guidelines are the same for cold climates.

To put the literature in context, biocliamtic and environmental design, as disciplines, evolve out of the environmental movement of the early 1960s. This movement is associated with the growing perception that existing living habits and growth patterns were not sustainable. Environmental and bioclimatic design postulate that architecture and urban design have an important role to play in making the physical environments where people work, reside, shop, recreate and travel more environmentally responsive and sustainable. The concept in itself was no novelty at the time it got increasing attention, but it became one of the focus of study in the architectural sciences curricula.

The main sources and contributions on bioclimatic/environmental design literature with a brief review of each follows, The first criteria for the order of appearance is relevance to the field and the second criteria is cronological.

- Olgyay, Victor: *Design with Climate*, published in 1963 is one of the first systematic studies on bioclimatic design. Following a discussion on peoples' historic natural tendency to design with climate, he proposes a framework for how to address a climate responsive design process. He proposes general design guidelines for a variety of distinct climates across the United States, illustrating their implications at the urban scale.

- Koenigsberger, Szokolay, Ingersoll, Mayhew: *Manual of Tropical Housing and Building*, 1973. Excellent manual for design professionals, understandable, readable, good balance between complexity and applicability. Deep and comprehensive analysis of all issues relating to bioclimatic design. Koenigsberger and Lynn: *Roofs in warm humid tropics*, 1965 -- important source for roof design. Szokolay: works on determining dynamic comfort zone, 1986, and climatic indices, 1990, useful article to visualize the dynamic character of comfort zone.

- Evans: *Housing, Climate and Comfort*, 1980. Good synthesis and general for all climates. Very readable and easy compendium of methods for designing with the climate. More application-oriented. Excellent organization.

- Gut - Ackernecht: *Climate Responsive Building: Appropriate Building Construction in Tropical and Subtropical Regions*, 1993. Good overview and organization of bioclimatic design issues. Somewhat simplified but good graphical illustration of application of bioclimatic design concepts.

- Givoni, Baruch: *Man and Climate and Architecture*, 1969. is a more detailed and scientific work on building materials and their properties. Also focus on physiological response to thermal stress and some dissemination on design implications. Also some articles on urban and building design (extracted from his book 1994 and 1998).

- Muniz, Pedro: *Enfoque Biotropical para la Arquitectura en Puerto Rico*, published in 1989 is a doctoral dissertation on the applicability of bioclimatic design in Puerto Rico in general. It provided very useful information for this work.

- Konya, Allan; *Design Primer for Hot Climates*, 1980. Very useful simple reference. Brief and selective yet complete. Excellent illustrations of bioclimatic design concepts.

- John B. Hertz: *Arquitectura Tropical, Diseño Bioclimatico de Viviendas en la Selva del Peru*, 1989. A study on the applicability of bioclimatic design in the northeast regions of Peru.

- Oakley, David J.: *Tropical Houses*, 1961. Early work on design of houses. Not very 'scientific' but a good generic guide and recommendations and good complete review of a building's components and how they are affected by climate.

Architectural and urban design are usually associated with the following objectives: aesthetics/ symbolism/identity, durability, efficiency, functionality, comfort, economy, sustainability. This thesis intends to address the energy efficiency and ways to minimize artificial requirements to obtain comfort conditions in buildings through the application of passive measures. It is intentionally not style-prescriptive because the guidelines that result from this study may be applied independently of style or aesthetic convictions. They are intended to give recommendations about ways to utilize climatic factors without giving concrete shape to these recommendations.

### 2.3. Integration

The importance of physical integration of transit systems into their surroundings cannot be overstated. Innumerable examples abound of technically well-designed systems with little attention to the people who will use them and the places they are located in. Integration, in general transportation terms, refers to the reconciliation of various separate system components such as fare, modes, information, schedule and architectural/urban design into a whole in order to optimize customer service and ease of use of the system.

In the specific context of physical integration it refers to the harmonic relationship of a facility with its surroundings and the ease with which all users and modes can be incorporated into the system.

Bioclimatic design is one ingredient in this broad picture and the focus of this thesis. Other issues that are critical to an evaluation of how well a system is physically integrated to its location include:

- Integration of pedestrians: pedestrians are often impeded from good access to transit stations. This is particularly important in the context of San Juan where many streets around future stations are not pedestrian-friendly, often lacking walkways, shading, and protection from vehicular traffic. Integration of pedestrians involves the design of the street leading to the stations to make them safe and attractive, including vegetation, street curb design (streetscape), street furniture.

- The availability of diverse activities to be done on the street is fundamental to perception of safety (social control) and attraction. Land-use planning consistent with the transportation system must be considered to allow mixed uses in station areas and their surroundings. Safety is of particular concern in the SJMA and should be given its due emphasis. Commercial activity can contribute substantially to creating a perception of safety around stations.

- Integration of the disabled and the elderly. The American with Disability Act of 1990 states that no person shall be discriminated on based on their physical abilities. This includes the possibility to use transportation services. A large proportion of transit users in the United States and Puerto Rico is the elderly people. Stations across the United States are being retrofitted to facilitate the use of transportation facilities, including raising platforms, minimizing distances and changes in grades, and providing ramps and elevators.

- Integration of the bicycle: Bicycle integration is an important feature often overlooked in planning of stations. The integration of bicycles involves various considerations: safe and protected parking areas, bike paths protected from traffic and the sun.

- Integration of parking areas: In many stations along Tren Urbano's alignment there will be Park and Ride facilities. These must be designed to make them attractive and keep users from driving the extra distance to their destination and not using the system. The path between the car and the station must be considered in detail: shading both for the car and the pedestrian, minimal interference with other modes of transportation (buses, taxis, other cars), reducing the walking distances by distributing the parking areas are all concepts that should be analyzed. There is a limit to how much can be done in this direction if the parking policy in San Juan remains unchanged.

- Uniformity/differentiation: one decision that must be taken at the beginning of the transportation system design process is whether the stations will be designed following uniform design language or allow for variations among them. The pros for uniformity are the system's ease of identification and standardization of construction and design functions. Against this argument is the excessive repetition and the lack of differentiation of station designs without attention to the context. In the design of the London Jubilee Line the concept of modular standardization was employed. This means that a certain palette of materials and parts was standardized and employed in all the stations with a variation to respond to location while maintaining clear identification. The latter allows more flexibility to adapt to climate as will be seen in following chapters.

- Safety and security considerations: safety and security are two different concepts. Security refers to the danger from assault from other persons. Design plays a key role in minimizing the likelihood of occurrence by avoiding obstacles for people to hide behind, and providing clear platforms, visibility, activity, colors and materials (perception). Safety refers to dangers from built conditions: minimal changes in grade, platform screens (trainscreens), buses with low floors or good elevated platforms on street curbs are some of the strategies to reduce safety concerns. Also important for safety are factors such as minimizing walking distances, especially for elderly and disabled, critical use of materials (texture and color).

- Visibility vs. visual impact: There is a potential conflict between local residential communities and the impacts of the transportation system. While the system needs to be visible to attract riders and businesses, the associated growth may decrease the value of adjacent property. In some cases the additional access to the area will offset this effect but in others this will not be the case. Careful attention must be given to this issue and involving the community is important part of the process.

## 2.4. Brief history of environmental design

The idea of designing with the climate is prehistoric. In reality, from a historic perspective the idea of *not* designing with the climate is relatively novel, partly as a result of technological advance that allows artificial conditioning of buildings and reduces the pressure for passive means of conditioning buildings. However, the rate and way in which changes have occurred would not have been possible without an accompanying policy climate.

In general the history of environmental design is very related to changes in urban settlement patterns. These in turn are results of advances in technology and transportation that have had drastic impacts on the city.

### From Prehistoric times

Vernacular architecture is what is generally referred to as architecture that is passed from generation to generation not by academic means but by the learning of each generation of the elements that affect comfort and how they are affected by the climatic factors in the region where each culture is located. Thus, though different outcomes in terms of stylistic and identification icons may result from different religious beliefs or other social factors, certain adaptive features are recurrent in climatically similar areas. This responds not only to availability of materials but to an efficient use of technology and trial and error processes of improvement and adaptation of building techniques.

Even certain cultures that colonized areas in the Americas with a set of pre-established settlement patterns and rules, such as the *Leyes de Indias*, adapted them to local conditions when faced with the foundation of new settlements. This is evident in places like Old San Juan where topographical and climatic conditions are clearly factors in the location and orientation decisions.

The Ancient Greeks located their cities in harmony with the climate, capturing the positive orientations, and protecting them from the inclement climatic conditions. The city of Priene and Mileto are examples of this. The orientation of the grid and the relationship to the topography are intentionally used to optimize the winds and solar capture.

### Early contributions to environmental design

An important early contribution to environmental design was the sanitarist movement of the late 19$^{th}$ and early 20$^{th}$ centuries. Among the driving motivations behind this movement was the reaction to living conditions prevalent in cities that had undergone rapid industrialization processes.

Le Corbusier was among the leading voices of this movement that sought to rationalize the provision of hygiene to all the inhabitants of these urban areas.

On the urban scale Le Corbusier proposed starting all over again to get rid of the inefficient city of the past that had led the people to live in squatter conditions. In his proposition for the Ville Radieuse he proposed a pattern of separate high rise towers to assure every unit had proper access to wind, sun and open space. The sun's trajectory was studied and optimal distances established to assure these qualities were provided. CIAM's annual meetings provided a forum for the dissemination of these ideas. The ideas have come under strong opposition by the postmodernist movement, especially at the urban scale, but constituted an important push for studying issues relating to residential comfort conditions and how they are affected by climate.

Some avant-garde movements of the early 20$^{th}$ century, such as the Arts and Crafts Movement, were also reacting to the consequences of rapid industrialization of production processes. These however reacted to these trends more from an artistic perspective, reevaluating natural values.

In Barcelona the architecture of A. Gaudi and the Art Nouveau Movement in Brussels are expressions of admiration and imitation of nature. In the United States, the architecture of Frank Lloyd Wright also shows a preoccupation for climatic conditions and their effect on buildings. His project for the Jacobs house is an example of a building that uses the climate as input for design decisions and responds harmonically to it. Also in the United States, landscape architect Frederick Law Olmstead used health concerns to justify many park systems he proposed such as Central Park in New York City and the park system in Boston, both heavily industrial cities.

### The car

In the late 1920s the car erupted and changed the city dramatically. It gave birth to the idea of 'artificializing' living conditions[1]. The car represents the principal revolution in the evolution of cities in the 20th. century: it changes radically the natural living habits of people. Walking is greatly reduced, thereby reducing the demand and value placed on comfortable outdoor conditions. The car allowed sprawl and opened up areas previously out of reach, creating a demand for highways which fed the demand for cars and a cycle was begun whose impacts on land use and urban growth patterns are still increasing in most major American urban areas.

Due to fuel rationing and industrial concentration on the war effort, World War II brought about a temporary halt on automobile production and its related effects on urban areas. This lead to a revival of public transportation patronage and a renewed interest in outdoor climate conditions. However, this was short lived to be followed by one of the periods of greatest urban expansion ever.

### Post-World War II urban expansion

The era following World War II represents what is referred to as the time of the 'baby boomers'. It brought major changes in most American urban areas. Many of the future concerns of the environmental movement were being created in this period as a result of irresponsible

[1]Along with the elevator and the air-conditioning.

mismanagement and over-exploitation of natural resources.

The economic prosperity and affluence that followed the Great Depression and World War II led to a consumer revolution that not only spurred more motor vehicle travel, but also was itself fostered by the mobility that motor vehicles provided many Americans. Rising incomes and affluence enabled more people to buy and operate motor vehicles and caused them to attach a higher value to time, making the speed and convenience of motorized travel increasingly valuable.

This consumption boom was promoted by transportation and housing policies that favored suburban sprawl. The Interstate highway program begun in 1956 and the Federal Housing Act promoted the ideal of the individual detached lot housing. Zoning ordinances promoted inefficient single-use housing developments that made car ownership a must for any activity. Taxing policy, in terms of low interest rates and tax abatements on mortgage payments, also favored an ownership expansion that put pressure on quick suburbanization. This lead to environmentally unfriendly quick expansion of infrastructure and housing stock and made service provision in general a lot more costly and inefficient.

The 90/10 matching highway funds mechanism gave incentives for the states to build highways regardless of need, feasibility or environmental impact. These projects were politically easy to accept because the regions experienced an infusion of capital at almost no 'apparent' cost. The incentives were channeled to capital cost only so that often these infrastructure investments were built with no attention to the possibility to maintain them, creating an inefficient use of resources and numerous environmentally unsound investments.

**Environmental Awareness**

By the late 1960s and early 1970s the effects of indiscriminate suburban sprawl began to be reconsidered by urban residents who realized the degree to which urban quality in many urban areas had been sacrificed to the car. Environmental awareness about air quality, congestion and encroachment upon natural resources grew. The environmental movement began to make its influence felt, reacting to the preponderance given to the private automobile. People vs. highways movements were organized in Boston and San Francisco leading to major reviews of transportation planning and investment policies.

Some of the evident problems caused by suburban sprawl were further compounded by the oil crisis of the early 1970s.

At the federal level in the early 1970s there was a change in policy to allow states the discretion to shift some of the capital grants earmarked for highway investments into transit investments. However, by then practically all of the public transportation systems in the country were bankrupt and had been bought by the public sector. The seeds that made them unprofitable had already been planted in the previous years of urban expansion.

**The 1980's**

The 1980s-Reagan era brought deregulation and a relaxation of environmental regulations in favor of economic development. After the energy crisis and high inflation, priorities shifted to economic growth, at times with no regard to the cost. Enforcement weakened and the environmental concerns relegated to second plane. Widespread tax reductions implied cuts on programs to control air quality standards.

**Policy shift of early 90's**

The 1990s have brought a resurgence of interest in environmental concerns. It is still to be seen how these concerns play out. However, a new series of legislation along with a perception that environmental problems pose a threat to sustainable development along the existing land-use patterns and the growing of age of the baby-boomers have shifted the debate towards increased, generalized awareness of environmental issues. The problem has also been addressed from the design discipline with dubious results so far.

The Clean Air Amendment (CAA) of 1990 imposed tough restrictions and standards on air ambient quality. While some doubts still remain about its the bill is a sign that shows commitment to the reduction of emissions and improving air quality standards.

In 1991 the Intermodal Surface Transportation Efficiency Act (ISTEA) was passed. This bill allows for more efficient allocation of transportation resources by imposing a stringent review-of-alternatives requirement for all federally funded projects, thereby reducing the possibility of perverse incentives to overbuild.

In conjunction ISTEA and CAA, create a framework for joint efforts to coordinate land use and transportation for the first time in a serious and consistent manner. This opens up the possibility for serious reviews of investment incentives and therefore could signal a renewed interest in environmentally sound proposals.

**New Urbanism - neo traditionalism**

From the architectural perspective, New Urbanism emerged in the United States on the scene. This is an extremely broad and often misinterpreted movement. It was originally a group of architects that criticized the rigidities of zoning, land use and transportation patterns dominant in most urban areas of the United States. They stressed the inefficiencies created as a result of these patterns and postulated the need for better use of natural resources, transportation investments, increasing density and allowing mixed uses.

New Urbanism presents the prospect for increased attention to environmental concerns and addressing the issues of sprawl. In practice, however, New Urbanism has gone in many directions, often creating products that resemble more typical suburban sprawl with a simple neotraditional style applied to its surface than a solution to inadequate use of resources, apparent in its manifesto.

It is ironic that most of the new urbanism products are in newly created areas given the vast amount of infrastructure available in inner cities. These vacant areas immediately adjacent to urban downtown areas can be densified and infilled to support many more habitants and activities using existing resources rather than creating new models at longer distances. Most often these products are inherently not transit-oriented due to the basic decision regarding their location. Eventually, probably due to market forces that have resisted the idea, these projects resemble what the New Urbanists criticize. The issue of environmental design and climate has not appeared in the New

Urbanist debate.

## 2.5. Description of Tren Urbano project[2]

July 1996 marked the start of the final design and construction phase of the first modern rail transit system in Puerto Rico. The 17-kilometer, 15-station Phase I line of this automated heavy rail system, called Tren Urbano, is slated to begin operations in the summer of 2001.

Though only 160 kilometers long by 56 kilometers wide, Puerto Rico has a population of 3.8 million. About one-third of the Island's residents, 1.3 million, live in the San Juan Metropolitan Area (SJMA), a region on the northeast coast encompassing 13 municipalities and 400 square miles. The population of the SJMA generates about 3.2 million trips per day. An estimated 4,206 vehicles per square mile in the central SJMA create one of the most congested urban roadway networks in the world. And by 2010 vehicle trips per day are expected to rise by 45% over 1990 levels.

### A Train to Keep Traffic Moving

Every transportation study of the San Juan region from 1968 to 1993 recommended construction of a transit system running in an exclusive guideway. In the spring of 1994 the present administration of the Government of Puerto Rico approved plans for a heavy rail transit system. This system was the centerpiece of an intermodal master plan for managing mobility in the SJMA developed by the Puerto Rico Department of Transportation and Public Works (DTPW) and its Highway and Transportation Authority (PRHTA). The initial phase of Tren Urbano will serve three central municipalities of the SJMA, Bayamón, Guaynabo, and San Juan, and cost an estimated $1.25 billion.

The Phase I line will operate 20 hours a day, with trains running every four minutes during peak hours in the morning and afternoon. Though trains will have operators aboard, the system will be completely automated, with a double-track guideway that will serve an estimated 115,000 passengers per day. The population densities within one-half mile of the alignment range from 10,000 to 20,000 people per square mile, and over 30% of the total regional employment, nearly 150,000 jobs, will be located within a third of a mile of the train corridor.

The Phase I alignment connects the populous eastern municipality of Bayamón with Santurce, the heart of San Juan, passing through the municipality of Guaynabo and the districts of southern and central San Juan known as Río Piedras and Hato Rey. The line is 17.2 kilometers from end to end; it has 15 stations and a centrally located storage and maintenance yard where the operations center will also be located. About 40% of the line will be at-grade and 60% elevated over principal avenues. The only exceptions will be a short section below grade in a bermed trench and a tunnel section through most of the heavily congested and historically rich district of Río Piedras. The map shows the complete Phase I alignment.

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[2] PRHTA, "Tren Urbano: On track to Alleviate Traffic Congestion in San Juan", http://www.dtop.gov.pr/English/tu/tu.htm

**Backbone of an Intermodal Solution**

Phase I of Tren Urbano will bring a new mode of public transportation to the most congested sections of the SJMA. Approximately 55% of the system's users are expected to arrive at the stations by bus or "público" (privately owned vans that run on fixed routes franchised by the government). Given the critical importance of intermodal connections, Tren Urbano stations are being designed to maximize the integration of the rail system with the existing modes of transportation. Convenient access interfaces will serve pedestrians, públicos, buses, taxis, and privately owned automobiles.


**Figure 2.1. Map of Tren Urbano Phase I alignment**

The DTPW is already planning future phases of Tren Urbano. The first will be Phase Ia, which will extend the initial line from the edge of Santurce to its heart at the Minillas Government Center. Phase II will branch the system from Río Piedras east to a major park and ride facility at a terminus in Carolina. In addition, the DTPW plans to build TU Conexión, a medium-capacity transit system that will go into service along Roosevelt Avenue by 2002, linking the De Diego, Domenech, and Hato Rey Centro stations of Tren Urbano with the Plaza Las Américas shopping mall.

Additional future Tren Urbano lines will extend the Tren Urbano system to the airport in Isla Verde, the city of Caguas, and eventually to Old San Juan, thus providing convenient access to all major activity centers of the metropolitan region.

# 3. CLIMATE ANALYSIS

*'The climate presents a challenge to the architect not satisfied with substituting mechanical equipment for good design',* Cowan, H.J. Editorial in Architectural Science Review, Nov. 1959.

The objective of this chapter is to identify the appropriate design strategies that apply to a location. The chapter begins with a discussion on comfort, the factors that affect it and attempts to measure it. Following this, a classification of tropical climates is presented in order to contextualize and differentiate San Juan's climate from others. A discussion about the basic climatic indicators necessary to analyze a climate follows. Charts and graphs are provided to illustrate how the indicators are recorded and how some conclusions can be quickly drawn. The chapter ends with the identification of the appropriate bioclimatic strategies, which emerge out of the climatic analysis, and a discussion on their limits of applicability. These will be translated into specific design guidelines in chapter three.

The ultimate energy performance of a building will depend on the designer's degree of understanding of the influence that climatic factors exercise on a building and his/her commitment to take them into account in the early stages of design. Clearly, a building may be retrofitted to improve its performance but a substantial part of the potential benefits may be lost if the decisions are not made at an early stage, when major decisions such as a building's location, form and orientation are still not determined.

The climatic analysis process is presented in a linear, progressive sequence but it is in the architect's ability to use the guidelines selectively and apply them as tools that do not limit design capacities but feed and enrich the design process. Other challenges and obstacles to implementation are touched upon in chapter five.

In order to illustrate the steps used to arrive at design strategies I will use the climatic data from San Juan's Muñoz Marin International Airport meteorological station. I will also compare this climate with that of a different location, Mexico City, to illustrate how to extract, graphically and easily, some of the meanings of the charts. The criterion for choosing Mexico City was to find a location not too distinct from San Juan so that some climatic indicators are similar (latitude) in both locations but others are not (altitude) and show how this difference translates into different strategies and therefore different design recommendations. Had I chosen an extremely distinct climate, some of the nuances of the process would be lost due to lack of comparability.

### 3.1. Comfort

As one of the primary functions of many buildings is to counteract at least some of the main disadvantages of the climate in which it is situated, it should be able to filter, absorb or repel climatic and other elements according to their adverse or beneficial contributions to the comfort of its inhabitants or users.

Although human comfort cannot be measured in terms of psychological factors only, one of the primary requirements is the maintenance of thermal balance between the human body and its environment. This involves keeping the internal temperature of the body within a certain range, regardless of the relatively wide variations in the external environment. The conditions under which such balance is achieved and the state of the body when it reaches equilibrium with the surroundings, depend on the combined effect of many factors; some such as metabolic rate (activity)[1] (fig. 3.1), acclimatization and clothing[2] (Fig. 3.2) of the subject are individual characteristics while others such as the air temperature, radiation, humidity and air movement are environmental factors.

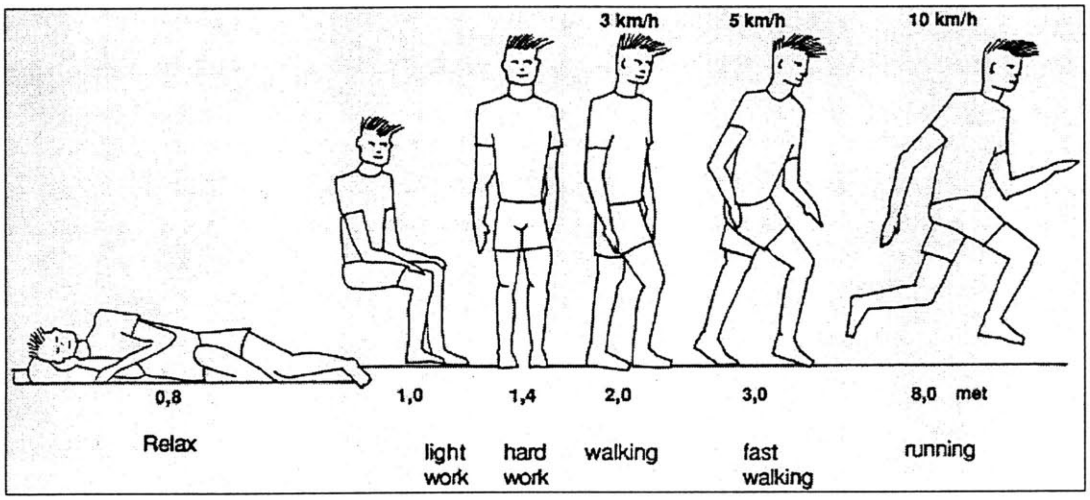


**Figure 3.1. Btu scale. Source Gut – Ackernecht.**

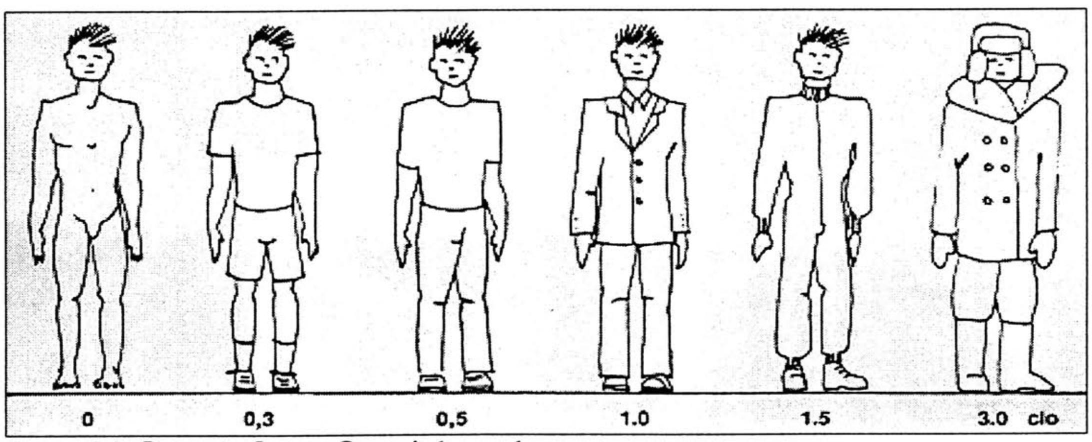


**Figure 3.2. Clo scale. Source Gut – Ackernecht.**

The body maintains a constant internal temperature by releasing superfluous heat to the environment and there is as a result a continuous exchange process of heat between the body and its surroundings which may take place in four physically different ways - conduction, convection, radiation and evaporation. These physical processes depend on the climate and are influenced in particular by the four mentioned environmental processes, each of which may aid or impede the dissipation of surplus heat form the body. These concepts are not very different to the processes buildings employ or building designers should employ to reach comfort. Fig. 3.3.

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[1]Scale of activity - expresses the rate of heat production in terms of BTU/h. Not always available but good approximations such as low (sleeping) medium (sedentary activities) or high (jogging) may be enough.
[2]Clo scale - measure of the insulation provided by clothing. Ranges from 0.3(low; light clothes like shorts and short sleeve shirt) to 1 (high; sweater).

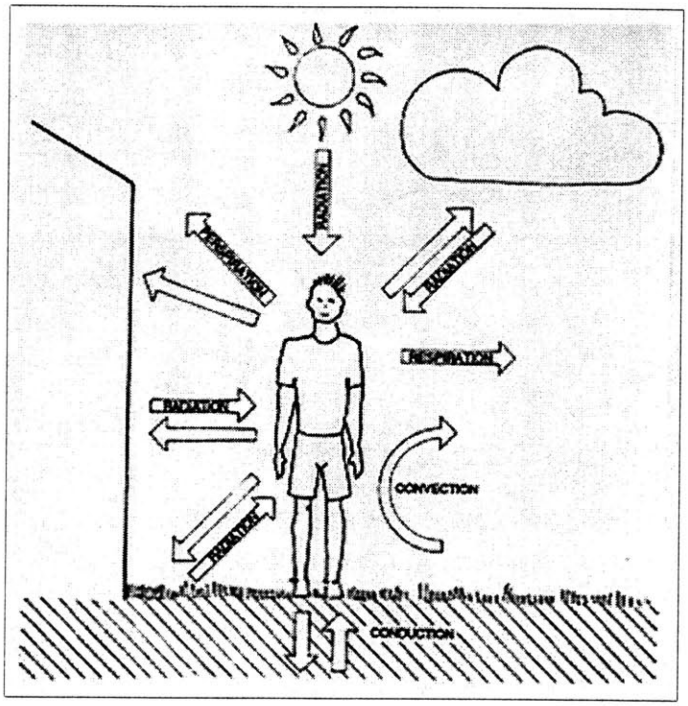


**Figure 3.3. Heat Exchange processes. Source Gut – Ackernecht.**

The contribution that conduction makes to the heat exchange process depends first and foremost on the thermal conductivity of the materials in immediate contact with the skin. A clothed person does not normally lose any great amount of heat by conduction and the physiological significance of heat loss by this process is limited to the local cooling of particular parts of the body when they come in contact with the colds materials that are good conductors. This is of practical importance in the choice of flooring and surface materials of all kinds.

The body exchanges heat with the surrounding air by convection. This form of heat exchange depends primarily on the temperature differences between the skin and air, and how much the air is moving.

Long-wave radiation on the other hand takes place between the human body and surrounding surfaces such as walls and windows. In this process the temperature humidity and movement of the air have practically no influence on the amount of heat transmitted, which depends mainly on the difference in temperature between the skin and the surfaces that surround or enclose it.

The body may gain or lose heat by these processes depending on whether the environment is colder or warmer than the body surface. In cold conditions the skin temperature is higher than the air temperature, while in hot conditions the situation is reversed.

When the surrounding temperature (air and walls) is above 25°C, the clothed human body cannot get rid of enough heat by either convection or radiation and the loss of perspiration becomes the sole compensatory mechanism. Water consumes heat in order to evaporate and, as humans normally lose about one liter of water per day, a fair a mount of heat is taken from the body to evaporate it. The extent to which heat is lost by evaporation depends on the clothing worn the levels of surrounding vapor pressure and the amount of air movement. The lower the vapor pressure and the more air movement the greater will be the evaporative potential. This is, however, lessened by clothing which reduces the air movement and increases the humidity over the skin.

The range of conditions in which thermal comfort is experienced is called the comfort zone - something which differs with individuals and is affected by the clothing worn, the activity performed, geographical location, age and sex. Although the comfort zone is defined as a subjective assessment of the environmental conditions, the limits of the zone do have a physiological basis; the range of conditions under which the thermo-regulatory mechanisms of the body are in a state of minimal activity. Comfort, which depends not only on the temperature of the air and that of the surrounding surfaces, but also on the relative humidity of the air and air movement, cannot be expressed in terms of any one of them as they affect the body simultaneously and the influence of any one depends on the levels of the other factors. Several attempts have been made to evaluate the combined effects of these factors on the physiological and sensory response of the body and to express any combination of them in terms of a single parameter or thermal index, which can be expressed in the psychrometric chart.

Other scales used to measure comfort are:

**Effective temperature**

This (and the subsequently developed *corrected effective temperature*) is the temperature of the air at 100% relative humidity that gives the same thermal sensation as a given combination of air temperature. humidity, air movement and mean radiant temperature. Effective temperature is one of the most frequently used scales of thermal sensation but it overestimates the effect of humidity both at cool and comfortable temperatures, and at very high temperatures. As a result the resultant temperature and equatorial comfort indices were developed using a similar concept and graphical format to overcome the drawbacks of effective temperature[3].

**Index of thermal stress (ITS)**

Developed by B. Givoni[4], it is based on the quantity of sweat that is necessary to maintain a skin temperature at 35°C. Comfort is achieved when the sweat rate is between 0 and 100 gm/hr. The variables included in the formula to establish the ITS are air temperature, humidity (vapor pressure), air movement, solar radiation, metabolic rate and clothing.

**BRS Method**

The method for establishing the comfort range of temperature developed by the British Research Station is based on the premise that comfort is attained when the body core temperature can be maintained at 37°C without sweating or shivering. The range is expressed in globe or dry bulb temperatures. This range varies with activity air movement and clothing. The comfort range is not reliable above 26°C as no allowance is made for the varying cooling effect of sweat that occurs with different humidities above this temperature[5].

**The Bioclimatic chart**

Developed by Olgyay, this shows the combination of temperature (on a vertical axis) and relative humidity (on a horizontal axis) which are comfortable(fig 3.4). The chart also shows the corrective measures required when the combination of temperature and humidity falls outside of the comfort zone. These measures include air movement, radiant heating, evaporative cooling and

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[3]Developed by T. Bedford, 1940, C.G. Webb 1960, and H. Missenard, 1948.
[4]B. Givoni, *Man Climate and Architecture*, 1969.
[5]M.A. Humphreys, 1970.

additional clothing[6]. This constitutes the first graphical effort to represent comfort conditions and define means to obtain them.

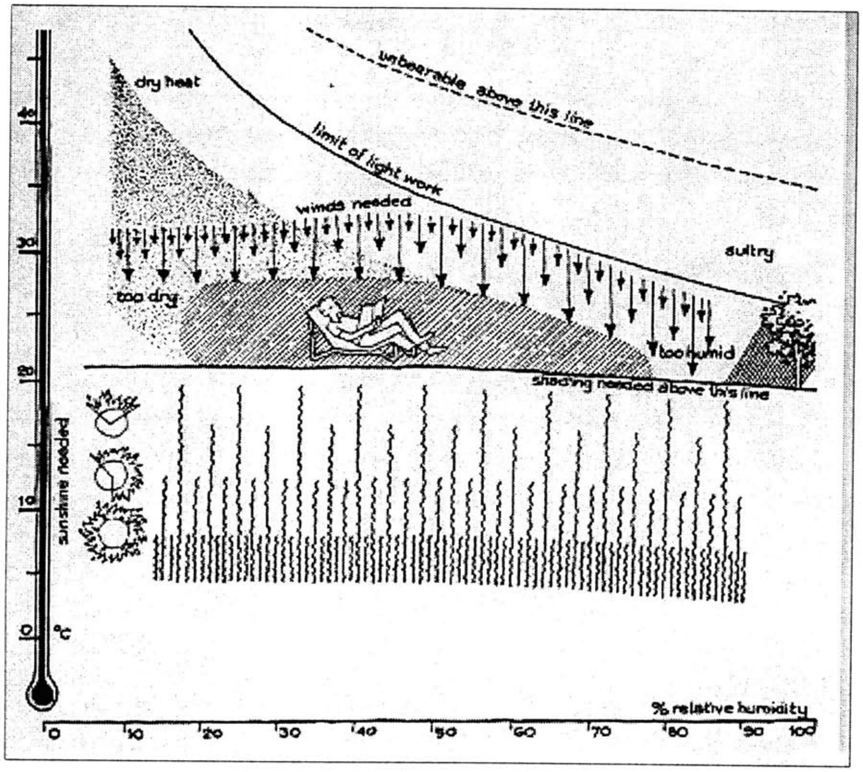


**Figure 3.4. Olgyay's Bioclimatic chart. Olyay, 1963.**

## 3.2. CLASSIFICATION OF TROPICAL CLIMATES

Before beginning the climate analysis it is useful to understand how the climate fits into the global climatic picture.

The interaction of solar radiation with the atmosphere and the gravitational forces, together with the distribution of land and sea masses produces an almost infinite variety of climates. However, certain zones and belts of approximately uniform climates can be distinguished. It is essential for the designer to be familiar with the character and location of these zones, as they are indicative of the climatic problems he is likely to encounter.

Boundaries of climatic zones cannot be accurately mapped. One zone merges gradually and almost imperceptibly into the next. It is, nevertheless, easy to identify the zone, or the transition area between two zones to which a particular settlement belongs.

Tropical climates are those where heat is the dominant problem where for the greater part of the year buildings serve to keep the occupants cool rather than warm where the annual mean temperature is not less than 20°C.

G. A. Atkinson[7] proposed the following classification of tropical climates in 1953. It is

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6V. Olgyay, *Design with Climate*, 1963.

7Atkinson, G.A., *Tropical Architecture and Building Standards*, Proceedings Conference on Tropical Architecture, 1953.

based on the two atmospheric factors that dominantly influence human comfort: temperature and humidity. The criterion is what extreme of these two factors is likely to cause discomfort.

Tropical climates are divided into three major climatic zones and three subgroups:

1. Warm humid climates – subdivided into warm-humid equatorial and warm-humid island climates.

2. Hot dry desert or semi-desert climate – subdivided into hot-dry desert climates and hot-dry maritime desert climates.

3. Composite or monsoon climate - subdivided into composite and upland climates.

Appendix A shows a more detailed description of each climate

From this classification, San Juan's climate falls into the warm-humid island climate category and Mexico City's into the composite upland climate category. This will be more evident as the climatic analysis is performed.

### 3.3. Analysis of climate

In general terms the climate analysis process follows the chart shown in figure 1. Climatic and site conditions are first analyzed. Monthly comfort requirements are identified. Hourly climatic conditions are determined and charted on the sun-path diagram. An analysis of the activities at the site and the time they are carried out is conducted to allow comparison of comfort requirements with level of activity at the site/building. Relating activities to be carried out in the spaces to be designed with existing conditions yields the climatic deficiencies, if any, of the site. These along with the comfort requirements are inputs to the psychrometric chart, which serves to identify the design strategies most appropriate for the location. These are then translated to guidelines in chapter three. Looking at microclimatic conditions and variations, which will fine-tune the guidelines applicable to a specific site, included in chapter four, provides further refinement.

It should be stated that some of the methods that follow are at times approximate and represent idealizations of variations that are not as precise and symmetrical as depicted in these graphs. However, they may be used to get good approximations of average conditions at any given time in any month. An example of a simplification is the depiction of symmetry between spring and autumn. In practice thermal inertia makes the period following the summer (hot season) - autumn- is warmer than the period following the winter - spring. The same argument can be made about the variation of temperature within a day: this however has been adjusted for in the nomogram so that the warmest temperature is not at midday, but a couple of hours after and similarly the coolest temperature is found towards 6 in the morning.

While passive (structural non-energy based) strategies as the ones represented in the psychrometric chart critically affect the performance of a building, they may result insufficient to surmount the comfort deficits a climate may impose on a building. Active (energy-based) means may be necessary in these situations. However, the understanding of climate's effects on buildings can help minimize the capacity required of these means. Moreover, a combination of design strategies will often be called for, as no single one is a panacea for design solutions.

### 3.4. Basic climatic indicators

The process of performing a climatic analysis relies on climatic data which should be collected from a meteorological station as close as possible to the site in which the design will be located. This is often difficult. The San Juan Metropolitan Area has only two meteorological stations of which only one, Muñoz Marin International Airport, has complete and reliable information.

The principal climatic indicators, when human comfort and building design are being considered, are solar radiation, humidity, wind, precipitation and special characteristics such as lightning, earthquakes, dust storms and so on. A certain amount of climatic data for a given location must be collected and analyzed: monthly mean maximum and minimum temperatures, the diurnal range, monthly mean maximum and minimum relative humidity values, average monthly rainfall, sky conditions, average amounts of solar radiation, and the direction and velocity of the prevailing winds, among other things. The frequency, likely duration and nature of any extreme climatic phenomena must be ascertained as even though they may be relatively rare and of short duration and therefore be acceptable from the point of view of human comfort, they must be considered in order to insure structural safety.

The modifying effects of microclimatic conditions must also be considered. Some knowledge of the character and abundance of vegetation, for example, is also essential because although it is generally regarded as a function of climate, it can influence the local or microclimate. Since the information for a specific site may be approximate, chapter four addresses how to adapt the design guidelines, resulting from interpretation of the climatic indicators for the area as a whole, to variations in microclimatic and site specific conditions.

The following is a discussion of the climatic indicators along with the data requirements for each.

**Temperature:** monthly mean maximum and minimum, and monthly mean and diurnal range. (absolute maximum and absolute minimum are optional but give a good reference of the potential extremes, especially for buildings of importance such as train stations, hospitals).

Temperature expresses what most people would consider to be the most characteristic of a tropical climate - the heat.

Since air temperature varies form one side of a building to another, from shaded to unshaded areas, from grassed or paved, it is an element which is difficult to define and in measuring it one can only hope to find a value which represents some average value of the temperature condition of a heterogeneous mixture of air.

The rate of heating and cooling of the surface of the earth is the main factor determining the temperature of the air above it. The air layer in direct contact with the ground is heated by conduction and this heat is transferred in turn to the upper layers mainly by convection and as a result of turbulence in the air. Since the heating of the lower parts of the atmosphere depends on convection and turbulence the nature of the ground is important to air temperatures. Soil particles, for instance, enclose a great deal of air which is an effective insulator and therefore a relatively thin layer of land heats and cools quickly so that in hot deserts the surface temperature may become very high.

At night and during the winter the surface of the earth is usually colder than the air as a result of radiation to the sky, and so the net heat exchange is reversed and air in contact with the ground is cooled. Generally, temperatures are lowest just before sunrise, as diffused radiation from the sky causes temperatures to rise even before dawn, and highest over land about two hours after noon, when the effects of the direct solar radiation and the high air temperature already prevailing are combined.

It is important for the designer to obtain not only the monthly mean maximum temperatures, but also the monthly mean minima, which will give an indication of the diurnal (day-night) variations. These can be large, for instance, in the hot arid zones, and building design must make allowances for this. A large diurnal range is indicative of dry weather and clear skies and the designer can anticipate intensive solar radiation by day and strong outgoing radiation by night pointing, broadly speaking, to the importance of shading, reflective coloring and possibly outdoor sleeping. A small diurnal range, on the other hand, indicates overcast skies and a humid climate or season, and points to the need for air movement and protection from rain, among other things.

**Atmospheric humidity**: monthly mean minimum and maximum and monthly mean relative humidity.

The term atmospheric humidity refers to the water vapor content of the atmosphere gained as a result of evaporation from exposed water bodies and moist ground and from plant transpiration. For any given temperature there is a limit to the amount of water that can be held as vapor, and the air's capacity increases with its temperature.

Several terms such as absolute humidity, specific humidity, vapor pressure and relative humidity are used to express the moisture content of the air. Absolute humidity is defined as the weight of moisture in a given volume of air ($g/m^3$), while specific humidity is the weight of moisture in a given weight of air (g/kg). The vapor pressure is that part of the total atmospheric pressure which is solely due to the water vapor, and ranges from a pressure of less than 2 milibars in cold regions and deserts to a pressure of 15-20 milibars in hot wet tropical regions.

Although the absolute humidity of a given body of air does not change unless water vapor is either added or taken from it, the relative humidity of the air concerned will vary with any change in the temperature. Hence, the variation in relative humidity during a day.

If the air contains all the water it can hold it is said to be saturated and its relative humidity is 100%, but if the air can contain more water its relative humidity is less than 100%. Relative humidity therefore measures the ratio of actual water content in a given volume of air to the maximum moisture capacity at that particular temperature.

As relative humidity affects the behavior of many building materials and their rate of deterioration, and vapor pressure affects the rate of evaporation from the human body, these two expressions of atmospheric moisture content, both of which vary greatly with the place and time, are most important from the designer's point of view. Whereas the diurnal differences in vapor pressure levels are small, they are subject to wide seasonal variations and are usually higher in summer than in winter. Relative humidity on the other hand may as the result of the diurnal and annual changes in air temperature undergo wide diurnal variations even when the vapor pressure remains almost constant.

Work in the late 1960s showed that the limiting condition regarding the measurement of humidity is the evaporation potential from the skin. The skin temperature, thus vapor pressure being almost constant for all humans, the evaporation potential depends only on the vapor pressure of the surrounding atmosphere. Hence ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standards set absolute humidity upper and lower limits of comfort at 4 g/kg and 12 g/kg, with the proviso that the 90% relative humidity curve should not be exceeded as such a high relative humidity would be unacceptable for other than thermal reasons[8].

**Precipitation:** monthly average precipitation (either in mm or inches) and maximum in any 24-hour period.

When unsaturated air is cooler, reducing its moisture holding capacity, its relative humidity rises until it eventually becomes saturated and any further cooling leads to condensation. Air may be cooled by coming into contact with cooler surfaces, mixing with cooler air and by expansion associated with rising air currents. It is only in the lower layers of air that cooling by contact with colder surfaces occurs and when condensation results it takes the form of dew on the cold surface. When the air not in direct contact with the colder surfaces is cooled below its dew point, fog -a dense layer of droplets lying close to the ground- is formed.

As air rises the pressure on it decreases and it therefore expands and is cooled. When a mass of rising air cools by expansion and reaches its dew point large-scale condensation occurs and when many of these droplets are maintained in the atmosphere by the upward movements, clouds are formed. As the air continues to rise, the small droplets coalesce into larger and larger drops until they are able to fall by gravity and precipitation, in whatever form, occurs.

It is important to ascertain not only the total rainfall for each month of the year, but also the maximum amount for any 24-hour period to be able to ensure adequate drainage from roofs and paved areas, apart from the maximum potential load the roof would be required to support if for any reason the water is collected.

**Air movement (Winds):** monthly frequency distribution, and average speed of at least the two predominant directions.

Direction, speed, gustiness and a frequency of calms are all important characteristics of wind, which is a very unstable parameter in most parts of the world, fluctuating markedly within a matter of minutes or hours and changing direction with passing weather systems. The variability of the winds is revealed in both its direction -which always refers to the direction from which the wind is coming - and its speed.

The winds over a region, their distribution and characteristics are determined by several global and local factors. The principal determinants are the seasonal differences in atmospheric pressure between places, the rotation of the earth, the daily variations in heating and cooling of land

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[8]Szokolay, *Climate Analysis based on the psychrometric chart*, International Journal of Applied Ambient Climatology, Vol. 7, 1986.

and sea, and the topography of the given region and its surroundings.

It is important to point out that, while it is beyond this work to make a full analysis of the causes of the influences responsible for winds, there are types of wind which occur and recur in place and time with regularity.

Over each hemisphere of the earth's surface there are belts and centers of high and low atmospheric pressure, some of which are permanent while others only exist for part of the year. The main cause of these centers and belts is the uneven distribution of solar radiation over the earth and the resultant variation in surface heating.

The weather at any place, however, can be affected not only by air moving under the influence of huge air masses, but also by winds of a more local origin which are typical of that area and are caused by a feature of the particular locality such as mountains, a lake or the sea.

Because wind affects ventilation, can be used for cooling, can carry dust and can require structures to be strengthened, the designer must determine the direction, speed and predictable daily and seasonal shifts of prevailing winds, and analyze how best to utilize or block the positive or negative aspects of the wind.

**Solar radiation:**

The three ways in which energy can be transferred from one point to another are radiation, convection and conduction. While transfer of energy by conduction and convection is relatively slow and requires the presence of some intermediate substance, radiation in contrast occurs with the speed of light and can take place without the presence of matter between the radiator and the receptor. Radiation transfers energy by means of electromagnetic waves, leaving an extremely wide range of wavelengths.

Solar radiation, which occurs in the so-called short wave-lengths is the source for almost all the earth's energy and is, as a result, the dominating influence on all climatic phenomena. The intensity of the solar radiation at the upper limits of the atmosphere varies according to the earth's distance from the sun and the solar activity, but the average intensity on a surface perpendicular to the solar rays is 1.94 $cal/cm^2/min$ and this value is called the solar constant.

As the radiation passes through the earth's atmosphere a series of losses occurs and the amount of reduction depends on the length of the atmospheric path it must traverse. A part of the incoming solar radiation is reflected by the surface of the clouds and part is absorbed by atmospheric ingredients such as ozone, water vapor and carbon dioxide, while a certain amount is scattered in all direction by the air molecules themselves. The intensity of the direct radiation depends, ultimately upon the solar altitude -- since that determines how much atmosphere the rays have to traverse -- and the amount of water vapor, dust particles, and man-made pollutants which the atmosphere contains. Part of the scattered radiation, called diffuse since it comes from all part of the sky, reaches the earth's surface and so the total irradiation or insolation (radiant energy received from the sun by the earth) is the sum of this diffuse and the direct radiation.

In the annual mean for the whole planet, only about half of the solar energy incident at the outer edge of the atmosphere penetrates as far as the earth's surface where most of it is absorbed and converted into heat while the remainder is either reflected back into the atmosphere or used up in the evaporation of water. As the surface of the earth absorbs energy, its temperature increases and it too radiates energy though in this case with a long wave-length which can be strongly absorbed by the atmosphere that tends to allow direct short-wave radiation to pass through without absorbing much of it. As the atmosphere absorbs energy its own temperature is raised and it in turn radiates heat some downward to the earth and some outward to be lost in space.

Solar radiation varies greatly with the geographic location, the altitude and the weather; in other words with the length of the day, the angle of the sun's rays to the ground with the length and quality of the atmosphere through which it passes and particularly with the cloud coverage. In general the greatest amount of radiation is found in two broad bands encircling the earth between 15° and 35° latitude north and south, where, in most areas the percentage of direct radiation is very high. The zone receiving the second highest amount of radiation, the equatorial between 15° north and 15° south, has a high humidity and is frequently clouded, so the proportion of diffused radiation is high in most of these areas.

The four main channels of radiant heat transfer affecting buildings are, in order of importance: direct short-wave radiation from the sun; diffused short-wave radiation from the sky-vault; short-wave radiation reflected from the surrounding terrain; and long-wave radiation from the heated ground and nearby objects. These affect buildings in two ways; firstly, by entering through windows and being absorbed by internal surfaces, thus causing a heating effect and, secondly, through being absorbed by the outside surfaces of the building creating a heat input a large proportion of which is conducted through the structure and eventually emitted to the interior. Another major form of heat transfer affecting buildings is the outgoing long-wave radiation exchange from building to sky -- an effect which is reduced when the sky is clouded and is strongest when the atmosphere is clear and dry as in hot-arid zones where it can be utilized as a source of energy for cooling buildings. In the hot climate areas of the world it is particularly important that these effects be determined.

Other climatic indicators may refine the depiction of climatic conditions but will not be used here as they are usually not available and not as critical to this process. They include cloud cover, days with thunder, days with frost, days with hail.

### 3.5. Recording the data

From this data the temperature can be plotted in the figure 5.5 to visualize the relative variations among seasons and within a typical day for every month. Thresholds depicting generic limits of yearly comfort conditions[9] are marked and different colors are used in the areas between the thresholds to reflect, in a quick graphical manner, the ratio of time in which the conditions are within the thermal comfort zone to time outside of it.

A clear difference is evident in the daily (diurnal) and seasonal (between summer and winter conditions) temperature ranges. In San Juan both thermal ranges are low while both of Mexico City's are higher. Moreover, a substantial part of the year San Juan's thermal conditions are within the comfort range while a smaller portion of it is within comfort in Mexico City.

[9]Comfort conditions depend on many factors and need to be adjusted for each month and case.

Relative humidity is plotted in the same chart and with the same rationale of using different colors to depict areas within certain generic average humidity comfort thresholds. Notice here also that there are considerable differences in humidity. While San Juan never reaches 100% relative humidity, it comes close, and Mexico City's almost never exceeds 75% and is often below the 40% mark. The amplitude in humidity is also different for both climates: while San Juan's humidity is relatively constant, Mexico City's shows steep changes between seasons.

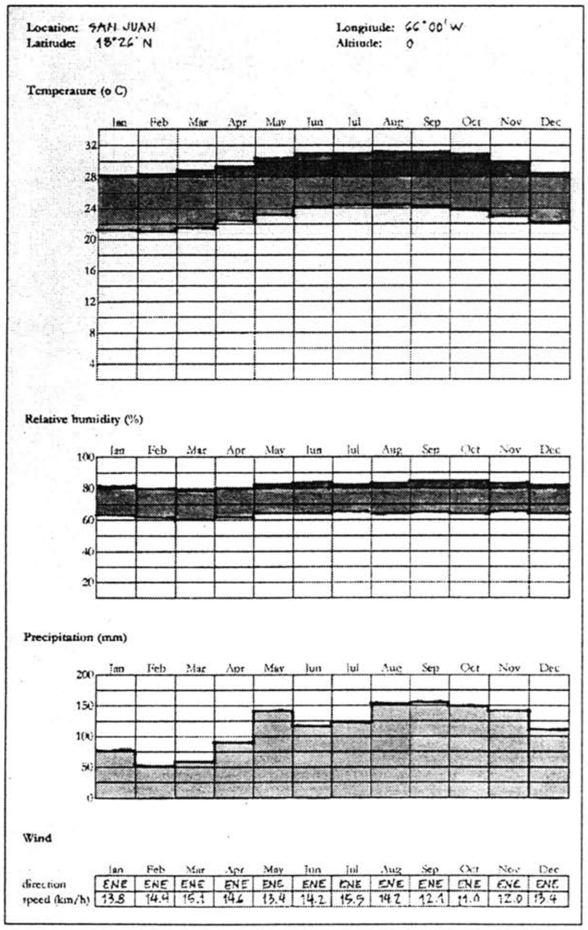


Figure 3.5. Climatic indicators, San Juan

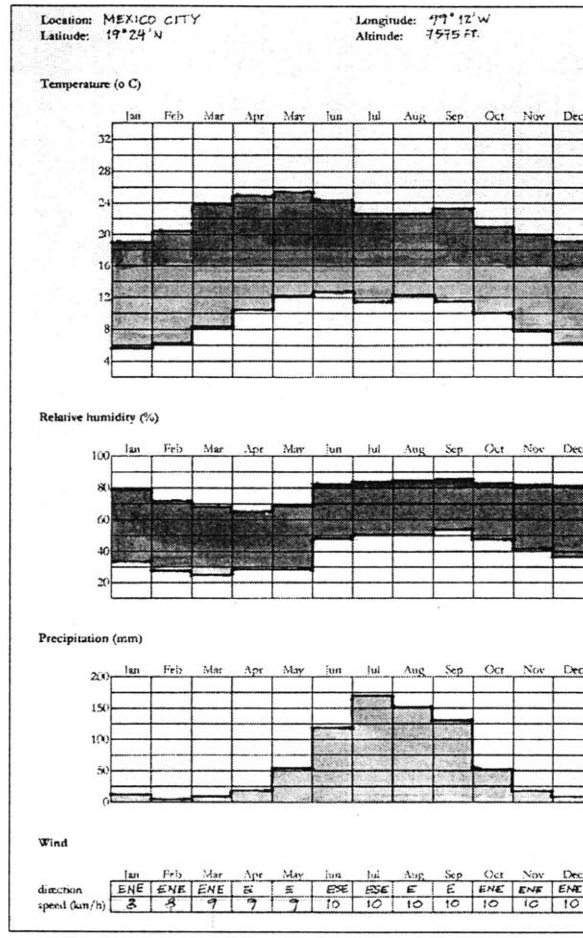


Figure 3.5. Climatic indicators, Mexico City

Solar radiation for both localities also shows considerable differences. Mexico City has higher average of clear skies than San Juan and therefore receives more solar radiation. This speaks of considerably higher direct radiation in Mexico City, offset partly by the large proportion of diffuse radiation in San Juan. Also adding to the radiation difference is the higher altitude at which Mexico City is situated. However, this may be tricky: Mexico City has considerable pollution which reduces the amount of radiation reaching the ground.

Lastly, precipitation is plotted in this chart. San Juan's annual average rainfall is approximately 55 inches. Mexico City receives an annual average of 28 inches of precipitation, with large variations among months. The presence of the mountain range in San Juan influences the variation of rainfall within short distances. Wind data is also recorded in this same chart.

From the information above it is possible to determine the hourly variation of temperature for a typical day in every month. This is done using a curve, called a nomogram (fig. 3.7), that represents an idealized (though very accurate) diurnal temperature variation pattern within any day, regardless of the location, using only the maximum and minimum temperatures of that month. Beside the graph that contains this curve and at the same scale, a chart contains a grid at the top of which the monthly mean maximum temperature is recorded and at the bottom the mean minimum temperature is recorded. Uniting the two points representing the maximum and minimum for each

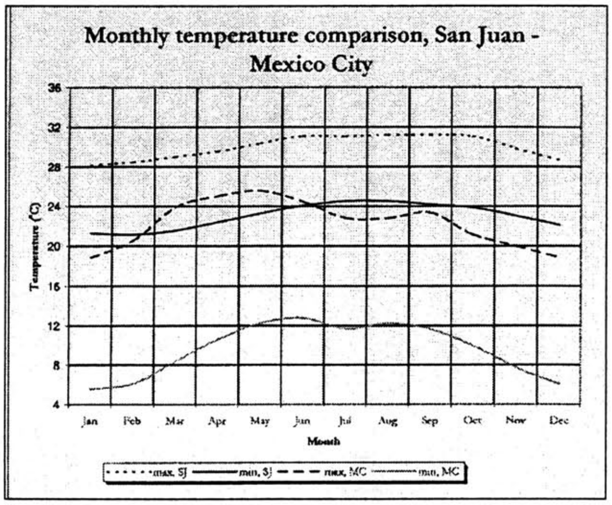


Figure 3.6. Temperature comparison.

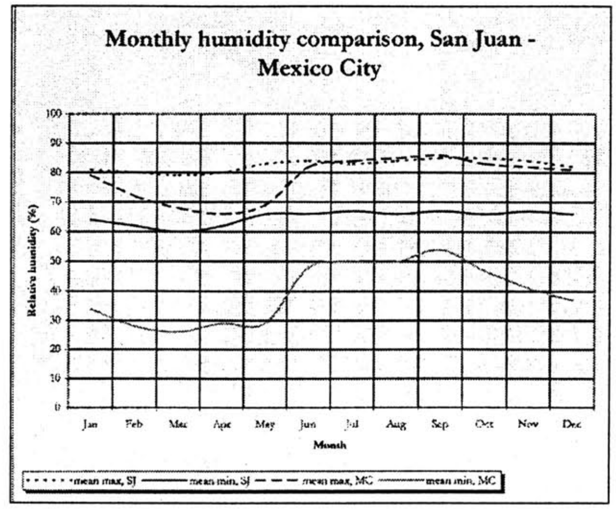


Figure 3.6. Relative humidity comparison.

month, yields a line that can be related to the curve to obtain hourly temperature figures. The steeper the line (the less the difference in temperature) the lower the diurnal range.

Having recorded each month's conditions it is possible to enter either graph to determine either: a) temperature at any given time of any month by entering the time (in the time graph) until it intercepts the variation curve and from there tracing a horizontal line until it intercepts the temperature line to see the corresponding temperature for that time, or b) at what time(s) a given temperature is reached, by entering the desired temperature (in the temperature graph) until it intercepts the temperature line and from that point tracing a horizontal line until it intercepts the variation curve and seeing what time(s) corresponds to this point, which may occur more than once in a day.

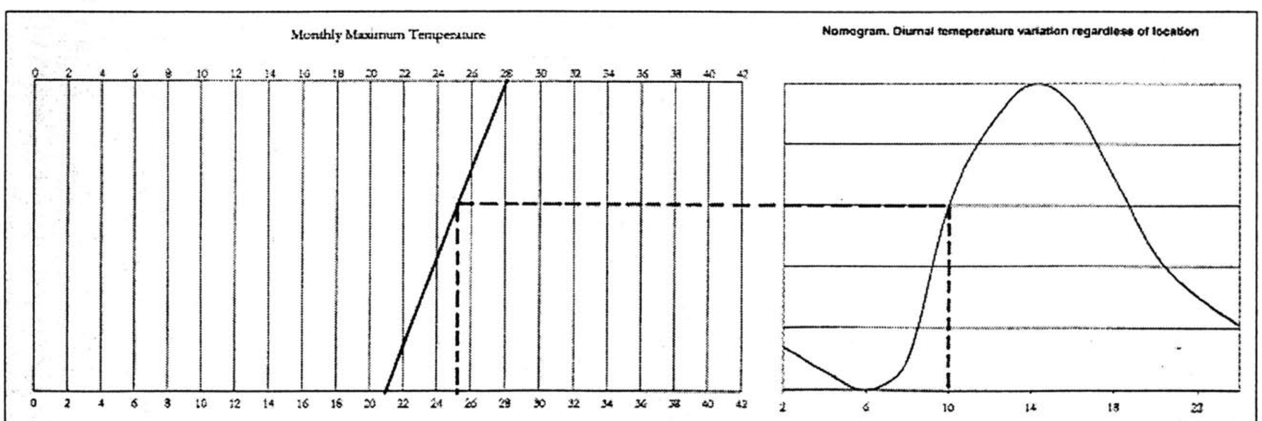


**Figure 5.7. Nomogram**

The information is then plotted into figure 3.8. This is a graphical representation of the climatic conditions month by month hour by hour. Using weighted average graphical interpolation it is possible to trace isothermal lines representing the threshold temperatures used in previous charts depicting generic comfort thresholds to draw the boundaries of when the conditions are in the comfort zone.

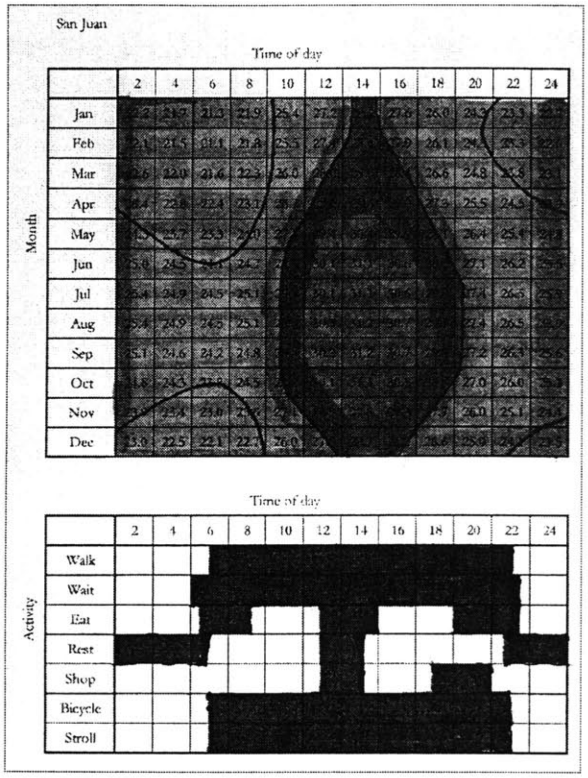


**Figure 3.8. Monthly hourly temperature and activities, San Juan.**

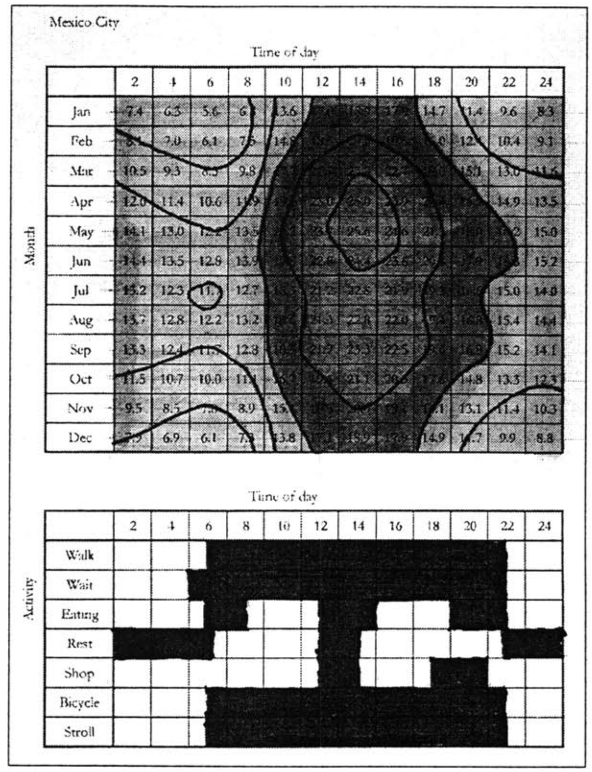


**Figure 3.8. Monthly hourly temperature and activities, Mexico City.**

A table below the yearly and hourly portrait of conditions and in the same scale represents the activities that are expected to be carried out (or known to be) at the site and at what times. This should be done for the three distinct and representative climatic seasonal conditions[10] as activities and their timing will shift with climatic variations. Of course activities also vary among localities due to climatic variations among climates and cultural differences. This provides a better understanding of when there are comfort deficits and what activity is being carried out at that time.

A more accurate and refined representation of the conditions is provided by plotting the data on a sun-path diagram, figure 3.9.[11]. This is a monthly bi-dimensional representation of the sun's trajectory with respect to one point, in the center of the circle. It allows us to determine the precise position of the sun at any time in any month. Therefore, it allows us to identify the position of the sun with respect to an object when uncomfortable conditions exist, since we can plot the isotherms identified in the previous chart on this chart. Chapter 3 explains how to use this chart to obtain the sun's most representative and important angles, from a design perspective.

[10]One for summer conditions, one for winter conditions and one for spring/autumn conditions which for simplification matters are assumed symmetrical though they are not

[11]This diagram of course varies with latitude

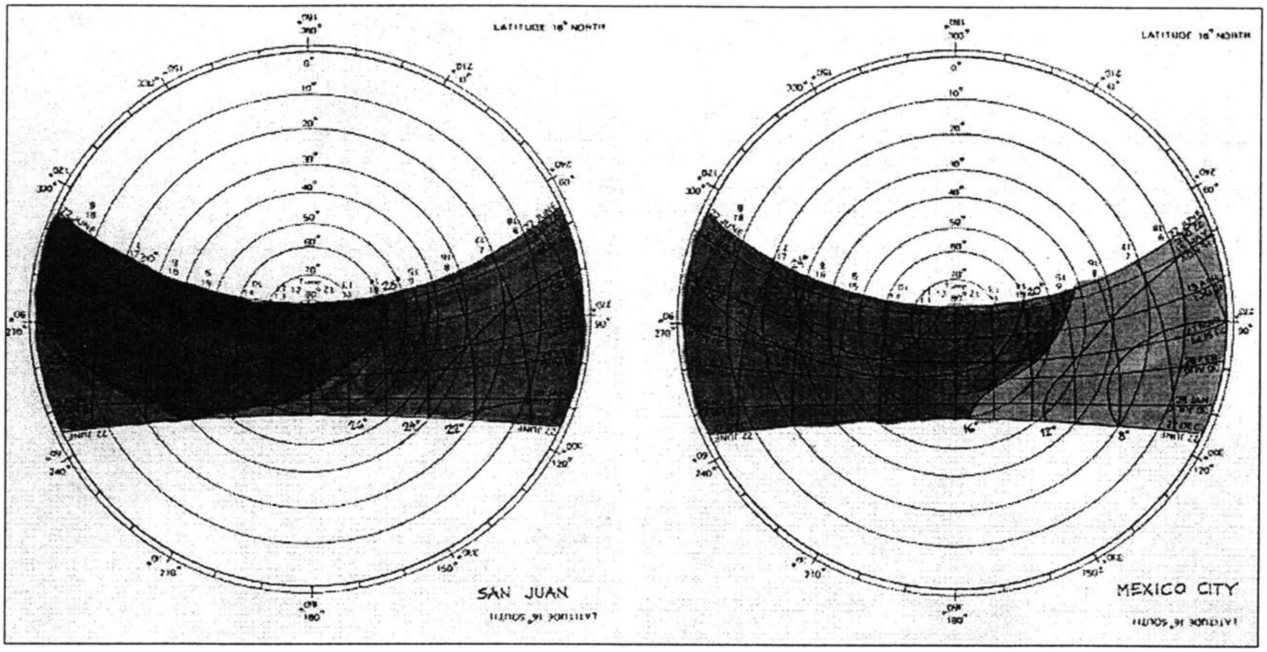


**Figure 3.9. Sun-path diagrams for San Juan (left) and Mexico City (right).**

The lines that stretch from east to west represent the horizontal projection of the sun's path for every month. The shortest day anywhere north of the equator and thus in San Juan is the 21st. of December, the winter solstice, and the longest the 21st. of June, the summer solstice. On the 21st. of March and the 21st. of September the sun rises exactly from the east and sets exactly at west. The day lasts 12 hours and so does the night. These are called the vernal and autumnal equinox.

The shorter lines that point to the center represent the time of the day. For example, the intersection of the 9 a.m. line with the December line determines a point. Tracing a line from this point to the center point (the object) generates a line which is the horizontal direction with which the sun is striking an object located at that center point (or the direction of the shade cast by an object if it were located at the center of the chart). This angle is called the azimuth and is measured with respect to 0° south.

The concentric circles represent the angle formed by the sun, the object (at ground level) and the horizontal plane of the earth[12]. This angle is a function of the latitude and can be determined mathematically (as we will see later) or graphically by interpolating between the concentric lines. In this case at 9 a.m. in December the angle would be 30°. The sun path for Mexico City is the same since sun geometry is determined by latitude, but the climatic data is different because of the difference in altitude and topography. This angle is called the solar height and is measured with respect to the horizontal plane.

With the information from the previous graph it is possible to draw the isotherms on to the sun-path diagram and get a more accurate picture of when solar protection or solar gain may be

[12]In order to study the sun with respect to a point certain fair assumptions are made: the sun's rays are considered parallel amongst each other and the earth at a certain site is considered plane.

necessary and where the sun is located with respect to the object when these necessities occur. If we add the wind to this chart we get a complete portrait of the climatic conditions.

### 3.6. Identifying the strategies

Having made this detailed climatic analysis and depiction of the climatic conditions and their deficiencies, we must see how they compare to the comfort zone, derived earlier. This is done in order to come up with design strategies that indicate general driving objectives that should inform the design process. The strategies, in turn, are associated with a set of design guidelines that specify design decisions regarding design variables at various scales. This is the subject of chapter 6.

Comfort is not a fixed condition: it is affected by many factors as explained previously. Szokolay suggests a method, using the psychrometric chart, to determine each month's comfort zone and the limits of applicability of each design strategy. The psychrometric chart is similar to Olgyay's bioclimatic chart. The only difference is that Olgyay plotted temperature to relative humidity while the psychrometric chart, used widely to dimension air conditioning units, plots temperature to absolute humidity and the upward curves represent relative humidity (level of saturation). Appendix B shows the monthly comfort zones for every month in San Juan. A year-round comfort zone using average annual temperature can be used as a good approximation. Figure 3.10 represents comfort zones and climatic conditions for both climates.

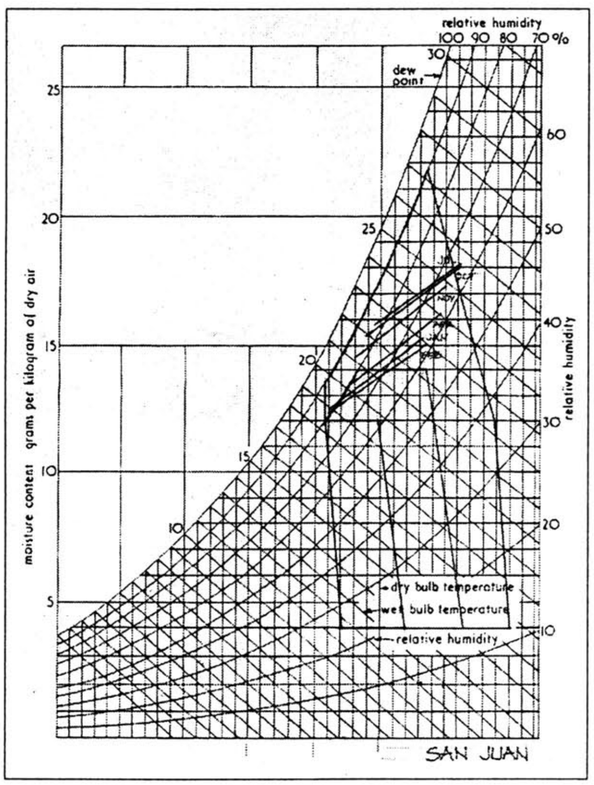


**Figure 3.10. Psychrometric chart, San Juan.**

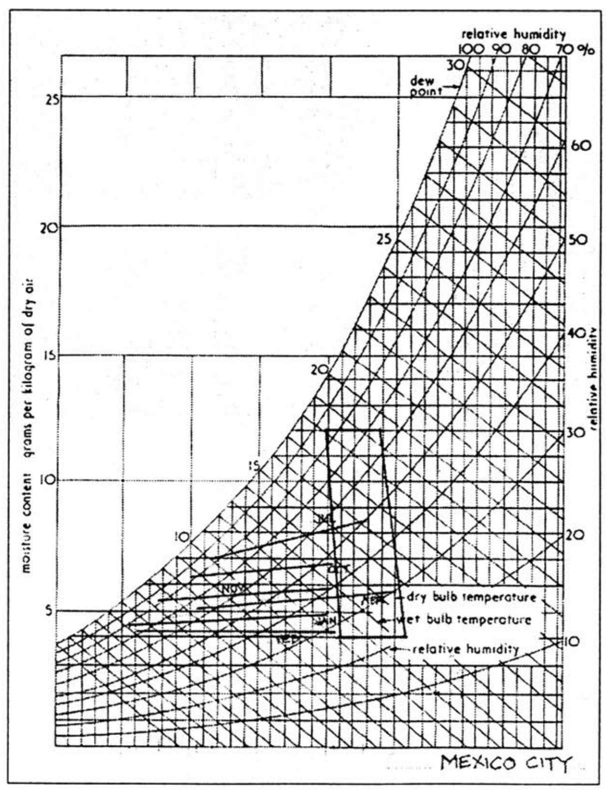


**Figure 3.10. Psychrometric chart, Mexico City**

To identify the bioclimatic design strategies, every month's conditions are plotted on the psychrometric chart with a line defined by its extreme conditions: its maximum and minimum temperatures and maximum and minimum relative humidity[13]. Then the area that represents the annual comfort zone is added. This allows us to see how far or close from the comfort zone the climate is. Overlaid in the chart, a set of areas outside the comfort zone covering the rest of the chart area, represent design strategies that should be used to bring conditions within those areas closer to the comfort zone. The strategies are general objectives such as humidification in arid climates or solar protection in hot climates or solar gain in cold climates. Since each month's conditions are represented by lines they often overlap into various strategies. Often a combination of strategies is required, not only due to amplitude within each month but because amplitude among months can be important, especially so if the extreme conditions were included in the chart.

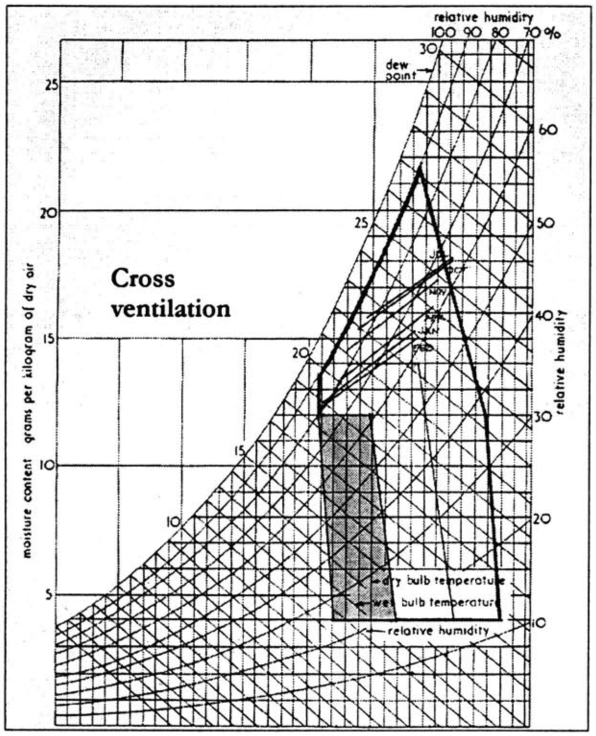


Figure 3.11. Bioclimatic strategies, San Juan.

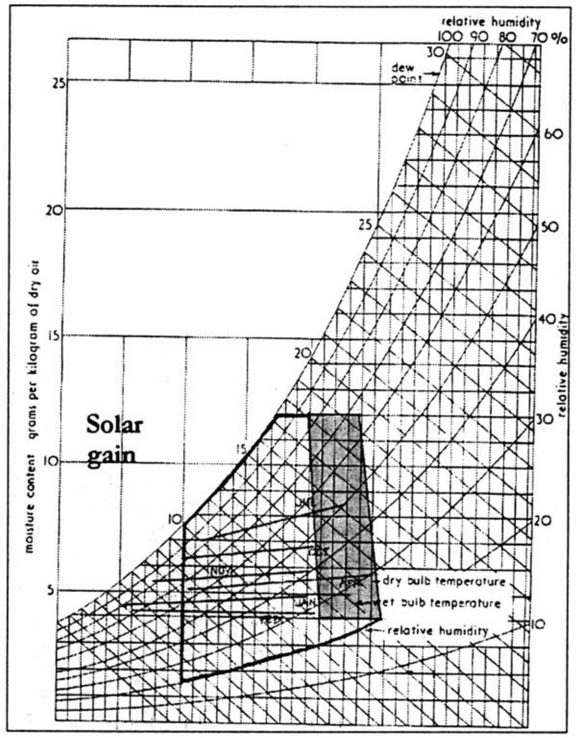


Figure 3.11. Bioclimatic strategies, Mexico City.

In this case San Juan's conditions show very little thermal amplitude while Mexico City's exhibit much higher amplitude. This is due to differences in the two locations' proximity to sea, altitude and proximity to mountains. The closer to the equator, the lower the amplitude and the distance from the sea also increases the thermal amplitude. Higher altitude, with equal sky conditions, also produces a larger temperature range (see variations in chapter 5).

San Juan requires cross ventilation and solar protection throughout the year, while Mexico City requires a mix of thermal inertia, and solar gain. These strategies are the bases of the design guidelines that govern every scale of the design process.

13For simplification it is assumed, quite accurately, that the lowest temperature coincides with the highest relative humidity and the highest temperature coincides with the lowest relative humidity.

# 4. GEOMETRIC - THERMAL PROPERTIES

This chapter introduces some of the basic geometric principles, thermal properties of materials and wind utilization principles that govern the relationship between climate and buildings. It also includes a discussion of the relevant thermal properties of building materials and their implications for design. Lastly, a review of the impacts of wind on buildings and vice versa is presented. Methods for quick solar and wind verifications of design proposals are presented.

## 4.1. Solar geometry

### Geometry --- general

The earth rotates around its own axis and orbits around the sun. Each rotation makes one 24-hour day. The axis of this rotation (line joining the north and south pole) is tilted to the plane of the elliptical orbit at an angle of 66° 5' and the direction of this axis is constant.

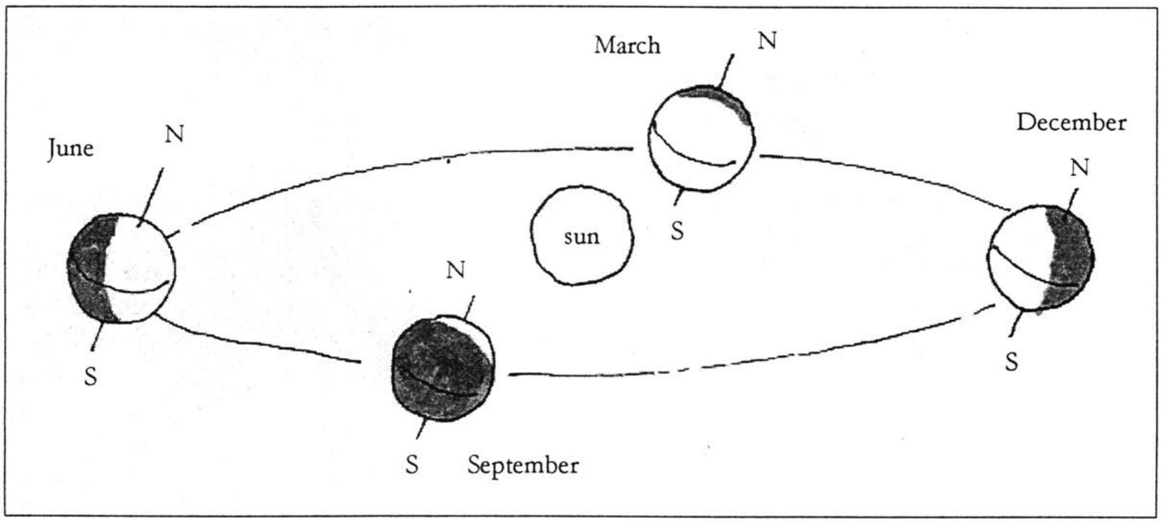


**Figure 4.1. Earth orbit around the sun.**

Maximum intensity of solar radiation is received on a plane normal to the direction of radiation. If the axis of the earth were rectangular to the plane of orbit, it would always be the equatorial regions, which are normal to the direction of solar radiation. Due to the tilted position, however, the area receiving the maximum intensity moves north and south between the Tropic of Cancer (23° 5' N) and the Tropic of Capricorn (23° 5' S). This is the main cause of seasonal changes.

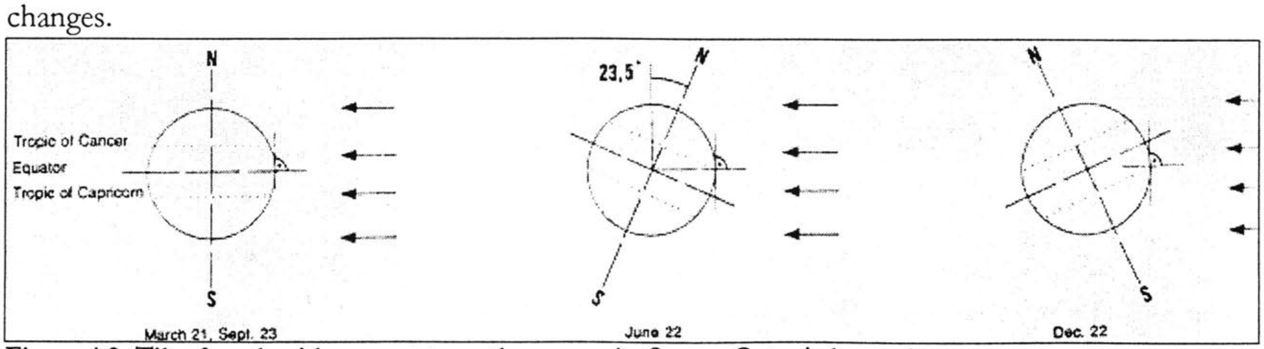


**Figure 4.2. Tilt of earth with respect to earth – sun axis. Source Gut - Ackernecht.**

The earth sun relationship affects the amount of radiation received at a particular point on the earth's surface in three ways[1]:

1. the cosine law: states that the intensity on a tilted surface equals the normal intensity times the cosine of the angle at which the sun incides on the surface.

2. atmospheric depletion, that is the amount of radiation absorbed by ozone vapors and other particles in the atmosphere. The lower the solar altitude the longer the path of solar radiation before it reaches the earth's surface and therefore the higher the absorption by the atmosphere.

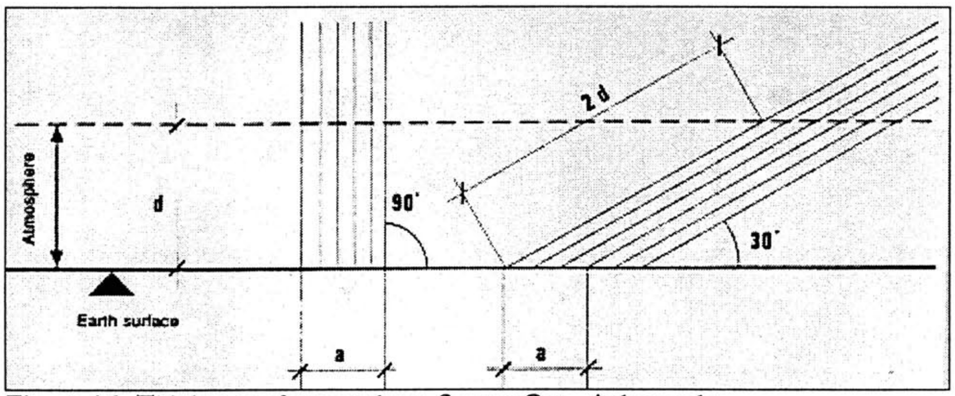


**Figure 4.3. Thickness of atmosphere. Source Gut - Ackernecht.**

3. duration of the sunshine, that is the duration of the daylight period, since sunshine and sunrise are a function of latitude.

### Solar angles

Solar angles are needed to design and verify at all levels of the design process from site design to buildings and building components, such as shading devices.

### Sun-path diagram, graphical representation of solar angles

The sun-path diagram (Fig. 4.4) is a very useful tool to understand and synthesize the geometry of the relationship between the earth and the sun. It can be used to obtain angles on the horizontal plane, solar height angles and duration of days, by month and time of day.

The lines that stretch from east to west represent the horizontal projection of the sun's path for every month. The shortest day anywhere north of the equator, and thus in San Juan, is the 21st. of December, the winter solstice, and the longest the 21st. of June, the summer solstice. On the 21st. of March and the 21st. of September the sun rises exactly from the east and sets exactly at west. The day lasts 12 hours and so does the night. These are called the vernal and autumnal equinox.

The shorter lines that point to the center represent the time of the day. For example, the intersection of the 9 a.m. line with the December line determines a point which represents both its

[1] Koenigsberger, Ingersoll, Mayhew, Szokolay, *Manual of Tropical Housing and Building*, 1973.

location and height. Tracing a line from this point to the center point (the object which we are studying) generates a line which is the horizontal direction with which the sun is striking an object located at that center point (or the direction of the shade cast by an object if it were located at the center of the chart). This angle is called the azimuth and is measured with respect to 0° south.

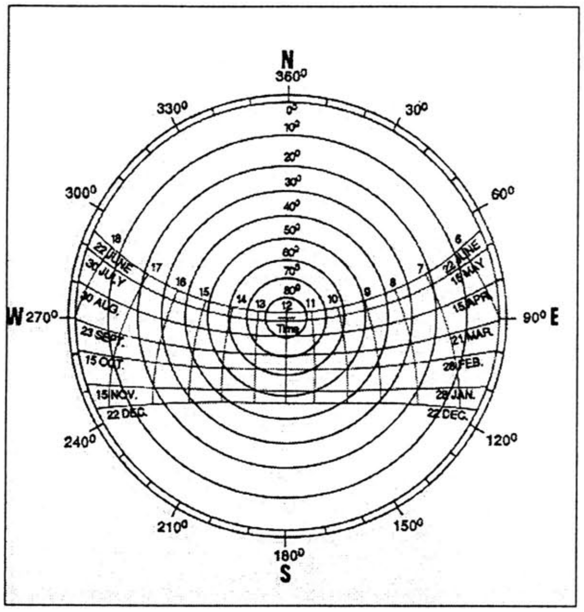


**Figure 4.4. Sun-path diagram, 20°N.**

The concentric circles represent the angle formed by the sun, the object (at ground level) and the horizontal plane of the earth[2]. This angle is a function of the latitude and can be determined mathematically (as we will see later) or by graphically interpolating the point arrived at between the concentric lines. In this case at 9 a.m. in December the angle would be 30°. The sun path for Mexico City is the same since sun geometry is determined by latitude, but the climatic data is different because of the difference in altitude and topography. This angle is called the solar height and is measured with respect to the horizontal plane.

**Analytical way to find solar angles**

To find the angle of incidence of solar radiation, the position of the sun in relation to the building elevation must be established for the given point in time.

The sun's position on the sky hemisphere can be specified by two angles:

The solar altitude angle (y), i.e. the vertical angle at the point of observation between the horizon plane and the line connecting the sun with the observer.

The solar azimuth ($\alpha$), i.e. the angle at the point of observation measured on a horizontal plane between the northerly direction and a point on the horizon circle where it is intersected by the arc of a vertical line going through the zenith and the sun's position.

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[2] In order to study the sun with respect to a point certain fair assumptions are made: the sun's rays are considered parallel amongst each other and the earth at a certain site is considered plane.

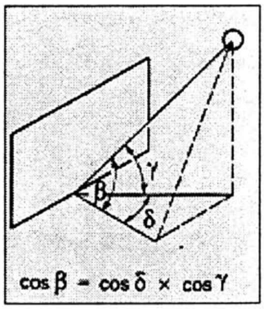



**Figure 4.5. Solar angles**

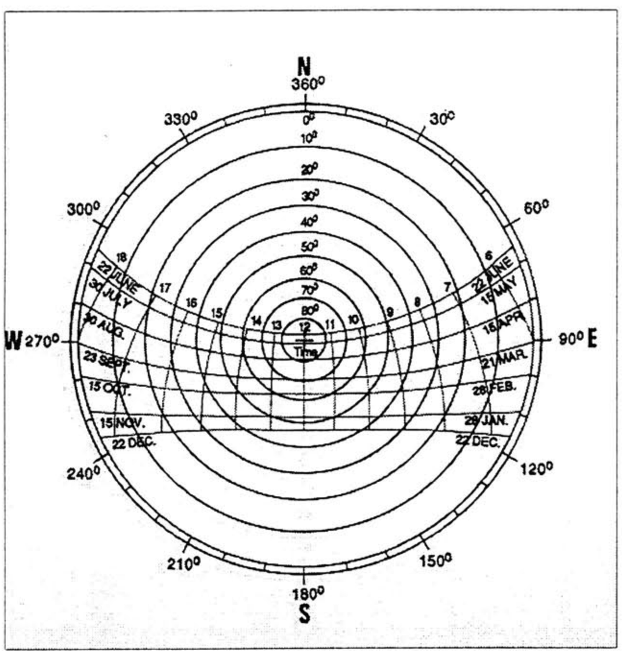
These two angles can be read directly for any date of the year and any hour of the day from the solar charts or the sun-path diagrams, given in Appendix B.

The sun's paths at various dates are shown by a group of curves extending from east to west (the 'date lines') which are intersected by the short 'hour lines'.

The series of concentric circles establish a scale of altitude angles and the perimeter scale gives the azimuth angle.

For example:

Find the sun's position in San Juan at 15:00 on the 15th of October. The horizontal angle (azimuth) would be 63° from the south and the solar altitude is approximately 38°.




From these two angles the sun's position in relation to the wall surface of any orientation (thus the angle of incidence) can be established.

The horizontal component of the angle of incidence ($\delta$) will be the difference between the solar azimuth and the wall azimuth. If for the above example, the wall is facing west (270°).

$\delta = 270° - 243° = 27°$

The vertical component of the angle of incidence is the same as the solar altitude angle itself (y).

In Fig. 4.5, the angle of incidence ($\beta$), i.e. the angle between a line perpendicular to the wall and the sun's direction, can be found by the spherical cosine equation.

$\text{Cos } \beta = \cos \delta \times \cos y$

In our example:

$\text{Cos } \beta = \cos 27° * \cos 38°$

$\beta = 45°$

This angle of incidence will be required for both selecting the appropriate solar gain in heat calculations through windows and for calculating the incident radiation on an opaque surface.

Both angles can be used to calculate the shadows cast by an object at any time of the day. This will help determine the distance between building according to either the need to capture the sun or protect from it.

**4.2. Daylight/glare**

In warm humid island climates the sun is not as strong as in the hot dry climates. However, a cloudy sky especially at midday can be very bright. The main source of daylight in these climates is therefore the bright and often cloudy or overcast sky. The chief design problem in these conditions is to reduce glare. Glare is caused mainly by strong contrasts. If the ratio between the brightest and the darkest portions of a room is excessive, glare conditions will exist. Since sky brightness is normally 100 times greater than room brightness, an ordinary window can create excessive glare because the degree of contrast it creates is greater than what the eye can comfortably tolerate.

Among the means to control glare conditions are:

- Avoid use of dark colors on window walls
- Avoid use of frosted glass in the lower panes of window
- Strip windows are superior to punched windows as they give more evenly distributed light over the length of the room, prevent 'pools' of glare, and assist in providing better ventilation.

Since large openings are required to ensure air movement in warm humid climates probably the best way to limit the amount of daylight is to cut off direct view of the sky. Adjustable wooden and aluminum louvers, and *brise soleils* are used widely for this purpose. Figures 4.6 and 4.7 show how the sources of glare are created, how to control it and the effects on indoor conditions.

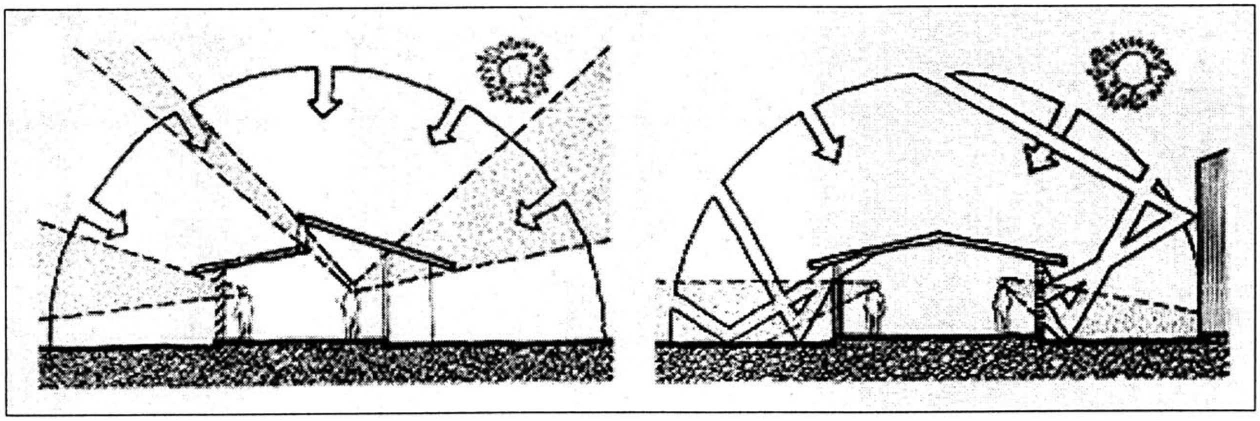


**Figure 4.6. Glare. Source Konya.**

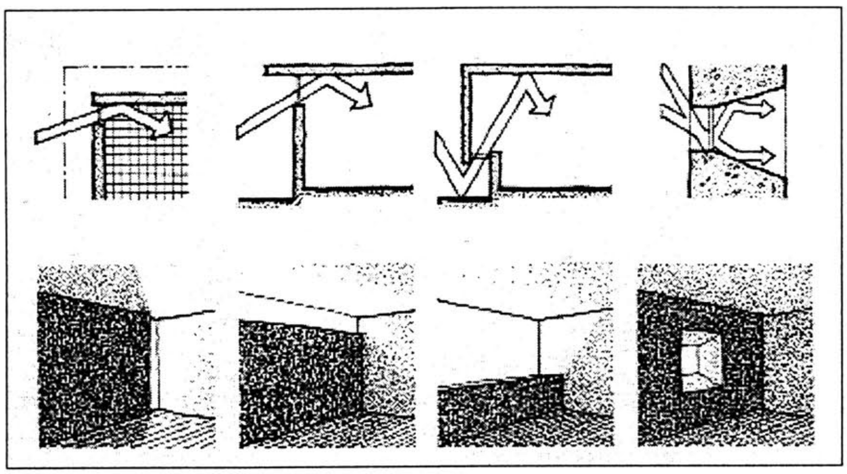


**Figure 4.7. Glare. Source Konya.**

## 4.3. Wind

Winds are convection currents in the atmosphere, which tend to even out the differential heating of zones. It is a mechanism of pressure compensation. The pattern of air movements is modified by the earth's rotation. At the maximum heating zone, which is somewhere between the tropics of Cancer and Capricorn, air is heated by the hot surface, expands, and its pressure is decreased. Therefore it becomes lighter and rises vertically, and flows off at a high level towards colder regions. Part of this air, having cooled down at the high level, descends to the surface in the subtropical regions from where the cooler heavier air is drawn in towards the Equator from both north and south.

The atmosphere rotates with the earth. As it is light it has a tendency to lag behind the rotation of the earth where it is fastest, the Equator. There is a slippage[3] at the boundary between

[3]Ibid.1. The slippage effect is called the Coriolis force.

the earth and its atmosphere, which creates a wind in the opposite direction to that of the earth's rotation. The resultant wind is a product of the thermal forces and the slippage effect: northeasterly winds north of the equator and southeasterly winds south of the Equator. These are called the northeast and southeast trade winds.

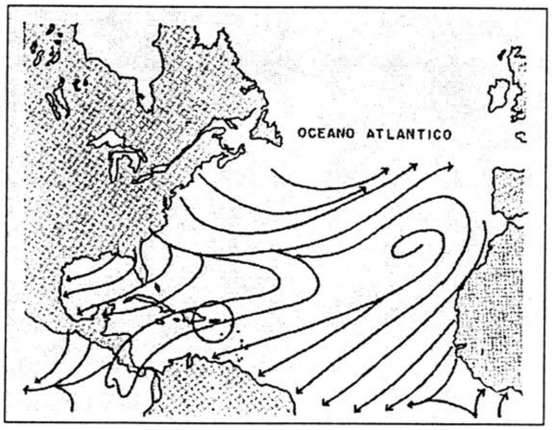



**Figure 4.8. Wind patterns, North Atlantic Ocean. Source Muniz.**

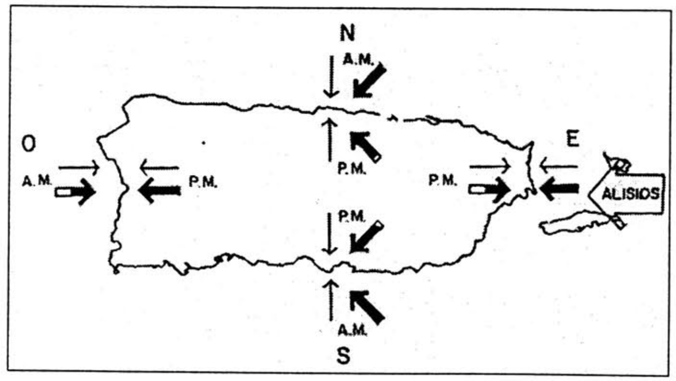



**Figure 4.9. Trade winds, Puerto Rico. Source Muniz.**

Figures 4.8 and 4.9 show wind patterns in the northern Atlantic Ocean and in Puerto Rico.

## Ventilation

Natural ventilation and air movement perform three separate functions: the supply of fresh air for health reasons, the cooling of the interior by convection and the cooling of the inhabitants under certain circumstances. The forces producing natural ventilation in buildings result from changes caused by differences in temperature -the stack effect, where warmer and lighter indoor air is displaced by cooler and denser outdoor air- and by air movement or flow produced by pressure differences. Whereas the movement of air at a relatively slow pace, as a result of thermal forces may be adequate for both the supply of fresh air and convection cooling, these forces are rarely sufficient to create the appreciable air movements required in some zones to provide thermal comfort. The only natural force that can be relied upon for this purpose is the dynamic effect of winds and every effort must be made to capture as much wind as possible.

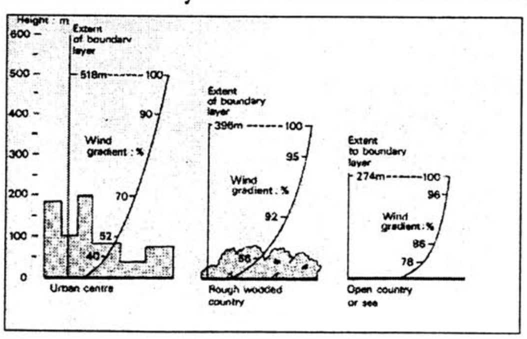



**Figure 4.10. Wind gradient. Source Evans.**

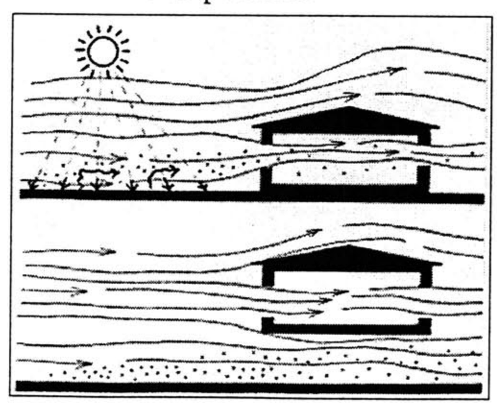


**Figure 4.11. Height – wind capture. Source Evans.**

The availability of air movement is affected by the height at which a building is located with respect to ground level and the degree of urban development (resistance to wind produced by development). Figure 4.10 shows the wind gradient in an urban, suburban and rural setting as a function of height above ground.

Topography is also a contributing factor to the availability of winds. Valleys channel winds, depressions keep it out, windward slopes are exposed whereas leeward slopes are protected from winds. Fig. 4.11.

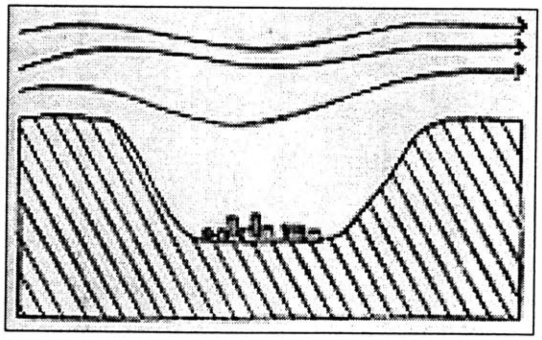


**Figure 4.11. Topography – wind. Source Gut. – Ackernecht.**

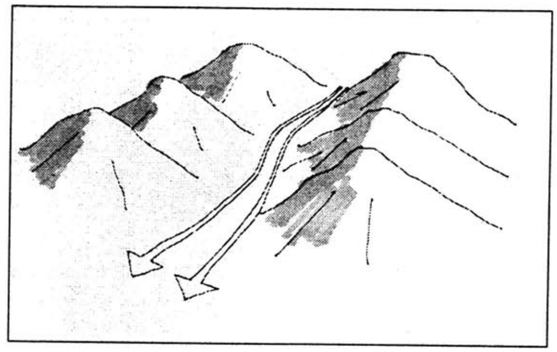


**Figure 4.11. Topography - wind**

Once a wind can be captured, its manipulation is an important tool for obtaining comfort. Generically, wind refreshes in hot climates (convection facilitates evaporation) whereas in cold climates it produces discomfort by adding to the cold. Therefore attention to winds is one of the key ingredients to creating comfortable conditions without recurring to artificial means.

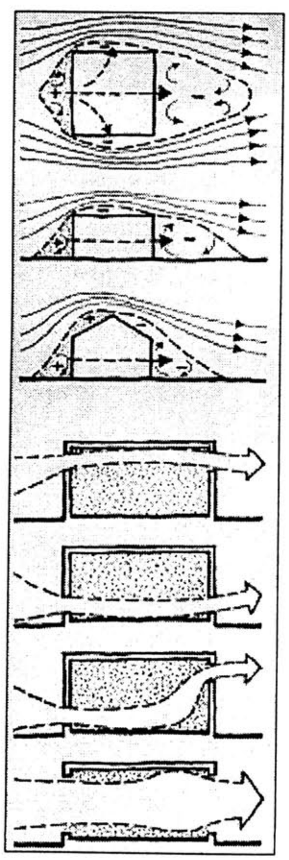


**Figure 4.12. Effects of wind in plan and section. Source Konya**

Areas immediately behind a building are protected from the wind (wind shadows). Negative pressures generate a suction effect.

Various effects can be taken advantage of to acclerate wind and produce air movement in warm climates.

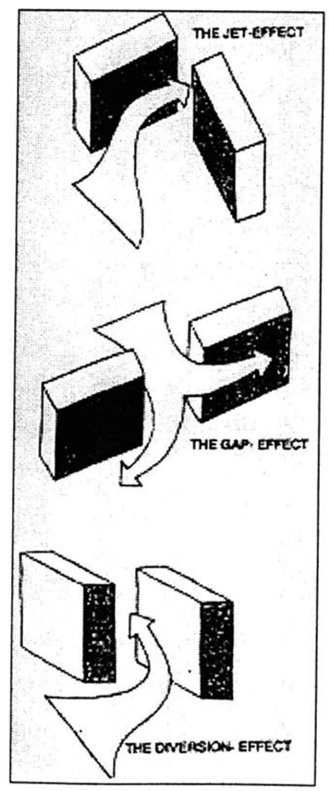



**Figure 4.13. Wind channeling and acceleration effects. Source Grut.**

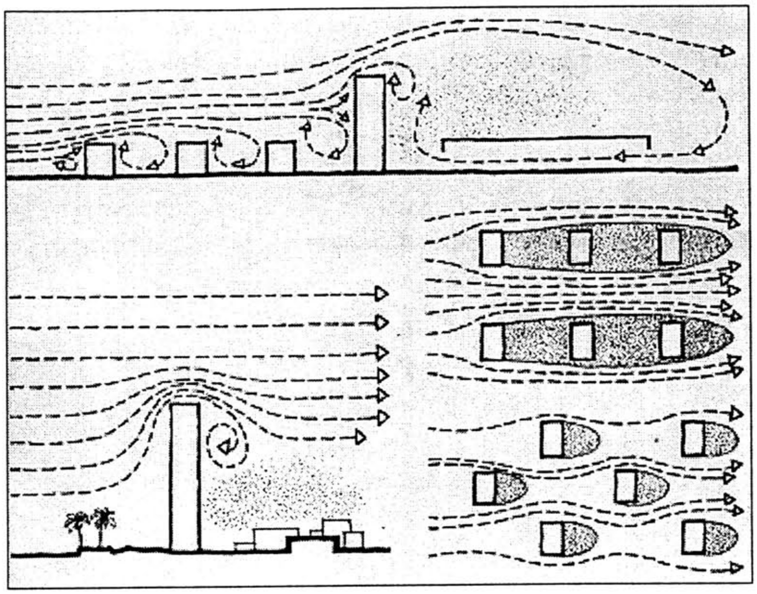


**Figure 4.14. Staggering buildings and effects on wind. Source Konya.**

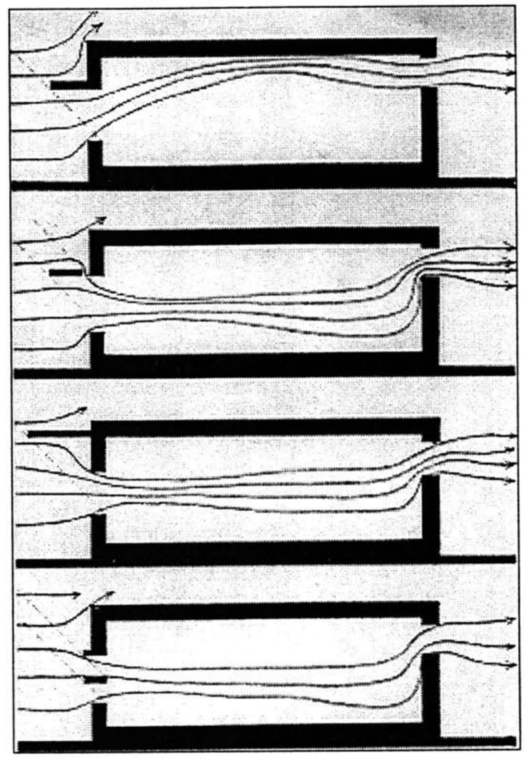


**Figure 4.16. Wind and openings/shading devices. Source Evans.**Location of openings and design of shading devices affects wind capture and distribution.

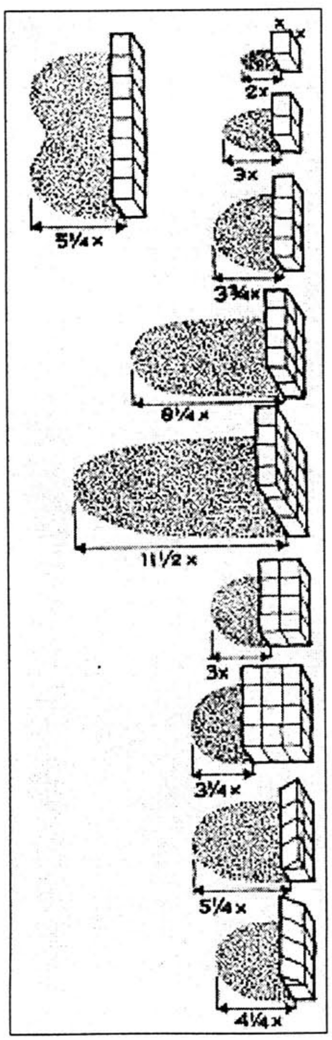
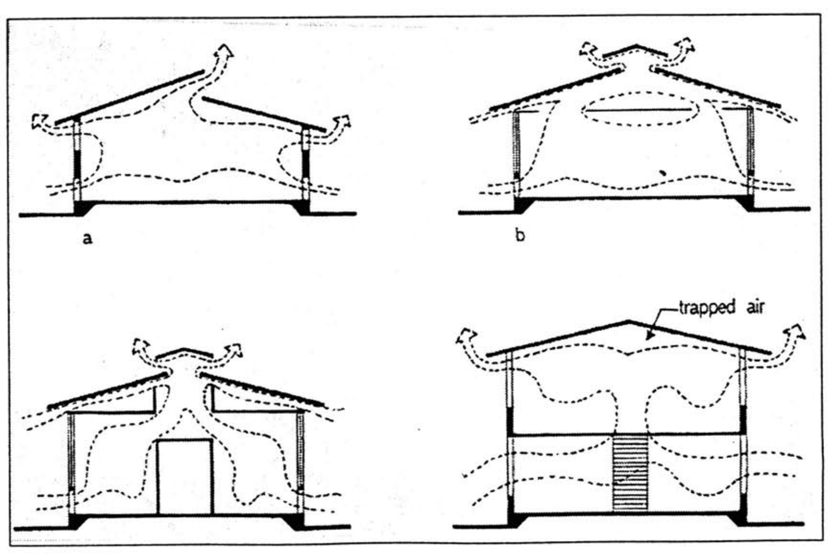



**Figure 4.15. Wind shadow produced by buildings as a function of their proportions. Source Konya.**Use of wind shadow determines distancing between buildings if desire is to protect or capture a wind. Scattering and staggering buildings creates smaller wind shadows.

**Figure 4.17. Wind and heat. Source Kukreja.** Warm air rises and is carried by air movement. There are areas of trapped air if no ventilation is available.



### 4.4. Noise

Noise is the term used to describe unwanted sound. The issue is of particular importance in the tropical areas because so many activities take place outdoors.

The main sources of noise in an urban area are:

- industry
- transit vehicles and railways
- buildings (mechanical equipment)
- vehicles (cars, trucks, buses)
- airplanes
- people

Usually a conflict between thermal comfort and noise control arises in warm-humid climates. Noise control calls for barriers or full enclosure while thermal comfort and wind requirements call for large openings. Selectively placed absorptive surfaces can help reduce noise.

Noise can be divided into those generated inside a building and those generated outside of it. Different strategies can be employed to control each type of noise.

The principal means for external noise control are:

- distance
- avoiding zones of directional noise
- screening (solid barriers)
- use of non noise-sensitive parts of building as barriers
- positioning of openings away from noise source
- noise insulating building envelope

For noises generated inside the building the following measures can be used:

- reduction at the source
- enclosing and isolating the source
- planning: place non noise-sensitive spaces as barriers in between areas
- use of absorbent materials in the space where noise is generated
- place noisy equipment in most massive part of building
- reduce structureborne sound transmission by discontinuity

Buildings in warm-humid climates should be of a lightweight construction. From the outdoor noise point of view, the building envelope will not be able to control noise. At the very best it can reduce the penetration of outside noise by skillful use of absorbent surfaces. From the point of view of inside noise the situation is somewhat better because noise is free to escape, and will be reflected less from bounding sources.

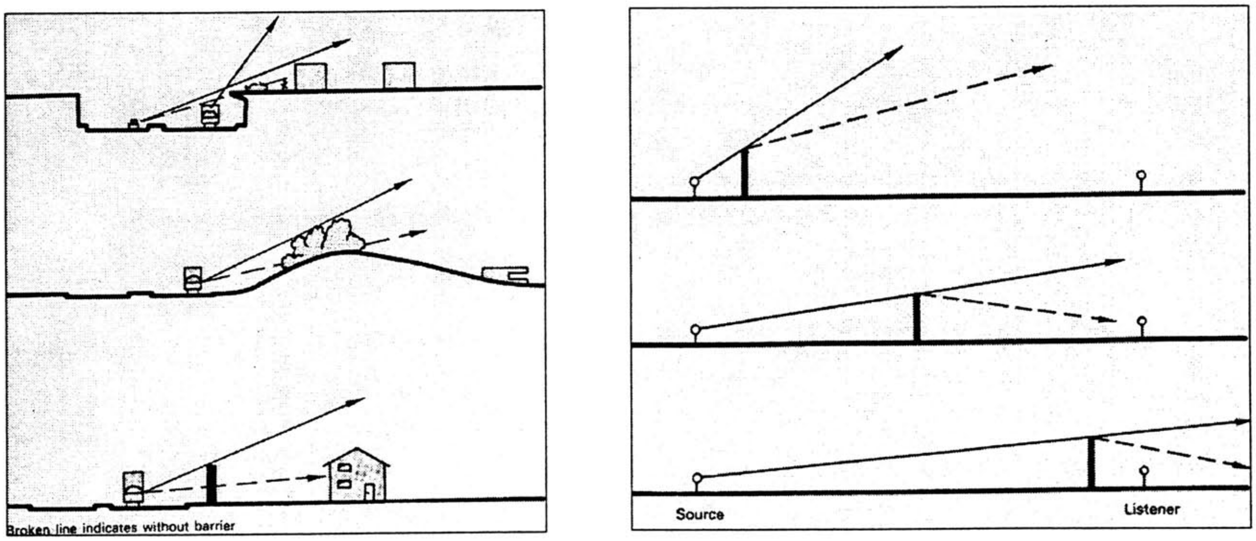



**Figure 4.18. Noise control. Source Koenigsberger, Ingersoll, Mayhew, Szokolay, 1973.**

Planning controls such as distance, positioning or various forms of barriers will have to be relied on to a great extent. There is one area of concurrence between thermal and noise comfort: densities should be somewhat lower than in other climates, therefore distance between buildings will be greater to allow air movement and this helps reduce noise problems.

## 4.5. Thermal properties of materials

Roofs, floors and walls of buildings will modify the internal temperature, and when the appropriate thermal properties are chosen it will be possible to achieve and maintain comfortable internal temperatures over a wide range of external conditions. Even when it is not entirely possible to achieve comfortable conditions, walls and roofs with suitable properties will minimize discomfort, or reduce energy consumption where heating or air conditioning are used.

There are three primary thermal properties, which will determine the way in which materials will absorb and transmit heat. These are:

1. Absorptivity. Property of a surface that determines the proportion of radiation falling on the surface which will be absorbed. Measured in %.

2. Conductivity (or k-value). Property that identifies the rate at which a unit area of material of unit thickness will transmit heat from one surface to the other when there is a unit difference in temperature between the two surfaces. Measured in W/m ° C. Varies from 0.3 W/m * ° C for insulating materials to 400 W/m * ° C for metals. See appendix XXX for values.

Resistitivty is the reciprocal of this quantity (1/k) measured in units of: m ° C/W. Better insulators have higher resistivity values. It represents the time required for the transmission of one unit of heat through the same piece of material given a difference of 1°C in the temperature of the two opposite faces.

Density is often taken as an indicator of conductivity: higher density materials normally have a higher conductivity or k-value, but there is no direct or causal relationship between the two quantities. The apparent relationship is due to the fact that air has a very low conductivity value, and as lightweight materials tend to be porous, thus containing more air, their conductivity tends to be lower.

3. Thermal capacity. Defined as the amount of heat required to raise the temperature of a unit volume of the material by a unit difference in temperature. Measured in J/° C

**Thermal properties of building elements**

The above properties can be used to measure the four thermal properties of wall and roof elements, which will determine the way in which they will modify the internal comfort conditions.

1. 'U' value or air-to-air transmittance. Rate at which heat is transmitted from the air on one side of a wall or roof to the air on the other side, per unit surface, per unit difference in air temperature. Measured in $W/m^2$ * degC. Note that the difference in temperature is written as degC to avoid confusion with actual temperature which is written as °C, since 10 degC is not the same as 10 °C (especially when converting to and from the Fahrenheit scale). Its reciprocal is air-to-air resistance, $R = 1/U$ (measured in $m^2$ * degC/W).

2. Solar heat flow factor. Proportion of incident solar radiation which is transmitted through a wall or roof element when the air temperature on both sides of the element is the same. Expressed as a nondimensional fraction.

3. Time lag or time delay. Difference in time between the temperature variations on the external surface and the consequent temperature variations on the internal surface, when the element is subject to diurnal fluctuations in temperature. Expressed in hours

4. Admittance. The ability of the surface of a building element to absorb or transmit heat to or from the air at a given rate when the temperature of the air adjacent to the surface is raised or lowered.

The relationship between the internal temperatures and the levels of air temperature and radiation influencing the external surface will depend on the thermal properties of all the building elements acting together. It will also be influenced by ventilation and heat generated within the building (or in the case of air conditioning, heat extracted from the building). The thermal properties must therefore be considered in relation to the total building envelope, the occupancy and the use of the building as well as the external climatic conditions.

**Sol-air temperature concept**

Heat transfer into the outer surface of building elements exposed to solar radiation will obviously be higher than that into similar shaded elements. For building design purposes it is useful to combine the heating effect of radiation incident on a building with the effect of warm air. This can be done by using the sol-air temperature concept. A temperature value is found, which would create the same thermal effect as the incident radiation in question and this value is added to the air temperature.

$t_{sa} = t_o + (I * a) / h_o$

$t_{sa}$ = sol-air temperature in o C
$t_o$ = outside temperature in o C.
I = radiation intensity on the surface in $W/m^2$
a = absorbance of the surface
$h_o$ = outside surface conductance ($W/m^2$ degC)

**Transmittance (U-value), conductance, resistance**

While conductivity and resistivity are properties of materials the corresponding properties of a body of a given thickness are described as conductance (C) and resistance (R = 1/C).

Conductance is the heat flow rate through a unit area of the body when the temperature difference between the two *surfaces* is 1°C. The unit of measurement is $W/m^2$ * degC.

The resistance of a body is the product of its thickness and the resistivity of its material.

$$R = b * 1/k = b/k$$

where b is the thickness in meters

If a body consists of several layers of different materials, its total resistance will be the sum of the resistances of the individual layers. The conductance of such a multilayer body ($C_b$) can be found by finding its total resistance ($R_b$) and taking its reciprocal:

$$R_b = R_1 + R_2 + R_3 .... = b_1/k_1 + b_2/k_2 + b_3/k_3 ... = \Sigma b/k$$

$$C = 1/R = 1/(\Sigma b/k)$$

In addition to the resistance of a body to the flow of heat, a resistance will be offered by its surfaces, where a thin layer of air film separates the body from the surrounding air. A measure of this is the surface or film resistance, denoted 1/f, where f is the surface or film conductance in $W/m^2$ * deg C.

Surface conductance includes the convective and the radiant components of the heat exchange at surfaces. Up to now heat flow was considered from one surface of the body to the other. If the heat flow from air on one side through the body to air on the other side is considered both surface resistances must be considered.

Therefore, the overall air-to-air resistance ($R_t$) is the sum of the body's resistance and the surface resistances.

$$R_t = 1/f_i + R + 1/f_o$$

where

$1/f_i$ = internal surface resistance
R = resistance of the body
$1/f_o$ = external surface resistance

**Solar heat gain factor**

This measure will determine the proportion of the incident solar radiation which will pass through a building element when the external and internal air temperatures are equal. If the intensity of incident solar radiation is I (Watts/$m^2$) and the rate of heat transfer through the construction is q (Watts/$m^2$) then the solar heat gain factor will be I/q (a dimensionless proportion).

The solar heat gain factor includes the effect of the absorptivity of the surface. The absorptivity of the surface or the proportion of incident solar radiation absorbed varies with the wavelength of the radiation which in turn depends on the temperature of the surface emitting the radiation. Buildings are subject to radiation from two distinct sources. Radiation from the sun is high temperature, short-wave radiation which is close to or within the visible portion of the radiation spectrum. Radiation emitted by building surfaces, the ground, etc. is invisible, low-temperature, long-wave radiation.

Emissivity is the property of the surface that describe the rate at which radiation is emitted as a proportion of the total radiation which could be emitted at that surface temperature.

The formula for the solar heat gain factor is derived using the sol-air temperature concept. The formula for this quantity is:

$$t_{sa} = t_o + \alpha I r_o - x$$

where:
$t_{sa}$ = sol-air temperature
$t_o$ = external air temperature
$\alpha$= absorptivity of the surface to solar radiation
I = incident solar radiation (diffuse and direct)
$r_o$ = external surface resistance
x = drop in temperature due to radiation emitted from the surface (sometimes neglected for simplicity)

The heat flow through a roof or wall subject to radiation per unit area will therefore be:

$$Q = U \text{ x } dt = U \text{ x } (t_{sa} - t_i) = U \text{ x } (t_o - \alpha I r_o - t_i)$$

if the temperature of the air outside is the same as the air inside
$t_o = t_i$ , then:

$$Q = U\, \alpha\, I\, r_o \quad \text{or,} \quad Q/I = U\, \alpha\, r_o$$

Since the solar heat factor is used to specify the maximum proportion of solar radiation that may be transmitted to the interior, the value of $r_o$ should be chosen for hot conditions. Normal surfaces usually have a $r_o$ of 0.05 and shiny metallic materials have an $r_o$ of 0.078. These values assume low air movement and low heat loss to the outside air.

Therefore
$Q/I = 0.05\ U\ \alpha$ (for normal surfaces)
$Q/I = 0.078\ U\ \alpha$ (for metallic surfaces)

or in percentage terms
$(Q/I)\% = 5\ U\ \alpha\ \%$ (for normal surfaces) and $(Q/I)\% = 7.8\ U\ \alpha\ \%$ (for metallic surfaces)

The formula shows that the amount of heat passing through a roof or wall depends on the absorptivity of the surface and the U-value. Note that the absorptivity value used should be for weathered conditions unless regular maintenance such as annual whitewashing can be ensured.

The solar heat gain factor can also be calculated for windows. The formula above does not apply because it does not take into account radiation passing directly to the interior, which happens with windows. Some of the radiation will also be absorbed within the thickness of the glass and the remainder will be reflected. The absorbed radiation heats the glass which is then lost by radiation and convection to the interior or exterior.

The total heat flow through a window per unit area to the interior is:

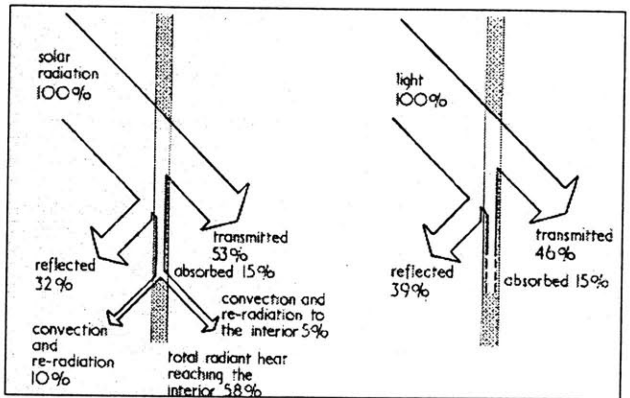
$$Q = I\,T + \frac{I\,a\,c_i}{(c_o + c_i)} \Rightarrow Q/I = T + \frac{a\,c_i}{(c_o + c_i)}$$

where
I = intensity of solar radiation (w/m2)
T = transmittance of glass (u-value)
a = absorptivity of glass
$c_i$ = internal surface conductance (w/$m^2$ degC)
$c_o$ = external surface conductance (w/$m^2$ degC)

The value for T varies with the angle of incidence and the proportions of direct and diffuse radiation. It will remain relatively constant as the angle increases from 0o (perpendicular to the glass) to approximately 60° (measured from a line perpendicular to the plane of the glass). The value for $c_i/(c_o + c_i)$ is approximately 1/3. For normal glass T is about 0.82 and the absorptivity is about 0.15. Therefore:

$$Q/I = 0.82 + 1/3 * 0.15 = 0.82 + 0.05 = 0.87$$

The solar radiant heat admission properties of different glazing and shading combinations are sometimes indicated as a proportion of the solar radiation transmitted through a single glazed window 3 to 4 mm thick. This proportion is known as the shading coefficient. It must be multiplied by 1.145 to obtain the solar heat gain factor or, conversely, the solar heat gain factor must be divided by 0.87 to obtain the shading coefficient.



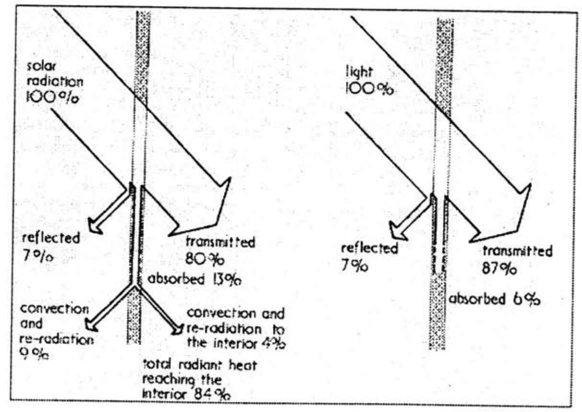




**Figure 4.19. Solar radiation in windows. Source Evans.**

All of the above equations and calculation methods are valid if and only if, both outdoor and indoor temperatures are constant. As perfectly static conditions do not occur in nature, the basis of the above methods is the assumption of steady state conditions. This is an obvious simplification of the actual situation but the results can be taken as reliable if the fluctuations in temperature do not exceed +/- 3 degC.

Calculations based on steady state assumptions are useful to determine the maximum rate of heat loss or heat gain, also for the purpose of establishing the size and capacity of heating and cooling installations. Prediction of the thermal behavior of the building is not the purpose of these calculations.

The steady state calculation methods can also be considered as preliminary studies, to lead up to the understanding of the more complex non-steady-state heat transfer problems.

In nature the variation of climatic conditions produces a non-steady state. Diurnal variations produce an approximately repetitive 24-hour cycle of increasing and decreasing temperatures. The effect of this on a building is that in the hot period heat flows from the environment into the building, where some of it is stored and at night during the cool period the heat flow is reversed: from the building to the environment. As the cycle is repetitive it can be described as periodic heat flow.

In the morning as the outdoor temperature increases heat starts entering the outer surface of a wall. Each particle in the wall will absorb a certain amount of heat for every degree of rise in temperature depending on the specific heat of the wall material.

The outdoor temperature will reach a peak and start decreasing before the inner surface temperature has reached the same level. From this moment the heat stored in the wall will be dissipated partly to the outside and partly to the inside. As the outdoor air cools an increasing proportion of this stored heat flows outwards, and when the wall temperature falls below the indoor temperature the direction of the heat flow is reversed.

The two quantities characterizing this periodic heat flow are the time lag and the decrement factor. The latter is the ratio of the maximum outer and inner surface temperature amplitudes taken form the daily mean.

## Time lag

The time lag is the delay between the impact of the diurnal variation of temperature and radiation on the external surface and the resultant temperature variation on the internal surface.

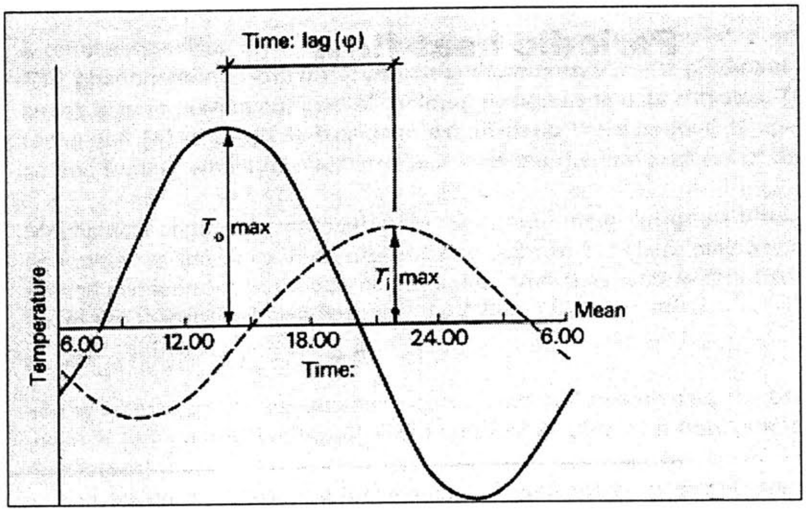



**Figure 4.20. Time lag. Source Koenigsberger, et al.**

The time lag for a homogeneous material subject to temperature fluctuations with a 24-hour period is given by the formula

$\phi = 1.38\, l \sqrt{1/K}$

where
$\phi$ = time lag in seconds
$l$ = thickness (meters)
K = thermal diffusivity ($m^2$/second)

Thermal diffusivity expresses the relationship between the conductivity, the density and the specific heat[4] of a material. It represents the rate at which a temperature increase spreads through a materials.

if:
k = conductivity (W/m*degC)
d = density ($kg/m^3$)
c = specific heat (J/kg*degC)

The dimension of this quantity is:

$$K = k/(d*c) = \frac{W/m\ degC}{kg/m^3 \times J/kg\ degC} = \frac{J/s\ m\ degC}{J/m^3\ degC} = m^2/s$$

[4]Specific heat of a substance is the amount of heat energy necessary to cause a unit increase in temperature of a unit mass of the substance. Measured in J/(kg*degC).

ϕ can be divided by 3600 to convert to hours which are more convenient for measuring time lag.

**Admittance**

The admittance of a surface is the rate at which the surface absorbs or emits heat from or to the air when the air temperature is different from the temperature of the surface. It will depend on the insulation and the thermal capacity of the surface layers of a wall. High admittance is achieved using heavy materials such as brick and concrete. Low admittance is achieved by using thin layers of materials with air cavities or insulating surface coverings.

**4.6. Verification tools**

The last part of the chapter presents a set of tools used to verify design proposals or to dimension components of buildings.

There are two important verification tools:

1. shades cast by a building
2. capture/protection of wind

Shades cast by a building can be verified either graphically or analytically using the trigonometric relations explained earlier in this chapter. It is done to verify if sun is reaching a surface or if a certain surface is protected, and therefore determine distances between buildings.

To verify graphically requires the use of figure 6.21. This graph is nothing but a translation of the information from the sun-path diagram so that the shade of a building is easily visible. Therefore, a different one should be used for each month. However, the value of this tool is to verify shades and distances between buildings so only extreme conditions of the climate being studied should be verified. Each vertex of the contour of the building is placed on the center point of this graph. The radial lines represent the time of the day and the direction of the sun at that time. The circular lines represent the shade cast by a post if it were placed at the center point and had a height of either 3m, 6m, 9m. etc. Graphic interpolation is necessary if an object's height lies between these values. It should be stated that these heights are drawn in a graphic scale.

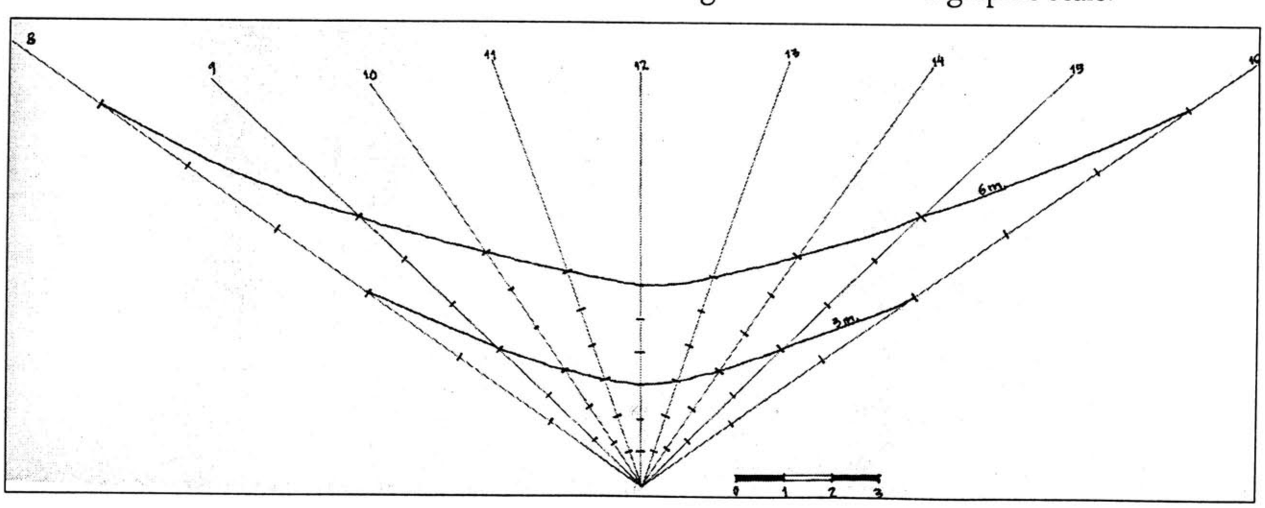



**Figure 4.21 Shadow verification, 22nd. December, San Juan.**

**Wind verification**

Verification of wind can be done analytically or experimentally. Experimentally, a model is placed in front of a wind tunnel and different scenarios are analyzed to see how the building performs. Using any colored smoke, placed between the tunnel and the model, it is easy to trace its path through the building.

Using figure 4.22 it is possible to have a good estimation of the effects of wind on a building. The table generates the length of the area behind the building that will be protected from the wind (wind shadow) as a function of the building's proportions.

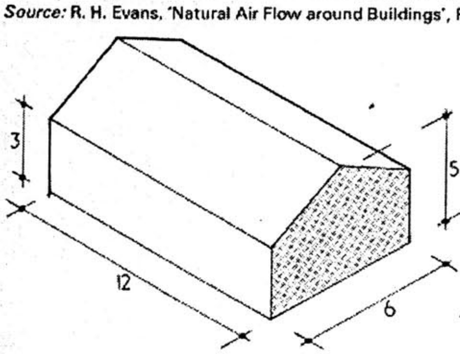
Koenigsberger, Ingersoll, Mayhew and Szokolay[5] (pages 112 – 117) show a method for dimensioning protection of windows according to shading requirements.

[5] Koenigsberger, Ingersoll, Mayhew, Szokolay, *Manual of Tropical Housing and Building*, 1973

**TABLE 7.1 LENGTH OF THE WIND SHADOW OF A BUILDING, IN TERMS OF THE HEIGHT, LENGTH AND WIDTH OF THE BUILDING FORM**

| Building form Width (W) | Height (H) | Roof pitch | Wind shadow length (×H) Length of the building (L) 2A | 4A | 8A | 16A | 24A | Wind direction → |
|---|---|---|---|---|---|---|---|---|
| A | A | 0° | 2½ | 3¾ | 5¼ | 8 | 8¾ | |
| 2A | A | 0° | 2 | 2¾ | 3¾ | 6 | 7 | |
| 3A | A | 0° | 2¼ | 3¼ | 4½ | 5¾ | 5½ | |
| A | 2A | 0° | 5¼ | 8¼ | 11¾ | 16¼ | 18 | |
| A | 3A | 0° | 6¾ | 11½ | 16½ | 18¾ | 20¾ | |
| 2A | 2A | 45° | 2¾ | 5¼ | 9¼ | 13¼ | 15 | |
| 2A | 1.6A | 30° | 3 | 4 | 6¾ | 10 | 13 | |
| 2A | 1.5A | 15° | 3 | 5¼ | 8¼ | 11½ | 14½ | |
| 2A | 1.5A | 15° | 2½ | 4½ | 6½ | 11 | 13¾ | |

*Source:* R. H. Evans, 'Natural Air Flow around Buildings', Research Report 59, Texas Engineering Experiment Station, Texas, 1957.

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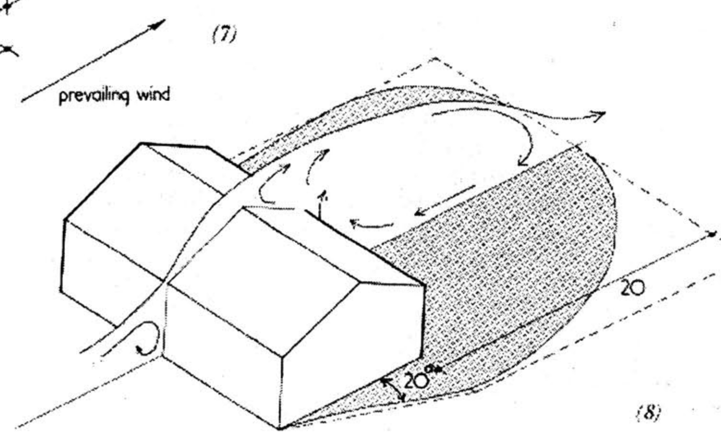


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**Figure 4.22. Wind verification. Source Evans**

# 5. VARIATIONS

This chapter addresses how different situations along the transit system in San Juan, both climatic and site-specific, affect the design of stations in order to make the guidelines in the following chapter, derived for the region in general, applicable to all of the stations along the alignment. The chapter begins by analyzing train stations' components and train operations in order to identify the impact of station configuration and station type on climate responsive design. Then, the effect microclimatic variations of a site upon design are considered.

## 5. Varying conditions along Tren Urbano

There are a variety of conditions along Tren Urbano's alignment. The variations can be classified into microclimatic and site-specific/context conditions.

All climatic variations, in this context, refer to differences between any location and the original meteorological station, that is Muñoz Marín International Airport.

Microclimatic conditions are variations in climatic indicators from those of a general area. They are circumscribed to a smaller unit of area, like a specific site and its immediate surroundings, and can usually be delimited by important topographical features. As stated previously it is often hard to have very precise microclimatic measurements. Therefore, microclimatic variations are approximated with reference to those of the original meteorological station. Most often these variations are recorded from on-site visual observation.

Site-specific conditions refer to decisions regarding the location of stations, the alignment of the track and the specific characteristics of rapid transit stations and their surroundings that are often beyond the control of the station designer. While climate design guidelines may not be the driving criteria behind the selection of location or alignment, they can serve to optimize their design within a site or to add an additional layer of criteria from which to evaluate alternatives.

## 5.1. Context/site, transit station and train-specific variations

The context specific variations are the constraints given by conditions usually not related to climatic considerations and determined by reasons other than design. These include alignment decisions, access points, modal integration, station-type decisions and train design decisions.

Stations have three general broad areas: the lobby/paid area, the platform area, and the access/transfer area.

Table 1 lists the main components of train stations, their function and degree of location flexibility and considerations for climate-responsive design.

Transit stations require programmatic analysis to understand how these may affect design decisions.

Table 1.

| Area | Component | Objective - functional considerations | degree of location flexibility | considerations for climatic design |
|---|---|---|---|---|
| **Station lobby/paid area** | 1. Roof | • in underground: shade, protection from weather<br>• at grade: shade, protection from weather<br>• elevated: usually protected by elevated guideway | medium | • most sun exposed surface: protect from sun<br>• capture winds<br>• control driving rain |
| | 2. floor | • safety (slipping)<br>• visual comfort (glare, aesthetics) | medium | • affects storage/ dissipation of heat<br>• thermal control (property of material) |
| | 3. walls | • thermal control (material properties), protection from weather (rain)<br>• security (protection)<br>• separate paid/free areas | high | • material: affects heat gain factor<br>• protect from driving rain<br>• maximize winds |
| | 4. openings | • thermal control (ventilation)<br>• visual/aesthetic considerations protection from weather (rain) | high | • protect from heat gain<br>• maximize for wind capture |
| | 5. turnstiles | • control access | low | • minimal impact |
| | 6. escalators | • level change | low | • engine: source of heat |
| | 7. elevators | • level change | low | • engine: source of heat |
| | 8. signage | • orient users | medium | • can be wind barriers<br>• may be used to re direct wind |
| | 9. concessions | • commerce | high | • can block wind |
| | 10. booths (security, ticketing) | • security, ticketing | low | • can block wind |
| | 11. public services (restrooms) | • user services | medium | • wet areas, need ventilation |
| | 12. station servicing | • system and train servicing | high | • enclosed, can generate heat |
| | 13. paid area | • post-payment area, standing, waiting | low | • need ventilation |
| | 14. free area | • pre-paid standing, waiting area | low | • need ventilation |
| | 15. lights | • security, visibility | medium | • source of heat |
| | 16. furniture | • user comfort | high | • materials to avoid heat storage |
| | 17. phones | • user service | high | • avoid blocking wind<br>• minimize glass |
| | 18. mechanical conditioning equipment | • thermal comfort | high | • engines: source of heat |
| **Platform area** | 1. roof | • protection from weather<br>• thermal protection (shade, insulation) | medium | • surface most exposed to sun: protect sun<br>• shelter from rain, especially driving rain<br>• maximize wind |
| | 2. platform floor | • safety, thermal comfort | medium | • affects storage/ dissipation of heat |

| | | | | |
|---|---|---|---|---|
| | 3. walls | • protection from weather | high | • affects storage/ dissipation of heat<br>• control driving rain |
| | 4. signage | • orientation | medium | • can block air flow<br>• can redirect wind<br>• can block driving rain |
| | 5. openings | • ventilation | high | • large for wind capture<br>• avoid west protect from sun |
| | 6. concessions | • commerce | high | • permeable: avoid blocking wind |
| | 7. booths | • user service | low | • permeable: avoid blocking wind |
| | 8. safety features | • safety | low | • permeable: avoid blocking wind |
| | 9. lights | • visibility, safety and security | medium | • source of heat |
| | 10. furniture | • user comfort | high | • attention to material |
| | 11. mechanical conditioning equipment | • thermal control | maximum | • engines: sources of heat<br>• source of noise |
| **Access/ transfer area** | 1. bus drop off shelters | • protection from weather, comfort while waiting | medium | • maximize wind<br>• avoid glass<br>• protect from sun |
| | 2. park and ride facilities | • user flexibility: drive, park + train, drive | medium | • protect connection to station from sun<br>• provide wind in connection |
| | 3. kiss and ride facilities | • user flexibility: drive + train | medium | • shelter drop off area: canopy, vegetation |
| | 4. pedestrian access streets | • facilitate pedestrian access | medium | • protect from sun: vegetation, overhang<br>• streetscape design pavement avoid glare, excessive heat storage |
| | 5. bike racks | • bicycle integration | medium | • materials: protect from sun<br>• ventilate walk to station |
| | 6. concessions | • commerce | high | • provide shade<br>• avoid wind block |
| | 7. light | • safety, security & visibility | medium | • source of heat less important: easier dissipated |
| | 8. vegetation | • thermal comfort (shade, thermal moderation)<br>• visual consideration (aesthetic) | high | • location: provide shade especially shade west<br>• type: canopy effect (thin tall trunk)<br>• foliage: moderate dense avoid wind barrier<br>• avoid shrubs (wind barrier) |
| | 9. furniture | • user comfort | high | • material: avoid heat storage<br>• shaded |

Transit stations in Tren Urbano will be used continuously during 20 hours a day, which means that stations must be prepared to withstand the extreme heat of the summer afternoon. Though heavy peaking is expected, the stations must be designed to provide comfort for all times of the day. The fact that San Juan does not have large amplitudes (either within a day or between seasons) simplifies the task. In Mexico City however, there are clear contrasts between rainy and dry seasons and considerable amplitudes within a day and among seasons. This means that many components must be designed to compromise between the two climatic conditions.

Much of the expected ridership in the Hato Rey Centro station is expected to arrive walking. This is exceptional within San Juan and must be given special attention. The creation of a friendly environment to facilitate walking will be key in this station.

**Elevated stations:**

Elevated transit stations present a better potential to capture winds, since wind speed is higher as height increases because there is less friction with the surroundings.

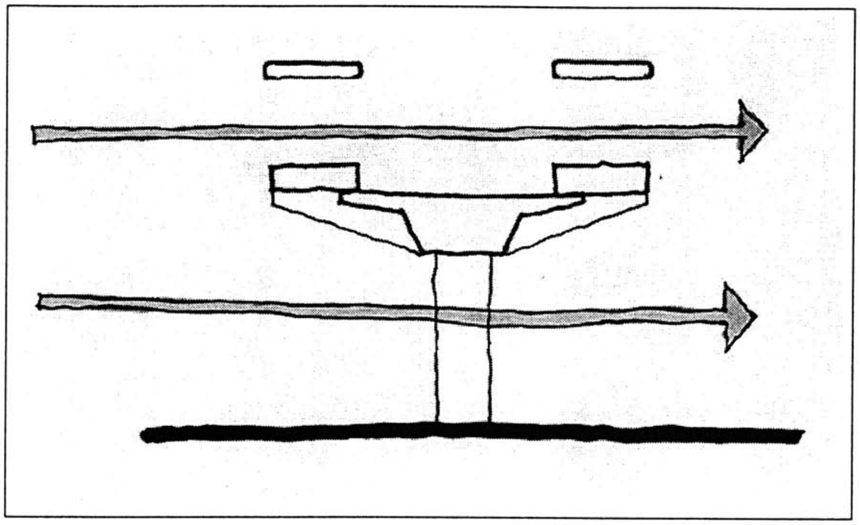

**Figure 5.1. Elevated stations have optimum wind capture potential**

At the same time elevated stations impose a large challenge for the integration of areas immediately around and under the structure. Visual impacts are larger, and especially with side platforms where escalators protrude from the building and can cause visual impacts. The shade under the tracks can be used to the advantage of the designer. Areas below the tracks are shaded due to the verticality of the sun and can be utilized for many activities. Moreover the narrow and elongated proportions of the track are very favorable from a climatic point of view in a warm-humid island climate like San Juan's.

However, and perhaps the major reason for deciding on elevated stations is the substantially lower cost of building an elevated system compared to underground systems.

**At grade stations:**

At grade stations are less imposing visually on their surroundings. In a heavy rail transit system like Tren Urbano, the tracks are separated from cross streets, thus an at grade station platform will likely be below adjacent streets. These stations face a challenge to maximize the wind, which is weaker at lower heights, especially given that many of the stations are in trenches. Means to deflect the wind both horizontally and vertically must be studied, to provide higher air movement. Especially in stations with unfavorable orientation, due to alignment, the roof becomes one of the few variables the designer may manipulate to improve wind capture. One possible solution to the problem of wind capture in stations in trenches is to have a waiting area (after payment) at grade or slightly elevated, where wind is higher, with easy, visible, and fast connection by stairs and escalator to the train access level. Moreover, stations in trenches tend to retain the heat produced by the trains and internal heat sources (people, lights, and machinery in general) more than in elevated stations.

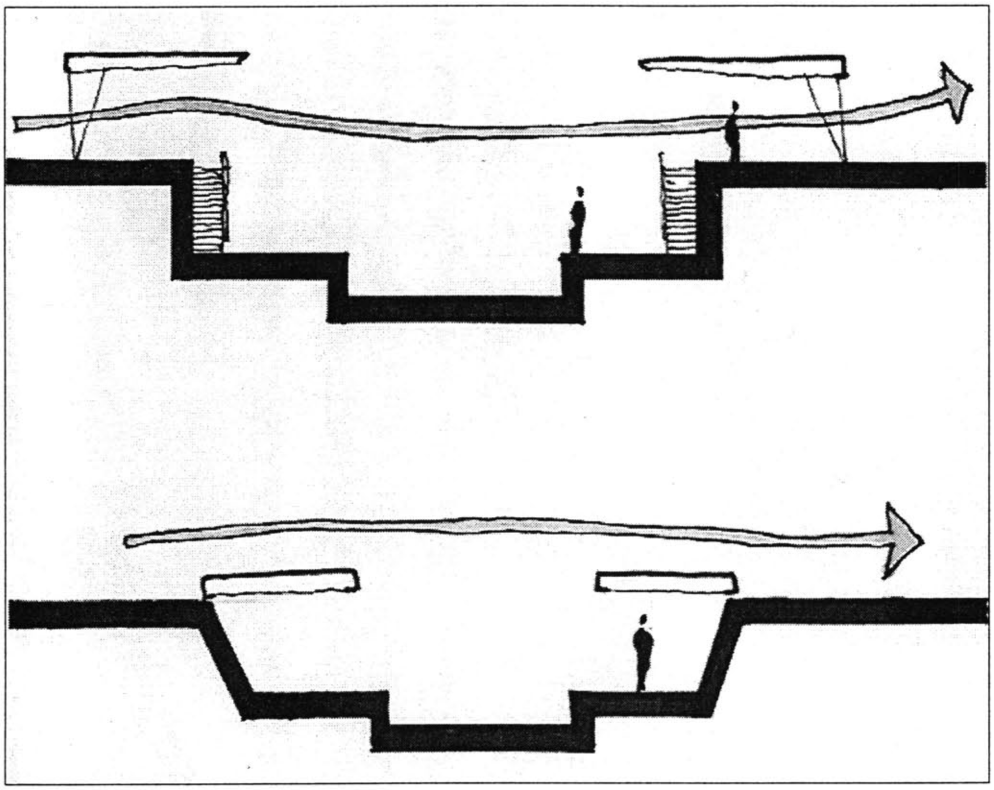

**Figure 5.2. At grade stations require special configurations to capture wind.**

The previous classification dealt with the location of stations with respect to street level. Many of the stations in Tren Urbano will be elevated, thus it is important to discuss, within this group of stations, how central and side platform stations differ in performance.

**Central platform:**

Central platform stations concentrate passengers and make the provision of comfort easier. Trains entering the station dissipate the heat they generate easier because one of their sides does not face the platform. However, the platform itself is farther from the edge of the station building and this calls for creativity in capturing air movement: the roof becomes the main variable architects must make full use of.

The same is true for controlling noise into the platform: as one of the surfaces of the trains is not exposed to the platform noise is better dissipated. But controlling noise to the outside of stations is harder as the train is directly exposed to the outside.

Central platforms are also less imposing visually on their surroundings as the escalators and elevators can often be concentrated, and kept away from view.

**Side platform:**

Side platform stations have the advantage of being closer to the edge of the station and therefore better wind capture. However, the heat from the train and other sources is more in contact with passengers than in central platform stations.

Driving rain is more problematic in side platform stations. The edge of the platform is directly exposed to the rain. This can be solved with a double set of louvers that redirects the wind towards human level while keeping the rain out. Some of the wind is lost, but the rain is kept out.

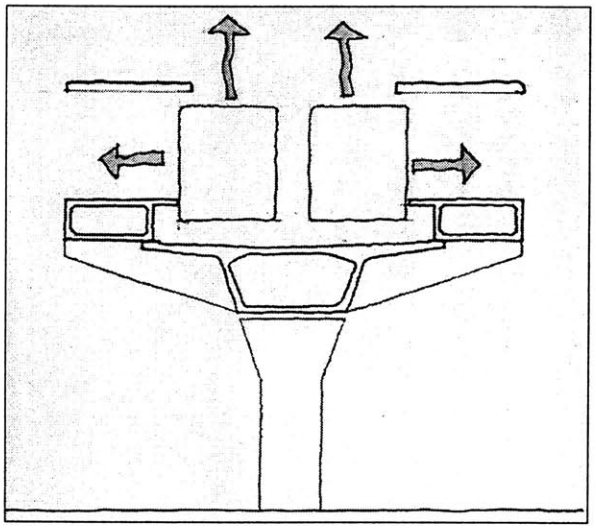

**Figure 5.3. Side platforms have direct contact with outdoor conditions. Pro: better wind capture and better noise protection for surroundings. Con: heat is not dissipated as easily and more intrusive on surroundings.**

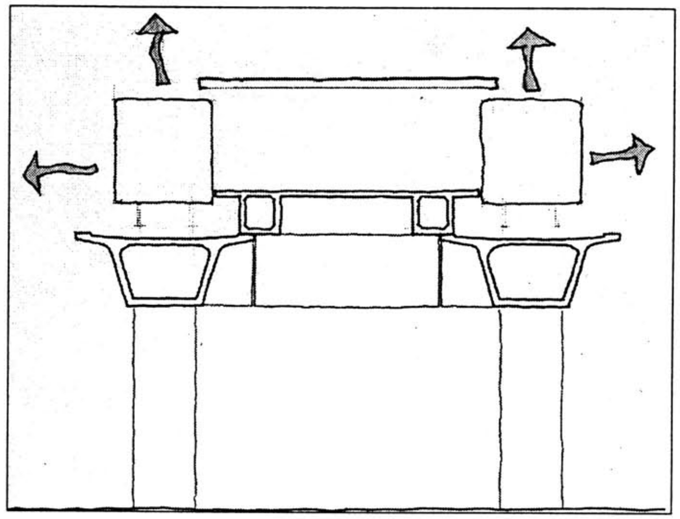

**Figure 5.3. Center platforms are more protected form outside conditions. Pros: heat gets dissipated to the outside easier, less intrusive on surroundings. Con: noise to surroundings and harder to capture wind.**

In terms of noise protection to the outside, the side platform configuration is better than the side platform configuration because the outer wall offers some resistance to noise waves, at the expense of noise within the platform area.

## Orientation of alignment:

The orientation of the alignment is beyond the control of station designers. Moreover, since Tren Urbano is a new system in an already consolidated urban area, the site of the stations requires expropriation of valuable land whose configuration is not determined by climatic considerations. This may lead to station sites oriented unfavorably from a climatic point of view.

In Tren Urbano, there are basically two dominant orientations of the alignment which determine the orientation of the waiting platforms: North - South on the Sagrado Corazon - Rio Piedras section and East-West on the Rio Piedras - Bayamon section. Though the platforms themselves are fixed in orientation, their proper design can offset some of the unfavorable characteristics the weather may impose on them. Division of platforms into areas to respond to different and conflicting conditions is one possibility. For example, protection from driving rain and capture of winds are desirable but may conflict: this may be overcome by creating screens in alternate parts of the platforms leaving the other parts open. Passengers have flexibility to move within the platform to accommodate to the changing conditions.

The orientation of the alignment affects the amount of sun protection and wind capture of the space under the tracks. An east – west alignment is better in terms of sun protection, whereas a north – south alignment offers good possibilities for capturing wind. Where possible middle ground solutions to maximize both effects should be considered, especially in areas where the possibilities for development in areas under the track might be desired.

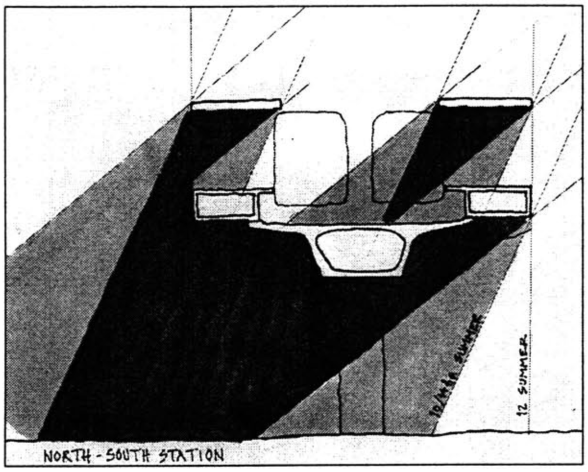


**Figure 5.4. North-south oriented stations shade smaller space and not directly under guideway.**

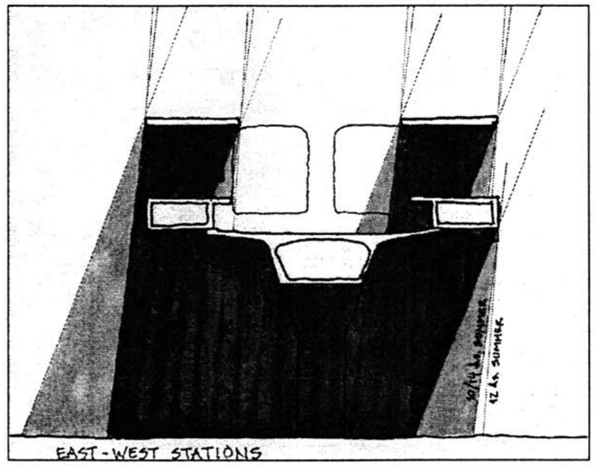


**Figure 5.4. East-west oriented stations shade larger space and immediately under guideway.**

## Underground stations

A decision has been made for Tren Urbano that underground stations are going to be air-conditioned. In these cases, trapping the air with the use of trainscreens, which also improve safety, can reduce the dimensioning of the equipment. Trainscreens are walls placed at the edge of the platform with doors that match those of the trains and are activated automatically when the train stops. Also important is the piston effect trains produce, especially in underground stations, which sucks the air from the station to the tunnel section, further strengthening the case for trainscreens.

Two components of stations are relatively rigid in their location and orientation: escalators and elevators are guided by the orientation of the platform and the turnstiles are guided by the access points to stations. These components must be carefully analyzed with respect to wind capture, solar protection, shading devices, and protection from driving rain. They are neuralgic points through which all users must pass, however briefly.

Other components of stations offer more flexibility in terms of location and orientation. The station area, paid area, pre-paid area, access streets/sidewalks, services, restrooms, information /safety booths, concessions may have some location flexibility to maximize thermal comfort. Booths and concessions should be located in a way that they do not block air movement.

## Integration of modes

Another important component of stations that requires consideration from a climatic design point of view, is the integration of various transportation modes of access into the station. Bus shelters and kiss and ride drop-offs must be shaded, as well as connections to the station building itself. Their orientation and location, where possible, should take into account the effects of solar radiation and exposed to the predominant wind. Park and ride facilities, apart from other criteria guiding their location, should provide sheltered connection to the station building.

More important is the materials employed for shelters: glass is often used for matters of security (visibility) and aesthetics. Climatically however, in San Juan glass is not recommendable in roofs, as it will increase the temperature of spaces below it. Openings are desirable in walls to allow airflow, and can easily be protected by a slight overhang, especially if located on north or south facades. Located on a roof however, glass can add discomfort to the interior. Glass skylights are a considerable source of heat, and their construction often requires extreme care to avoid leakage into the interior.

**Train cars as sources of heat**

The train generates heat, which is dissipated to its surroundings. The two basic sources of heat from trains is the breaking system usually located at the bottom of the train, and the air conditioning system which can be located under or above the train car. The latter is preferable for the expulsion of the heat since the hot air rises and does not reach the human body level, except where there are lobbies and circulation spaces above.

Ronald Eash[1] studied the energy consumption of rapid transit trains as a function of a set of variables: track profile, speed, braking policy, number of trains, and spacing between stations. In general, the latter two are predetermined, guided by demand characteristics and beyond the control of the operator. However, speed, braking policy and track profile could have an impact on energy consumption and may provide an area for improving energy performance of the trains. Breaking policy refers to allowing trains to coast rather than speeding to maximum speed and then breaking, which reduces energy consumption without major delays. Related to this, maximum speeds affect energy consumption though speed is subject to station spacing. Lastly, track profile was also found to affect energy consumption: the higher the grade the lower the energy consumption.

**Station mechanical infrastructure**

Escalators, elevators, fans, lighting and any other equipment that uses electricity also generate heat. The heat dissipated to the platform, waiting, queuing areas or access areas can be substantial. Therefore, the location of these heat sources should be carefully thought through to avoid adding heat stresses. This also implies avoiding locating them upstream of the predominant air movement, as the warm air will be transported and produce discomfort.

**Noise**

Noise is a serious problem and obstacle for the use of areas immediately around transit stations. Trainscreens, which may be employed to reduce the loss of air-conditioned air on the platform, can be a good solution to protect from noise, especially in the underground stations where noise is concentrated and channeled and where trainscreens are justified for thermal reasons.

At grade stations channel noise less than in underground stations but more than in elevated stations, especially in stations that are in trenches where the trench is usually made of concrete, a reflective surface.

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[1] Ronal W. Eash, *Energy Efficient Transit Operation*, Transportation Research Record #662, 1978.

In elevated stations, however, noise is more diffuse and harder to control. Trainscreens require much higher investment and are counterproductive in terms of wind and thermal comfort. The conflict is created in that in order to control noise, absorptive surfaces are required, but for thermal reasons, materials with low absorptivity are better. Selective placement of absorptive surfaces must be designed. As mentioned above noise to the platform and to the outside is more easily controlled in central platform configurations. Of course, to a large degree noise will depend on the design and maintenance of the trains.

### 5.2. Microclimatic variations (Variations in climate)

The adaptation of design guidelines is more approximate than the process outlined in the climatic analysis, because site microclimatic data is not readily available. They are meant to give the designer the tools to critically assess the implications of the differences in a given site in order to refine and complement the guidelines and improve the design outcome.

The San Juan Metropolitan Region does not present extreme climatic variations in the area served by the first phase of Tren Urbano. However, the sea does have a definite impact on the coastal area and future extensions of Tren Urbano, to Old San Juan, Condado and Isla Verde, should consider these variations. Moreover, the potential extension into Trujillo Alto reaches into an area considerably closer to the mountain range, with a hilly topography and higher rainfall. Both topography and rainfall will affect the design of stations in this extension.

The meteorological data from the nearest meteorological station may not give a true picture of the climate experienced at the building site. This may be due to the distance between the two, or differences in altitude, topography or proximity to the sea or large bodies of water. In these cases it may be necessary to attempt to estimate the likely variation between meteorological station and site. This should be avoided if possible since there are no simple or reliable rules for adjusting climatic data, and if variations between the meteorological station and site are small, the design requirements for both sites will be the same.

Two complementary techniques may be adopted to assess the degree of climatic variation. The first is to take spot readings at the site, which are compared to simultaneous readings at the meteorological station. A considerable number of readings are required for each season of the year before any conclusions can be drawn. The second technique for assessing the climate changes between stations is to plot their locations on a map of the region and to draw isotherms for the maximum temperature in the hottest month and the minimum temperature for the coldest month together with isohytes (lines of equal rainfall) for typical month for each season of the year. This information is often not available so some discretion will be required to determine the likely effects of the site's characteristics upon climatic indicators.

Variations will rarely be proportional to the distance between them. Changes in altitude and distance from the sea may have a major impact. Natural vegetation is often a useful indicator of climate and change but vegetation changes because of agricultural development may be misleading particularly where extensive irrigation is necessary.

Clearly latitude is one of the variables that affects climate the most. An urban area, however, covers such a relatively small area that variations in latitude within an urban area are minimal and negligible for climatic design purposes.

### Altitude

Changes in altitude will cause changes in climate. As air is forced to rise as the wind blows towards a range of mountains for example the barometric pressure is reduced, the air expands and is cooled. The temperature reduction with dry or unsaturated air will be up to 1°C for each 100m increase in altitude. If the air contains moisture, which condenses as it cools, the temperature change will be less. Radiation tends to become more intense as the altitude increases, since solar radiation passes through a thinner layer of the earth's atmosphere before reaching the ground. Conversely, at night, the ground surface loses more heat by radiation to a clear sky. This leads to greater temperature ranges at higher altitudes as long as the sky remains clear.

In this case San Juan does not present major variations in altitude. The extension to Trujillo Alto does enter a higher altitude area but the difference is negligible from a climatic point of view. Mexico City is at a very high altitude, which does not mean that there are variations within it that affect design. Precisely, the most densely populated areas where the subway system reaches is a relatively flat area within the valley. The altitude variations would be more of a factor in the design of dwellings in the mountains surrounding the city.

### Distance from the sea

Since the sea has a much greater thermal capacity than the land, it will experience a lower range of temperature variation, both during the day and over the year. Coastal areas generally within 10 km. of the sea, will also benefit from a reduced range of temperature variation, although the transition of climate from maritime to continental can sometimes be traced over thousands of kilometers. The direct effect of coastal influences is unlikely to be felt more than 30 km. from the coast.

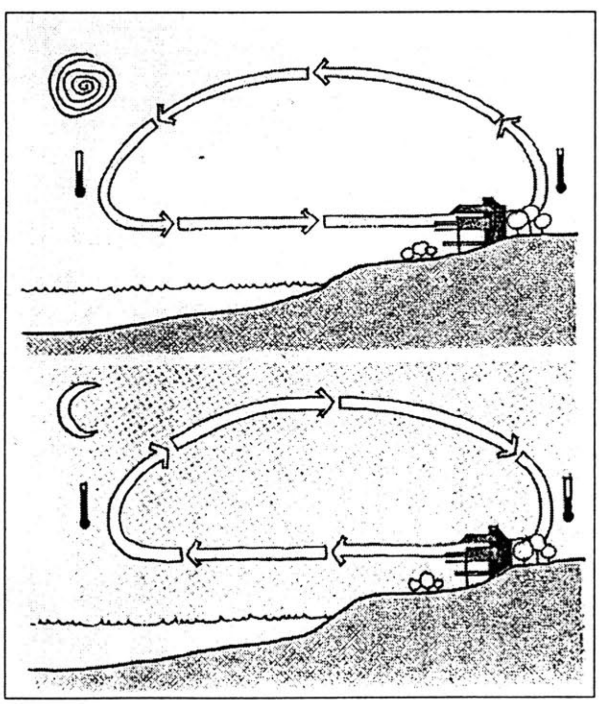

**Figure 5.5. Sea breezes in the morning and land breezes at night alleviate heat stress. Source Muniz**

The proximity of bodies of water can moderate extreme temperature variations: land on the lee side of water will be warmer in the winter and cooler in the summer. Humidify is also affected. The larger the body of water the greater the impact on the microclimate. The farther from the sea (the more inland) the greater the temperature amplitude will be.

In summer during the daytime, the earth heats up considerably in comparison with the water: the hot air rises and cool air must flow in to replace it. The shores of lakes and oceans as a result benefit from a daytime breeze, blowing from the water to the land, which has a cooling effect felt for between 400 to 800 meters inland. At night the air over the land cools faster than that over the water and the process is reversed, with the breeze blowing from the land to the water. Experiments done on a clear winter night have shown that temperatures gradually decrease as one moves away from a lake or ocean shore.

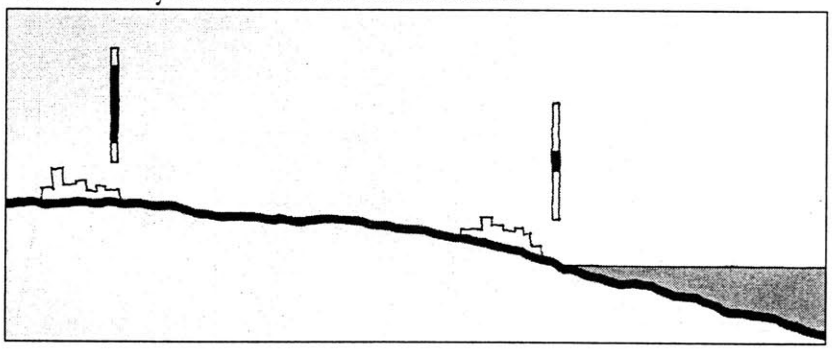

**Figure 5.6. Distance from sea or bodies of water affects thermal amplitude**

## Ground surface

The portion of solar radiation that reaches the earth to raise the temperature of the ground depends on latitude, the season, the slope of the ground, the hour of the day and the nature of the terrain. During the daytime the highest temperature is always found at the boundary between the ground and the air. The temperature, in other words, increases considerably as one approaches the ground. At night, as a result of the loss of heat by evaporation and the effective outgoing radiation, the reverse is true and the temperature decreases as one approaches the ground. A peculiarity of microclimate, therefore, is that the closer one is to the ground the more extreme the temperature variations become.

The natural cover of a terrain tends to moderate extreme temperatures and stabilize conditions. Plant and grassy cover reduces temperatures and while they may still be further reduced by other vegetation cities and man-made surfaces tend to elevate temperatures and reduce humidity. A fairly common mistake, which can have most unpleasant result in hot climates is to place paved surfaces - which store up a great deal more heat and remain hot longer than unpaved or grassed surfaces - close to the windows of houses or buildings. Not only do these paved areas add appreciable heat to the air layer near the surface, but they also radiate and reflect large amounts of heat into buildings, aggravating already uncomfortable conditions.

These conditions are especially important in the context of San Juan where there is widespread deforestation in urban areas to make room for 'development' and road expansion. The areas around Hato Rey Centro are particularly instructive. There are large areas of unshaded asphalt which create heat island problems.

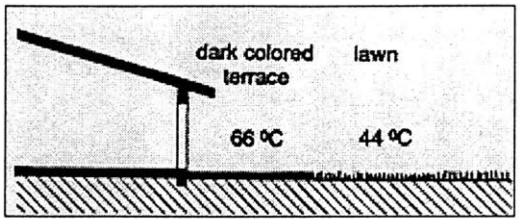


**Figure 5.7. Ground cover affects air temperature. Source Gut-Ackernecht.**

## Topography

The shape, orientation, exposure, elevation and hills or valleys at or near a site must be investigated as they can have an effect on not only temperature but also the distribution of solar radiation, wind and precipitation. The influence of small hills (300 m or more) on rainfall patterns can be quite pronounced, particularly when moisture bearing winds blow regularly from the same direction. In Puerto Rico the difference between areas is considerable: in San Juan's International Airport the average rainfall is around 55-60 inches, whereas not far from it to the east but uphill in El Yunque forest the rainfall averages 200 inches. The windward slope in this case can be expected to receive a rainfall of more than the regional average and the leeward slope correspondingly less. The higher or steeper the slope the greater the effect will be.

Temperature in the atmosphere decreases with altitude and this is important in hot climates where temperature may be more favorable in higher elevations.

At night however, this effect is reversed as cold air drains down to the lowest points. In hot climates this can be used to advantage by designers as a raised wall or impermeable hedge on the lower side of a site can dam up the cool air which flows down the slope. It would be desirable to provide a gate or use a deciduous hedge so that the flow of air is not blocked. This is the case in San Juan, where the free flow of air is fundamental. If, on the other hand, it were necessary to protect a site from an undesirable wind caused by flow of air down slope, as is the case at times in Mexico City, a wall or hedge running across the slope above the site would deflect the wind.

### Urban and rural location

Most of the data for climatic variations between large urban areas and the surrounding countryside results from observations in Europe and North America. The experiments show different results for different climates. In hot dry climates, for cities with widespread climate responsive design, city centers may actually be lower due to the induced cooling effect of evaporative cooling and the increased density desirable for reasons of compactness. Moreover, the use of water irrigation will lead to lower temperatures as a result of evaporation and higher humidities. In warm humid climates however the situation is different. The higher temperatures that are likely to appear in city centers will lead to lower average humidity. Therefore, sites in the countryside tend to experience cooler temperatures, especially due to the absence of interference to the wind in more rural sites.

### Wind speed

The variation in wind speed between meteorological station and site will depend largely on ground cover and topography. The wind speed is usually measured in flat open locations, such as airports (because they serve purposes other than climate design such as meteorology defense) at a height of 10m above ground level. In order to convert this to an equivalent wind speed at 3 m in flat urban or suburban locations the wind speed must be multiplied by a reduction factor, which ranges from 0 in the open at 10m. height to 98% in a building at a height of 3m[2].

These reductions factors are only approximate indication of the likely variation and will not apply in very heavily built-up areas, close to high-rise buildings.

Physical features such as neighboring buildings, walls, trees that influence air movement and cast shadows must be taken into account. There is a difference between the shelter offered by windbreaks composed of plants and that offered by solid screens or buildings, as the extent of shelter depends not only on height but also on the degree of permeability. Plants, which permit a certain amount of air to pass through, cause less turbulence than solid screens and, as a result, a greater total area of shelter.

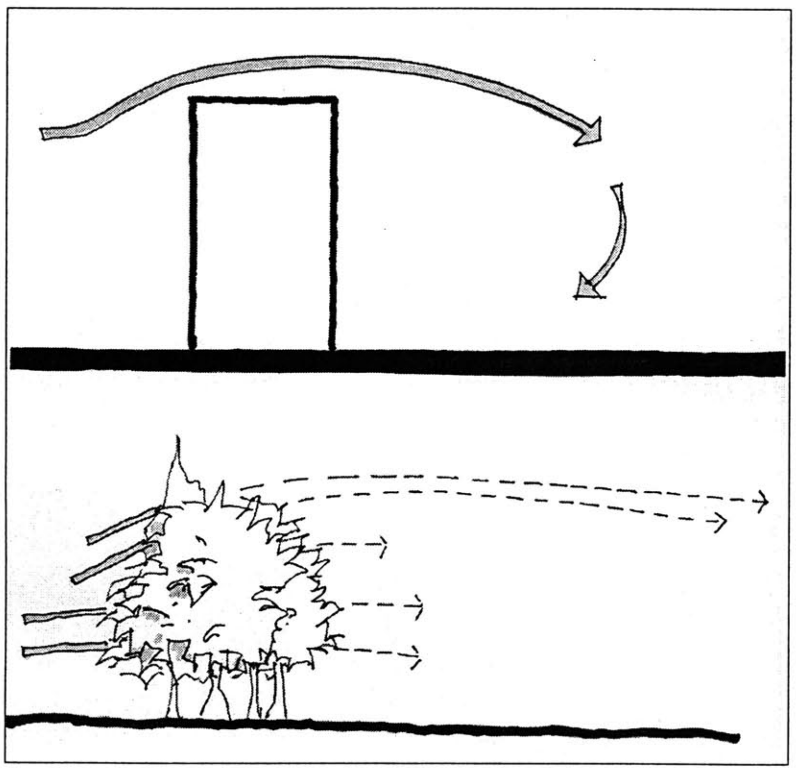

**Figure 5.8. Different types of wind barriers create different effects on wind.**

## Vegetation

In warm humid climates both winter and summer average daily temperatures drop by a few degrees in areas under vegetation. In the daytime when the tops of the trees are being heated by solar radiation, what cool air there is - being heavier than warm air - sinks down to the ground level. The leaves of the trees re-radiate heat at night in a manner similar to that of the bare ground and this produces cooling with the cooled air once again sinking to the ground level. As a result vegetation plays an important role in moderating conditions and these processes produce a very uniform temperature at the ground level of forested areas. Vegetation also protects from glare.

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2 Evans, *Housing, Climate and Comfort*, 1980.

**Pollution**

Pollution affects the amount of solar radiation captured at a site. More pollution captures and traps the reflected heat from the ground, creating a greenhouse effect that can raise the temperature.

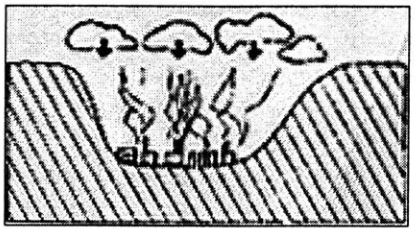
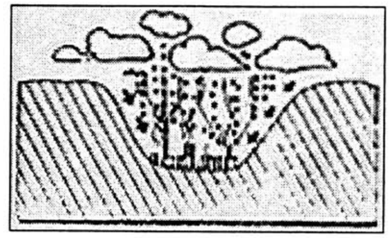


**Figure 5.9. Pollution affects amount of radiation emitted back to the atmosphere. Source Gut-Ackernecht.**



## 6. DESIGN GUIDELINES

*'The use of massive air-conditioning plants to correct an ill-conceived environment does not differ in principle from the use of masonry façade to hide an unnecessarily ugly concrete structure'*, Cowan H.J. An historical outline of architectural science, 1966.

This chapter describes how the design strategies identified in chapter 2 translate into specific design decisions. The chapter adopts a design-guideline format and illustrates the implication of each guideline upon design decisions with the aid of graphic representation, photographs and other appropriate media. First, a description of the design variables and their relevance for design, from a climatic point of view, is presented. Then, design guidelines are presented for design variables at every decision-making scale for both San Juan and Mexico City. Lastly a step by step illustration of the application of the guidelines is presented. Using one station in the system, Hato Rey Centro, each scale of the design process is comparatively addressed for both climates.

The guidelines are ordered in decreasing scale of detail from site to building component design. They are divided into general climatic considerations, site-planning guidelines, building design guidelines and building component guidelines.

The guidelines are meant to be used from the beginning of the design process. Certain decisions are crucial to the outcome and performance of the building. If used as a stylistic ornament added at a late stage of the design process they are likely to be inadequate and ineffective.

The guidelines intentionally do not prescribe style nor are they absolute. They provide recommendations, which other circumstances may or may not allow to be fully applied. Any step in the direction the guidelines recommend will improve the energy performance of the building.

The guidelines are derived from the climatic analysis carried out in the previous chapter using data from San Juan's Muñoz Marín International Airport meteorological station. Therefore, they provide a good analysis of the general principles that may be used in the SJMR as a whole and are not site-specific. In order to contrast and refine the guidelines, they are compared to guidelines that would apply for Mexico City. Chapter four provides guidance for adapting these guidelines to the microclimatic and site-specific urban conditions at the sites of Tren Urbano's stations and illustrates their application using one station in Tren Urbano.

Design solutions to take advantage of favorable conditions or offset unfavorable external conditions are divided into passive and active means. Active or mechanical means are those that require energy for operation such as air conditioning or heating. Passive means, such as orientation or shape, are those that do not require energy for operation. These guidelines focus on the passive means to obtain comfort.

Table 1. summarizes the design guidelines for both climates

Table 1.

| . | variable | San Juan | Mexico City |
|---|---|---|---|
| **Site planning** | **Topography** | • on northern or southern slopes<br>• windward slope of hills<br>• towards crest of hill | • in lower to middle part of hill<br>• southern slope |
| | **Orientation** | • orient site and development to capture wind<br>protect from sun | • south facing slope ⇒ benefit from winter sun<br>• selective capture of wind |
| | **relationship between buildings** | • scattered<br>• staggered | • semi-compact ⇒ avoid excessive wind penetration in winter<br>• |
| **Building Design** | **Shape** | • elongated and narrow, 1:3 at least | • semi-compact, patio house |
| | **surface-to-volume ratio** | • maximum ⇒ maximize exposed surface so building can breathe | • average ⇒ allow for both types of seasons: allow building to breathe in summer and capture in winter |
| | **height** | • medium ⇒ avoid excessive exposure to sun<br>- detached from ground to capture winds | • can use ground for thermal inertia. |
| | **Orientation** | • oriented for wind<br>• avoid west and to some extent east<br>• long axis east-west | • oriented to capture sun<br>• must be controllable in summer<br>• avoid west |
| | **depth** | • minimal ⇒ allow cross-ventilation<br>• single banked buildings | • more compact than San Juan<br>• capture sun and avoid its escape in winter<br>• double banked building arrangement |
| **Components** | **Walls** | • light weight materials<br>• some insulation | • materials with some heat storage capacity (thermal mass) |
| | **Openings** | • large and protected<br>• on opposite facades<br>• louvers and brise-soleil protect | • oriented to south (for north hemisphere) avoid overheating from west in summer<br>• mid-sized ⇒ control ventilation |
| | **Roofs** | • pitched<br>• insulated<br>• lightweight materials | • can be flat ⇒ avoid concrete due to expansions<br>• insulated |
| | **materials** | • lightweight,<br>• reflective ⇒ light colored materials<br>no thermal mass nor time lag | • some absorption necessary<br>• moderate time lag and thermal mass |
| | **vegetation** | • canopy effect ⇒ tall with permeable foliage<br>• evergreen ⇒ protect west<br>• avoid wind blocking shrubs | • deciduous, moderate foliage density |

### 6.1. Guidelines. Design scales and general variables.

#### 6.1.1. Site planning

The decisions regarding the location of a building within a predetermined site is an essential factor for the eventual bioclimatic performance of the building. The site planning decisions made at the beginning of the planning process will affect the potential of every subsequent decision about the design of the building.

Other site-specific factors may be more important in the site-planning process such as ease of access, predominant flows or proximity to other existing infrastructure. These guidelines are aimed at adding an additional layer to this process or to add another criterion that may help evaluate alternatives.

The variables the architect can manipulate in terms of site planning include:

**Topography:**

Thoughtful use topography affects the level of exposure to sun and wind of a building. It also determines the orientation of the buildings as a whole and therefore the potential creation of microclimates. Slopes in windward orientations are favorable to capture winds, while leeward slopes are protected from winds.

The orientation of the slopes is also an important factor as these will determine solar access for the grouping as a whole. Slopes may be favorable on some grounds and unfavorable on others.

The relative placement of a building within a slope is also an important tool for thermal purposes. Placing a building on top of a hill will have better flow of air but

**Landscaping**:

Landscaping can make an important contribution to creating comfortable outdoor conditions. The use of vegetation, as will be seen, is critical for protection from the sun.

**Orientation:**

Choosing general site orientation will influence the relative exposure of different facades to radiation. Much is decided when the orientation of the grouping as a whole is determined. While a designer may have control over a site's orientation, his/her criteria in distributing buildings within a site will affect the performance of each component. The orientation must take into account the relative weight of the climatic indicators that distance a site from the comfort zone.

**Relationship between buildings:**

The relative relationship and placement of buildings will determine the availability of winds to each one. Scattered and staggered buildings will generate and channel winds, whereas compact building groupings tend to protect from winds. These decisions also affect thermal comfort for the site as a whole: compact massive groupings will reduce thermal amplitudes whereas open scattered groupings allow air flow and reduce heat stress.

**Outdoor spaces**

Guidelines for the design of outdoor spaces are not substantially different from those of the design of buildings. They are often neglected and designed as residual spaces. However, it is important to have an understanding of the type, time and intensity of use to which outdoor spaces will be given. Warmer climates conduct a large share of activities outdoors or in very open spaces. Composite climates require a more selective thought regarding the orientation and location of outdoor spaces.

### 6.1.2. Building design

While the site planning process critically affects the outcome of each component, the inverse is also true. A building creates a microclimate and affects every structure around it.

The building design scale refers to the following variables:

- **Shape:**

Shape refers to the proportions and form of a building. Depth affects the rate of heat gain and loss of a building. Deep buildings take longer to heat up and cool down, and wind does not penetrate far. Narrow buildings allow the walls to breathe and expel the heat and, if properly designed, provide ventilation for the whole depth of the building.

- **Orientation**

The orientation of a building is perhaps the single most important variable a designer must take into account. It determines the radiation each surface will receive and the possibility of obtaining comfort. Orientation is also guided by air movement factors: whether it is capturing or protecting from it, the wind greatly affects comfort conditions. These two factors often conflict.

Orientation must also take into account the latitude of the site in which the building is located: in latitudes close to the equator the sun is very vertical, making north and south facades easy to shade whereas east and west facades are harder due to a relatively more horizontal sun. In lower latitudes the sun is more horizontal and careful attention must be placed in designing facades to act for changing conditions. South facades (for the northern hemisphere) are desirable for sun capture but may require shading in summer. East and west facades may be very hard to shade due to the horizontal nature of the sun when it is those orientations (morning and afternoon).

- **Surface to volume ratio**

Surface to volume ratio is a good measure of the ease and rate with which outdoor conditions are transmitted to the inside of a building. In general, the criteria is that the larger the thermal amplitude the lower the surface to volume ratio should be. Elongated buildings have a higher surface to volume ratio and are therefore more permeable and breathe better allowing air movement to cool surfaces. Compact and massive buildings have a lower surface to volume ratio and keep indoor conditions stable when outdoor conditions vary. This is, in essence, the same as the time lag concept used in the material selection portion of the guidelines.

### 6.1.3. Building component design

- **Roofs**

The roof is the surface that is exposed to the sun the most. The material it is made will greatly affect the amount of heat that is transmitted to the interior. The color of the roof is also important in that it affects the amount of heat reflect versus the amount of heat absorbed. The pitch of the roof is a function of precipitation. The roof is often used as a shading device by extending it out to protect certain facades.

- **Walls, internal and external**

The design of walls, coupled with appropriate materials, affects the rate at which buildings heat up and cool down and the amount of heat transmitted to the interior. The texture of walls and the color of materials employed for walls also affect the two conditions. Interior walls may be designed to act together with exterior walls, i.e. the exterior wall may be insulated and the interior walls very absorptive if outdoor conditions are very cold with high levels of radiation.

- **Openings**

The variables of an opening a designer can manipulate are; size, height, location, orientation, color, and shading devices. The need to capture winds or protect from them is a critical factor in designing openings. If cross-ventilation is needed openings should be large, at human level, and on opposite sides of a façade exposed to the wind. In cold climates winds may be needed selectively and windows that allow for flexibility to respond to changing conditions are appropriate. The color of a window frame affects the radiation it will absorb and the likelihood that glare will be produced.

- **Floors**

Floors can absorb or reflect the radiation they receive. The choice is similar to that posed by the choice in materials: whether the designer wishes to store or avoid storage of radiation. One particularity of floors is that they tend to reflect more radiation than walls and can be uncomfortable visually if they create glare.

- **Materials**

The materials chosen for building components affect the rate at which buildings gain and lose heat and the proportion of the heat that reaches the interior. The most important properties outlined in chapter 3 are the heat gain factor, transmission and time lag.

### 6.1.4. Others

- **Vegetation**

The adequate use of vegetation is a key component for bioclimatic design. The type, size, foliage and location of the vegetation must be carefully thought out to maximize the contribution it can play to create comfortable microclimates.

The roles vegetation can play are solar protection (permanent or selective) of outdoor/indoor spaces or wall surfaces, wind protection, air movement, privacy, humidification. Understanding these roles and how they relate to bioclimatic design is essential in order to be used effectively.

**Type:** plants and trees can be classified as evergreen (never loses foliage) or deciduous (loses its foliage during the cold months and gains it again in the warm months). The decision to choose one or the other may be limited by availability, but generally the predominant vegetation in a region is best suited to provide comfort in that region.

Evergreen vegetation is preferable where the climatic conditions are constant and seasonal variations are such that the comfort requirements or design strategies do not vary considerably from season to season.

Conversely, climates with considerable seasonal variations are more apt for deciduous vegetation as the comfort requirements vary with seasons from the need to protect from solar gain to the need to capture it.

**Structure/size:** the structure of the vegetation refers to the size and relative location of the foliage and trunk. When air movement at the human level is desired a high, wide overhanging foliage and a thin 'naked' trunk that does not obstruct air movement is optimal.

**Foliage:** Density of foliage is an important criterion for selecting which type of tree or plant to utilize. When air movement is required the foliage density should be as low as possible to avoid obstructing air movement.

**Location:** the location of vegetation with respect to a building or an outdoor space will ultimately determine if it will fulfill the objective that it is designed to fulfill. This involves understanding the dynamic character of the sun trajectory and geometry in order to estimate the shade being produced. This understanding also helps to make the right tradeoffs, compromises and decisions to meet the average annual requirements rather than concentrating on one particular requirement.

- **Street Furniture**

Street furniture will only be used if designed to serve the purpose it is designed for: comfort. This implies choosing the correct materials in order to assure it is shaded and/or exposed to sun when necessary. Moreover, it requires a clear understanding of the activities that will take place at the site in order to design for those uses and times.

## 6.2. General considerations for both climates

### 6.2.1. San Juan - Warm humid climates

Solar radiation is intense and, to a great extent, diffuse due to haze. Generous shading devices are therefore needed. The haze may cause sky glare which can also be reduced by large shading devices.

Vegetation is rich and provides an excellent means of improving the climatic conditions. Its surface does not heat up and it provides sufficient shading at low cost. However it has to be arranged in a way that does not impede air circulation.

The principle of heat regulating measures by thermal mass and heat storage does not apply to this climate, because the temperature difference between day and night is minimal. The designer is limited to measures that avoid heat absorption and storage. The use of low thermal mass, high reflective outer surfaces or double skin structures is the result.

The indoor temperature can hardly be kept much below the outdoor temperature. However, by efficient design it can be avoided that the indoor temperature exceeds the outdoor temperature and inner surfaces can remain relatively cool. Together with proper ventilation, comfortable conditions can be achieved in most cases.

Existing air movement should be utilized as much as possible to provide evaporative cooling and to avoid mold growth.

### 6.2.2. Mexico City - Tropical upland climates

This type of climate is the most complex one from the designer's point of view. Buildings must satisfy conflicting needs of hot-dry and warm-humid periods within the year. Therefore some of the general considerations for warm humid climates are also partly applicable in the tropical upland climates. In addition in upland areas the designer must consider the principles of heat conservation and solar heat gain and sometimes active heating as well.

As a consequence solutions are often a compromise between these conflicting needs. Where incompatible needs arise a careful analysis of the relative length and severity of seasons should be conducted to find a balanced solution.

Buildings should not cool down too much during the cold nights and should not overheat during the periods of strong radiant heat gain.

A moderate amount of thermal mass together with moderately sized openings and sufficient thermal insulation properties will produce the best outcomes for the major part of the year.

## 6.3. Site Planning

### 6.3.1. San Juan - warm humid island climate

In hot-humid climates the main climatic strategies concerning site planning and layout are:

- Topographical location with maximum air velocity and shade
- Orientation to minimize sun radiation impact
- Orientation to maximize natural ventilation by winds
- Scattered pattern of buildings
- Hazards such as hurricanes and floods to be considered

**Sun**

Topographically, the site should take advantage of northern or southern slopes. The warm-humid island climates are near the equator, meaning a very vertical sun trajectory throughout the year. As a consequence, east and west slopes, where the sun is relatively more horizontal and receive more radiation than north and south slopes, are disadvantageous. Moreover, in the morning when the sun is in the eastern half of the sky it will often be obscured by an overcast sky, whereas in the afternoon the clouds usually disperse and the strongest radiation intensity will be received from the western half of the sky. As a consequence west-facing slopes are more disadvantageous than east-facing slopes. The difference between north and south facing slopes is almost negligible, though a slope facing away from the equator is better (northern-slope in this case). Significant differences will not be felt until slopes are at least 10°.

In selecting a site there may be a conflict between avoiding radiation and catching breeze. In these cases sites which receive breezes should be selected even though they receive increased radiation. The lack of air movement will cause greater discomfort than the average increase in radiation (in locating openings in buildings these priorities are reversed, since direct radiation will cause greater discomfort than the lack of air movement).

In order to provide shading and given the verticality of the sun's trajectory during most of the day, the use of existing structures may have limited potential for providing shade. Locating buildings close to one another to take advantage of the shade they produce would obstruct air movement and be counterproductive.

External public spaces, streets, squares and footpaths should also be protected from the rain and sun. However, the provision of shade must not interfere with air movement.

Various means can be employed to provide shading to the access areas. Well-located vegetation is an essential element in creating shade and can also serve other functions like creating an environment for gathering. Additional means for shading include the use of pergolas, galleries, balconies, loggias, porches, arcades, outdoor awnings and other structures that can serve dual ventilation and shading functions such as wind deflectors, screen walls, etc. Open spaces left under buildings elevated on stilts can also be put to use as shaded out-door spaces.

Trees and plants can be relied on for shading, as plants carry full foliage all year round. Rarely will a structure be built just to provide shade to an open space but pergolas and light framing to be covered by climbing plants can be provided cheaply and can be very effective.

## Wind

Ideal sites are windward slopes near the crest or near the sea as these locations are subject to regular winds. The ventilation effect can also be improved by effective arrangement of vegetation. Enclosed valleys and sheltered locations will be restricted in taking advantage of the wind for improving comfort and therefore should be avoided. Locations close to swamps or trapped water should also be avoided as they are likely to be a source of insects. On the other hand in a warm-humid island climate wind speeds may be excessively strong and highly exposed sites can suffer from this. An additional problem of excessively exposed coastal sites is the presence of salt from sea spray.

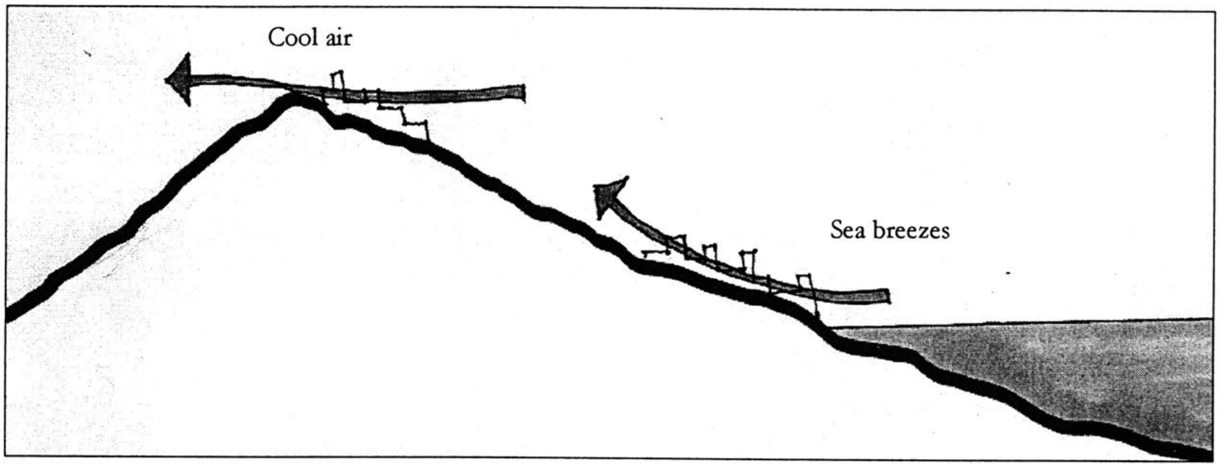



**Figure 6.1. Windward slopes are preferable in warm-humid climates**

An open settlement pattern is the appropriate response to the climate. To provide air circulation buildings should be scattered and have a low population density. Buildings should be separated with large free spaces between them to allow unobstructed airflow. This provides ventilation for cooling and a hygienic environment. On the other hand, walking distances should be minimized and the footpaths shaded.

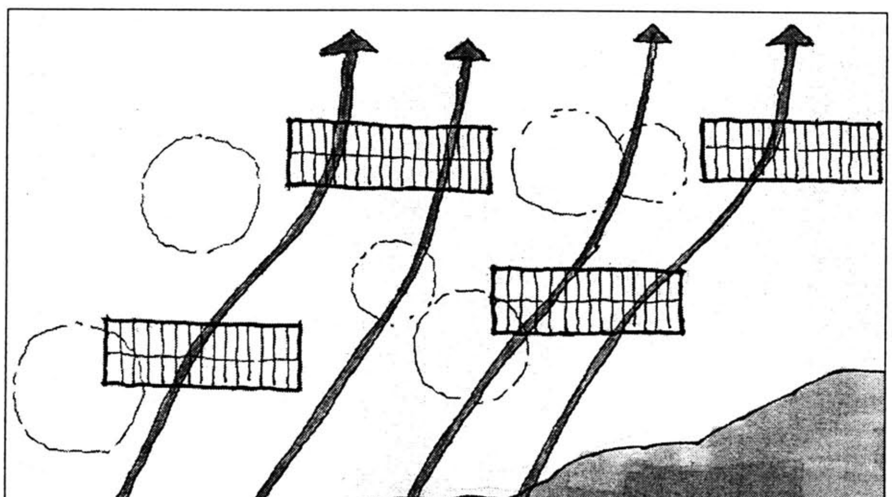


**Figure 6.2. Open, scattered and staggered settlement pattern for warm-humid climates**

Groups of buildings should not be built in a compact manner. Extended settlements, arranged in a line across the prevailing wind direction give low resistance to air movement and therefore are a good solution. Where developments include several rows of buildings these should be staggered to avoid wind shaded buildings in the downwind rows.

It is difficult to provide privacy as well as allowing for the passage of air in dense settlements. However various systems of paling fences and screen walls have been devised consisting of louvered or overlapping timber boards or planks which do not permit direct view but allow breezes to penetrate. Distance between buildings is a tool for providing privacy, when the settlement is not in a dense surrounding.

### Hazards

Although the wind velocity is generally not very strong, occasional hurricanes can occur. Therefore a firm structure is required. Floods are common in lowland locations and must be taken into account.

### Others

### Landscaping and vegetation for warm-humid island climates

One of the principle strategies in our analysis is to provide air movement at the human scale and shading. Vegetation in San Juan should be evergreen with thin, tall trunks and thick, high foliage to maximize shading. Palm trees and other trees that provide a 'canopy' effect are ideal for this climate. Vegetation should be used to protect west and east facades from the relatively more horizontal (and therefore more perpendicular) sun direction. Tall shrubs should be avoided because they obstruct airflow, especially at the human level.

An unshaded pavement exposed to the sun heats up and can reach very high temperatures. A vegetable cover of the ground however keeps it relatively cool and contributes to a cooler outdoor microclimate. Air should not be allowed to pass over such hot surfaces as it will warm up the air an make the air movement undesirable when it reaches the object being ventilated.

- **Street furniture warm-humid island climate**

The street furniture must be carefully designed. The material, colors and location of the furniture will determine if they are used. High radiation calls for materials that do not absorb large amounts of solar radiation, such as timber.

Protection for the street furniture calls for a careful study of where furniture should be located. These variables should be related to the periods where temperatures are highest and the activities that are likely to take place during those periods.

Color of the furniture is problematic: on the one hand reflective colors are needed to avoid heat absorption, but excessive reflection produces an uncomfortable glare. A solution is to assure that the furniture is properly protected from the sun.

### 6.3.2. Mexico City - Tropical upland climate

The main site-planning objectives in an upland climate are:

- South sloping topography preferred
- orientation to benefit from winter sun
- Protection from winter winds
- Semi-compact form

#### Sun

More selective decisions are needed in this type of climate. Whereas in the warm humid climate objectives were consistent throughout the year, the climate analysis for upland areas must identify the relative weight and duration of each season.

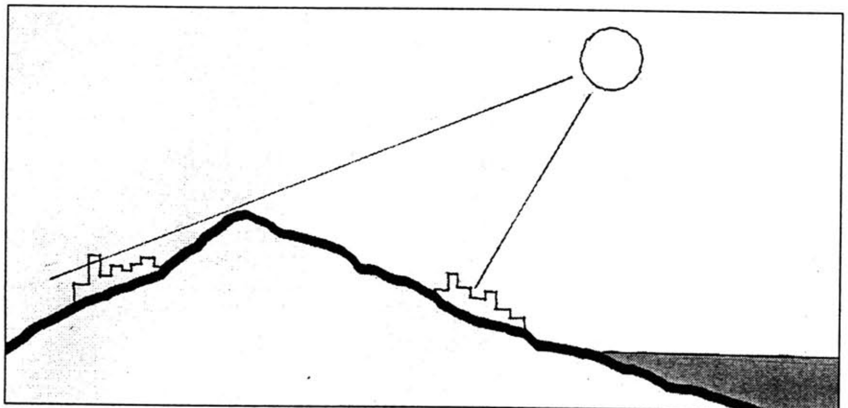


**Figure 6.3. Orient settlement to capture sun.**

Shelter against the wind and orientation for solar radiation gain are required all year round. East-facing slopes together with slopes facing northeast and southeast will receive maximum radiation in the morning when temperatures are cooler and are therefore advantageous. West northwest and southwest slopes will get maximum solar radiation in the afternoon when temperatures are likely to be warm or hot and are therefore less desirable. Sites located in the middle or the lower-middle of the slope are preferred. Here solar gain is best. Excessive wind effects as well as cool air pools should be avoided. The layout of buildings should follow the same goal of sheltering against winds and utilizing the effects of the sun's heat.

The moderating effect of large water bodies are beneficial because they reduce the diurnal and annual thermal range which is higher than in warm-humid climates.

#### Wind

The availability of winds is no longer a critical requirement for site selection. Indeed when temperatures are cold protection against the wind is desirable.

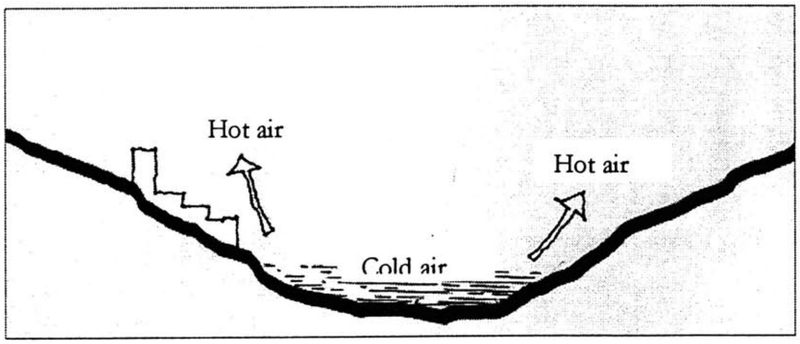



**Figure 6.4. Avoid valley bottoms because that's where cold air**

Depressions are less comfortable and difficult to design for because cold air accumulates there. Buildings should be protected from the wind while assuring solar penetration. Wind protection can be provided by existing topography or vegetation or newly planted vegetation or other structures.

## 6.4. BUILDING DESIGN

### 6.4.1. San Juan - warm-humid island climate

The main objectives for building design are:

- The main elevations and most intensively-used rooms should be placed facing north and south
- Rooms and elevations should be oriented towards the prevailing winds
- The form of buildings should be elongated and spread out
- The building should provide generous shade from direct and diffuse radiation
- Buildings should provide effective cross-ventilation

### Sun - Orientation of buildings

Although the intensity of radiation in hot-humid climates is normally less than in hot-dry regions, it is nevertheless a significant source of heat; therefore its entry into the building should be prevented.

In hot-dry climates the radiation is mostly directional and shadow angles can be established in quite precise terms. In hot-humid climates much of the radiation is diffuse, coming from the whole of the sky hemisphere, and the shading devices should provide a greater coverage, obstructing most of the sky and not just the location of the sun. As the openings are far larger than in hot-dry climates, the shading devices will be much larger. Openness and shading will be dominant characteristics of the building.

The building should be oriented to minimize exposure of east and west elevations. Thus the best orientation for protection from the sun is along the east-west axis. The lower solar angle implies higher radiation because the sun's rays are more perpendicular to the surface than in the north and south elevations' radiation. Therefore, shading of the east and west elevations is difficult, and may require special and larger devices whereas the north and south elevations can be easily protected with an overhanging roof. Moreover, the west elevation is usually exposed to the periods of highest temperatures and orienting any opening in this direction should be minimized if not avoided.

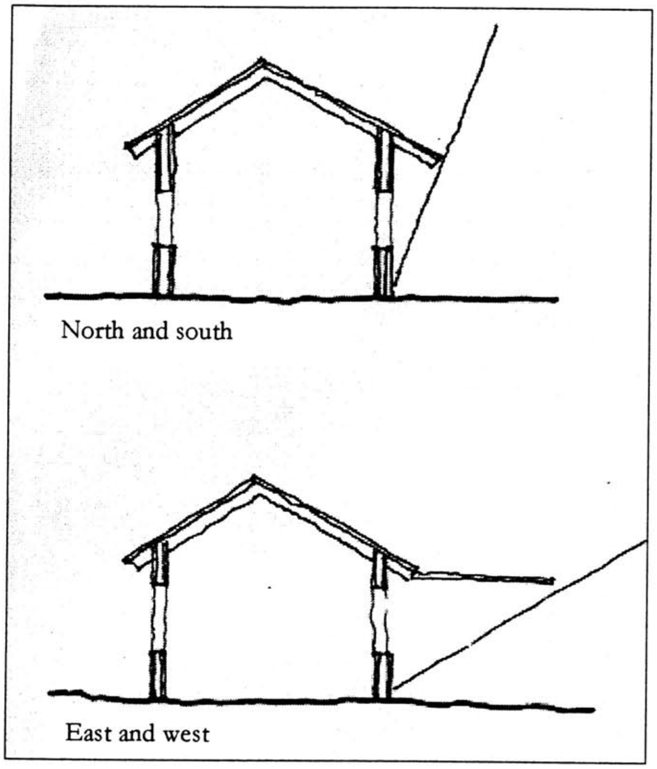



**Figure 6.5. Orientation: avoid west and east. Solar angle is considerably lower than in north and south and harder to protect.**

The arrangement of rooms depends within a building on their function. Since the thermal load is related to their orientation rooms on the east side are warm in the morning and if not built with much thermal mass, cool down in the afternoon. Rooms on the west side are cooler in the morning and heat up in the afternoon. Rooms facing north and south remain relatively cool if provided with adequate shading. Thus, the rooms can be arranged according to their functions and according to the time of day they are in use.

In general there are conflicts between optimal sun orientation and orientation for wind capture. A reasonable compromise should be made based on detailed analysis of the specific situation, considering the possibility for diverting the wind direction by means of vegetation and structural arrangements, such as parapet walls within the external adjoining space.

As a general rule, with low-rise buildings where the walls would not receive much radiation orientation according to the wind direction is more advisable. With high-rise buildings the opposite holds true and protection from the sun radiation should be the decisive criterion.

## Form, Shape, Volume

The form of buildings can be adjusted to take advantage of beneficial aspects of the climate and to reduce the impact of unfavorable aspects.

The volume of a building is very related to its capacity to store heat, while the surface area is related to the building's ability or rate to lose or gain heat. The ratio of volume to surface is therefore an important indicator of the speed at which a building will heat up by the day and cool down at night. Since the temperature range in San Juan is low throughout the year, the ideal is to avoid heat storage either by using materials that insulate (see chapter XXX) and by reducing the volume to surface ratio. A large amount of surface gives the building the possibility to breathe and expel its internal heat gain.

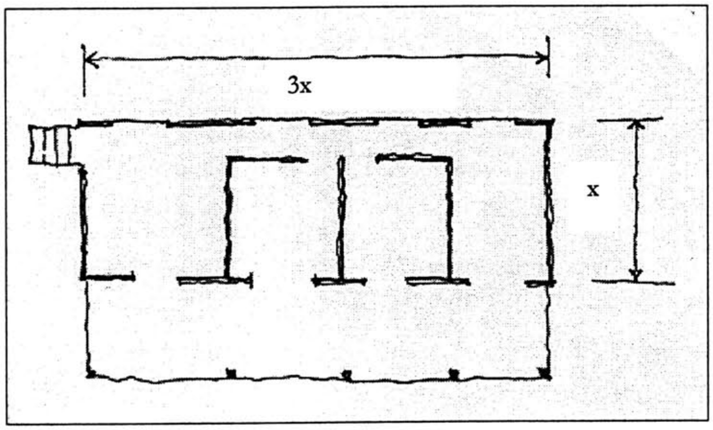



**Figure 6.6. Shape, elongated and narrow. Single banked**

Another important aspect of a building form is its depth determined by the distance between the opposing facades. As good internal air movement is a requirement in this climate, buildings should be "shallow", that is, narrow with single banked organization, or one ambient with a corridor adjacent designed in a way that air movement is not obstructed. Opposing facades should have large openings to induce air movement.

### Wind

As movement of air is the only available form of relief from climatic stress, therefore vital to indoor comfort, the building will have to be opened up to breezes and oriented to catch whatever air movement there is. Failure to do this would produce indoor conditions always warmer than a shaded external space, which is open to air movement.

Where a predominant wind direction can clearly be identified, long shaped buildings should be arranged perpendicular to this direction.

From the point of view of solar heat gain the best arrangement would be to orient the building with the long axis along the east–west direction. This may often conflict with the requirement of orientation for wind. It should be kept in mind, however, that the solar geometry cannot be changed, but the skillful use of elements built outside such as screen walls or the projecting wing of a building can change the direction of air movement.

The high humidity and warm temperatures require maximum ventilation which leads to very open buildings. This is valid not only for the design of the elevations but also for the floor plan.

Free passage of air for cross ventilation through the interior is important. This can be achieved by large openings not only in the outer walls but also in the interior partitions. An even more efficient solution is that of single-banked rooms with access from open verandahs or galleries. The floor is preferably elevated from the ground to allow better ventilation.

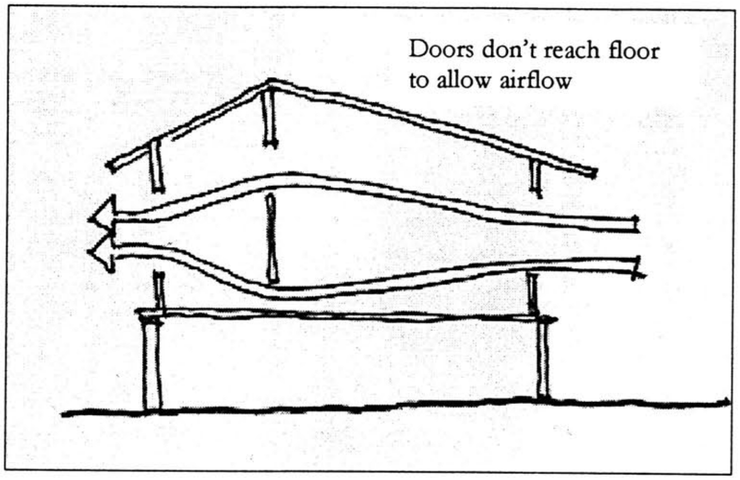



**Figure 6.7. Wind capture and elevation of building to maximize wind.**

In general, the height of buildings should be kept within 3 stories. Higher buildings receive too much radiant heat and obstruct wind movement to neighboring buildings. However, wind is stronger at higher elevations and a clearly predominant wind direction may make it desirable to maximize its capture and, if properly protected from radiation, a high building may be an appropriate solution. Moreover, wind obstruction can be dealt with by elevating the building on stilts to allow air movement at ground level or by producing openings in building masses to allow wind to pass through the building, thereby reducing minimum distances between buildings.

### 6.4.2. Mexico City - Tropical upland climate

The main objectives of building design are:

- Orientation and rooms should face south (for northern hemisphere)
- Shade in summer and heat gain in winter are necessary
- Ventilation selective: must be controllable in winter
- Semi-compact form

#### Sun - orientation

The orientation of the building greatly influences the solar heat gain. Normally buildings should have an elongated shape along the east-west axis. The southern elevation (for the northern hemisphere) can easily be designed for proper utilization of the winter sun and for protection against the summer sun. Windows on the eastern elevation receive substantial heat during the morning, which may be highly appreciated in winter time. Larger windows on the west elevation are to be avoided, as the solar heat gain through these would coincide with the highest air temperatures.

**Shape, volume, form**

Buildings are preferably compact. However, because of the conflicting climatic conditions several solutions are possible, depending on local topographical and functional requirements. Courtyard buildings with proper wind protection are a suitable solution.

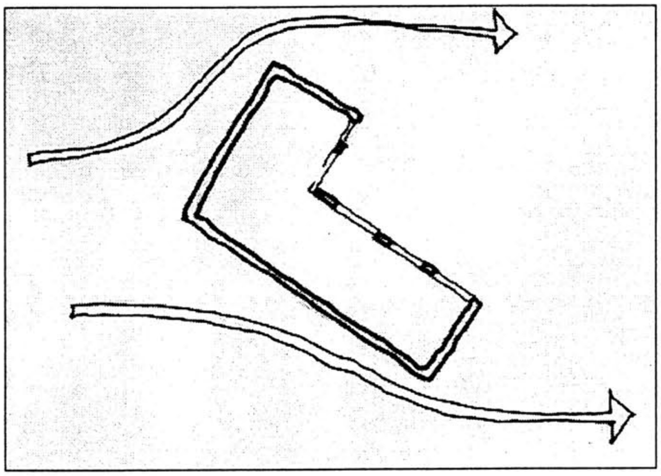


**Figure 6.8. Shape to protect from winter winds.**

**Wind**

Buildings should be arranged so that they benefit from summer winds because this season is usually humid and a proper cross-ventilation is required for cooling and hygienic reasons (prevention of mold growth). At the same time shelter should be provided from the winter winds.

In these climates the guiding design principle is to determine the relative weight of the cold and warm periods in order to identify which strategy is more important and to design for both, when possible. Winds often change from season to season so that both capture in summer and protection in winter is possible. Solar protection devices for openings can be calibered to allow sun in winter and block sun penetration in summer. Deciduous vegetation can also contribute towards selective capture of sun.

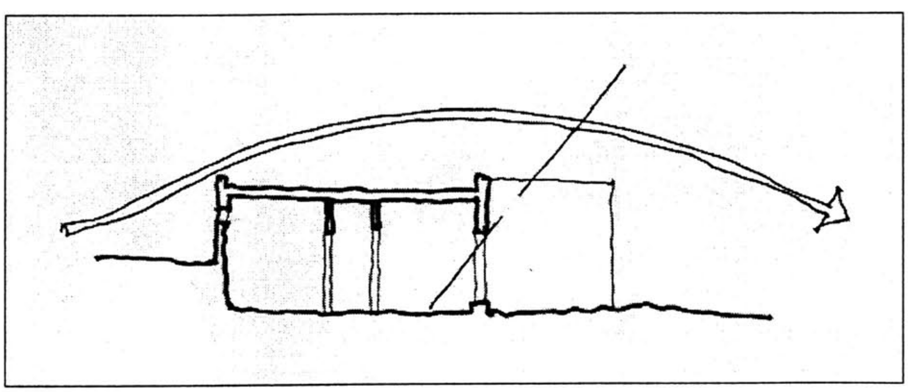


**Figure 6.9. Use terrain to increase thermal mass and protect from winds**

In this type of climate it would seem reasonable to conceive one part of the building for the cold period and another for the warm period.

One solution would be a building type consisting of a ground floor with massive walls and an upper floor of a light structure[1]. The ground floor would be relatively cool in the daytime and relatively warm at night. The light structure on the upper floor would perform the opposite way. As a consequence, in the winter time the inhabitants would use the upper floor in the daytime and the lower floor at night. In the summer time the pattern would be reversed.

Another possibility is to use different sites in different climatic conditions - a warm in the winter and a cold one in the summer - and to migrate from one place to the other.

In practice however for both economical and organizational reasons such day and night or summer and winter configurations are often not feasible and a building has to be designed to serve all year round. The large range of thermal conditions requires the utilization of radiation and wind effects as well as protection from them. Hence, arrangements must play a dual role.

## 6.5. BUILDING COMPONENTS

### 6.5.1. San Juan - warm-humid island climates

Objectives of building components:

- Minimize heat storage and time lag
- Thermal insulation effective only on surface exposed to direct solar radiation
- Materials should be permeable to air yet protect from precipitation
- Reflectivity and emissivity are important

Due to the relatively narrow diurnal temperature fluctuation it is not possible to achieve much cooling by utilization of the thermodynamic properties of building components. The main goals is on the hand to store as little heat as possible in the structure in order to obtain the maximum benefit of the cooler night temperatures.

On the other hand maximum ventilation throughout the day enables cooling by perspiration. Another point is the reduction of radiation and its reflection, meaning direct and diffuse solar radiation as well as radiation by the surface of heated-up parts of the building and the surroundings.

Constructions with a high thermal capacity and a long time lag should be avoided. It would cause undesirable re-radiation of heat at night. Due to the high relative humidity problems of condensation could also appear in the morning hours because the surfaces would be somewhat cooler than the air. As an exception in buildings used during the daytime only, a certain heat storage capacity may be advantageous. Depending on the diurnal temperature differences a reduction of the daytime indoor temperature by a few degrees may be possible. A relatively short time lag of some 5 hours may be adequate.

Thermal insulation has very little effectiveness. Due to the free flow of air the ambient air temperature inside and outside the building are very similar. Insulation may be justified in places where sun radiation is received, such as roofs and sun-exposed walls. The use of reflective materials

[1] Gut , Ackernecht, *Climate Responsive Building*, 1993.

and surfaces is more important. These measures keep the temperature of the inner surface low. The same effect can be achieved with properly ventilated double skin constructions.

High emissivity and reflectivity are required properties for keeping the indoor temperature and the inner surface temperature low.

**Foundations, basements and floors**

Direct contact with the ground does not necessarily provide cooling because the temperature of the shaded surface is about equal to the mean air temperature. A certain cooling may be possible by conduction for barefooted persons or persons sitting on the floor.

As a consequence it is better to raise the floor and ventilate the space underneath. The floor should be of low thermal capacity (such as timber floor with void). The advantages are better ventilation due to the elevated space and maximum benefit of the slightly lower night temperatures.

**Walls**

Walls both external and internal should be as light as possible with a minimal heat storage capacity. They should obstruct the air movement as little as possible and should reflect radiation, at least in places where solar radiation strikes the surfaces. The outer surfaces should be reflective and light colored.

Walls should be shaded as much as possible. If, however, exposed to the sun they should be built in the form of a ventilated double leaf construction, the inner leaf having a reflective surface on its outer side and with thermal insulation.

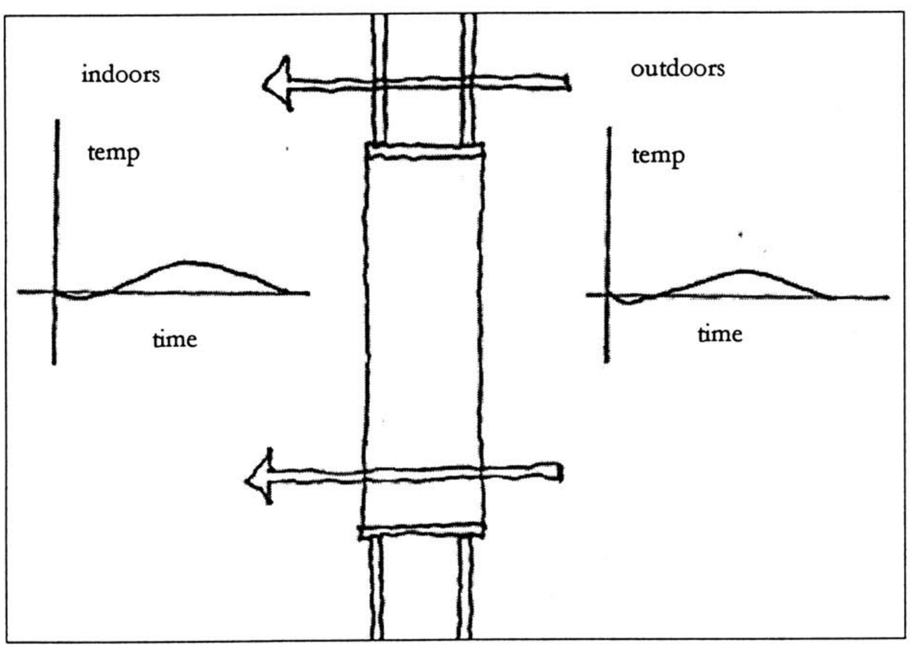



**Figure 6.10. Light materials. Little outdoor – indoor differentiation**

Light and thin materials such as timber or bamboo are recommended. Other materials forming light panels can be used with a frame structure to take care of the structural requirement.

See chapter 6 for other materials and their properties.

## Openings and windows

In warm humid climates openings are important elements for the regulation of the indoor conditions. They should be large and fully openable, with inlets of a similar size on both sides of a room to allow for a proper cross-ventilation. Windows are preferably equipped with flexible louvers allowing a regulation of ventilation. Door shutters may also incorporate louvers or grills. Windows with fixed panes are of no advantage and should be avoided.

To avoid direct solar radiation and glare, openings should be shaded by an overhanging roof, screens, lattices, grills etc.

All these measures have to be designed to give minimal resistance to air movement. Mosquito screens are essential in these climates but they reduce airflow considerably are therefore best installed away from windows such as around verandahs or balconies.

Openings should be placed according to the prevailing winds so as to permit a natural airflow through the internal space. This airflow is most effective if concentrated at body level.

A difficult problem is the design of large openings which at the same time protect from driving rain. Louvers can be used but they must not direct the wind upward because air movement is necessary at body level. Moreover, most ordinary louvers are not designed to withstand driving rain.

Modified louvers keep the wind at lower levels and provide protection form driving rain nut reduce the airflow to some extent. Yet another alternative is to use two sets of louvers to fulfill both objectives of keeping air movement at body level and protecting from driving rain.

## Roofs (surface or orientation with the highest radiation exposure of all)

In warm humid areas the roof should preferably be pitched. This makes it easier to achieve a construction, which is waterproof, by allowing heavy rains to run off. Large overhangs protect the walls and openings from radiation and precipitation.

The roof should be made of lightweight materials with a low thermal capacity and high reflectivity. Metallic and light colored surfaces have the best reflective capacity. Painting the surfaces in light colors, e.g. a yearly-applied coat of whitewash, is an economical method to increase reflectivity. However in most cases a single leaf construction will not satisfy the comfort requirements.

A more efficient solution is the properly ventilated double roof. The inner layer (ceiling) may be well insulated and provided with a reflective upper surface. The inner surface of the ceiling should not exceed the air temperature by more than 4°C. This can be achieved by an insulation board 3 to 4cm. thick. This gives a U-value of 1.5 $W/m^2K$.

A typical ventilated double leaf roof structure should include a roof covering, a ventilated cavity, a reflective foil, an inner ventilated cavity and insulation board and an inner ceiling.

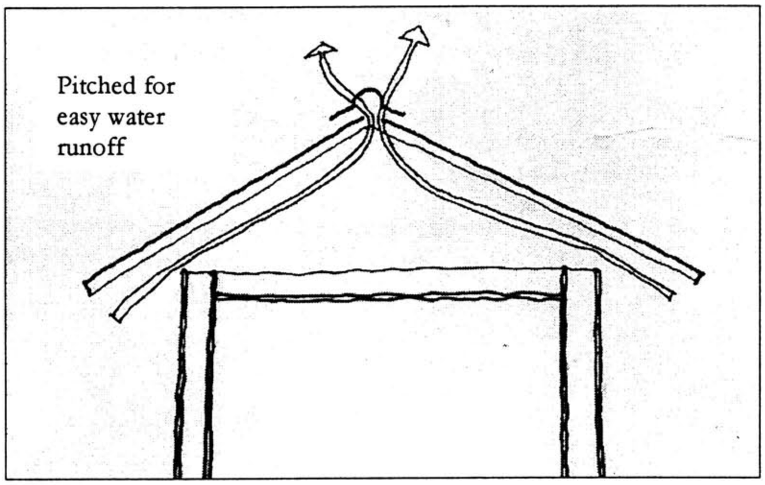



Figure 6.11. Ventilated double roof to avoid overheating.

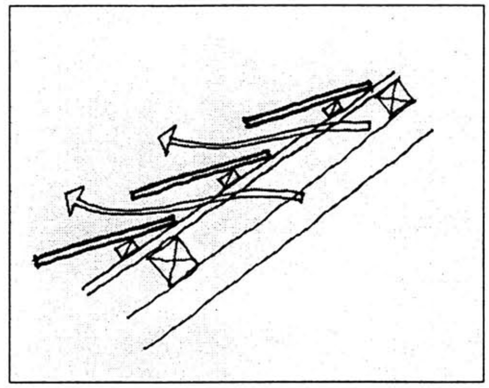


Figure 6.12. Detail to allow ventilation of roof.

Koenigsberger et al. 1974 showed that in two identical houses roofed with corrugated asbestos sheets and with an outdoor temperature of 22°C a difference of 14°C in the ceiling surface was observed. In one case where there was no ceiling, the temperature was 48°C and in the second case where there was a paper ceiling lined with aluminum on the upper surface the temperature was 34°C.

Air that passes through a double roof space should not be allowed to enter the areas where humans perform their activities as this air will be much hotter than the normal outdoor air.

## Shading devices

Although the intensity of radiation is normally less than in hot-dry regions it is nevertheless a significant source of heat and its entry into the building should be avoided. In warm humid climates, such as San Juan, due to the moisture in the air most of the radiation is diffuse, coming from the whole of the sky.

Shading devices should therefore provide great coverage, obstructing most of the sky and not just the sun. Furthermore, the openings should be large (for wind capture), which is another reason why the shading devices should be large.

Fly screens and mosquito nets are a necessity if any kind of lamp is used indoors. Such screens can reduce the air flow. A cotton net can reduce air velocity by 70%. A smooth nylon net is better, with a speed reduction of approximately 35%[2].

Vegetation can also play a decisive role in providing shade especially facades that would be hard to shade (west and east) using conventional shading devices due to the relative horizontality of the sun's rays.

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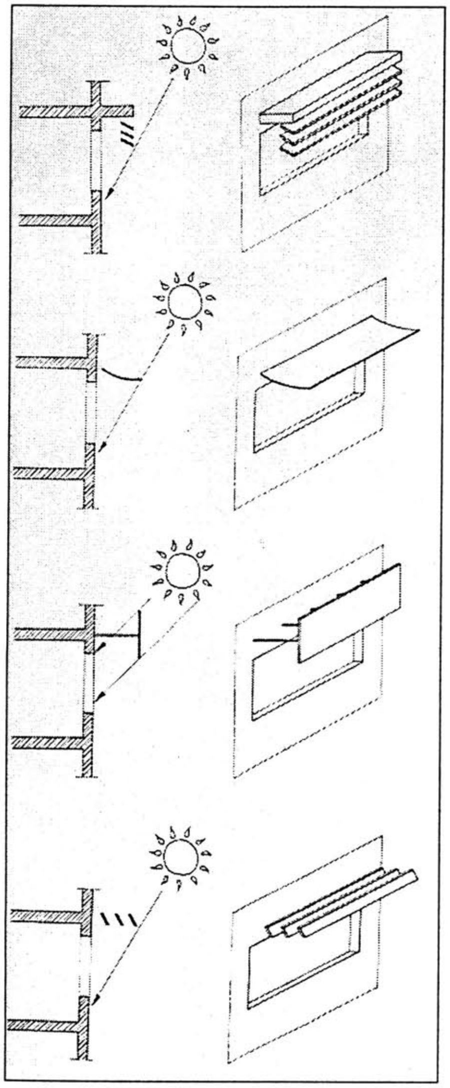
[2] Koenigsberger, Ingersoll, Mayhew, Szokolay, *Manual of Tropical Housing and Building*, 1973.



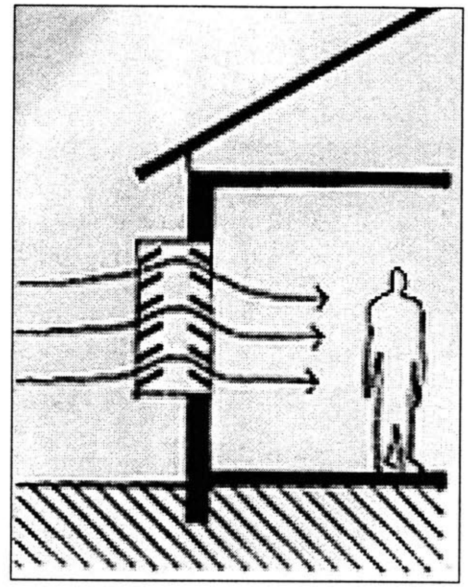


**Figure 6.13. Double set of louvers for rain protection and wind capture. Source Gut – Ackernecht.**

**Figure 6.14. Different shading device configurations. Source Gut – Ackernecht.**

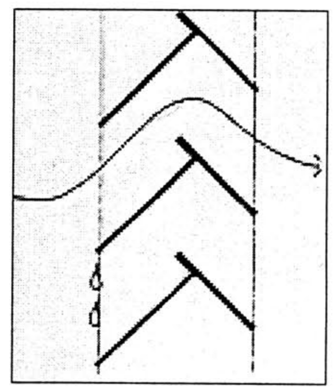


**Figure 6.15. Detail of modified louver. Source Gut- Ackernecht.**

### Passive cooling

The possibilities for evaporative cooling in humid regions are limited. The potential of the air to absorb humidity and with it the potential for cooling is limited.

In island climates, however, where the peak temperature is combined with a relative humidity of approximately 65%, methods of evaporative cooling are possible, although the efficiency is less than in hot-dry climates.

## 6.5.2. Mexico City - tropical upland climates

The general objectives building components should fulfill are:

- Medium heat storage capacity and time lag required

- Thermal insulation needed
- Reflectivity and emissivity is less important
- Proper protection from precipitation needed

Heat accumulated during the daytime should be stored by an adequate thermal capacity of the walls, ceilings and floors to balance the temperature. A properly dimensioned thermal mass means that rooms do not overheat during days with high temperature and high solar radiation gain, and do not cool down too much at night, or even during cooler days.

The retention of the nighttime low temperatures is desirable in the hot dry season. In the cold season the retention in the evening of heat gained during the daytime is desirable. Both can be achieved with a solid floor, wall and roof structure with a time lag of approximately 8 hours. This thermal capacity is preferably provided by internal walls, floors and roof, permitting the outer walls to be used more freely for large openings, which help to meet the requirements of the warm humid period.

An excessive thermal mass should be avoided. This would make the space almost unheatable during the evening hours of the cold season. If thermal insulation is used it should be placed on the outside of walls and roof so that the beneficial effect of thermal storage capacity is not reduced.

**Foundations, basements and floors**

The floor may be in direct contact with the ground, with medium insulation and thermal storage capacity. Materials with low thermal transmission properties are suitable. In addition, thermal insulation may be necessary. Floor areas receiving direct solar radiation should possess absorption properties and a heat storage capacity.

**Walls**

A medium heat storage capacity of internal and outer walls is appropriate to avoid overheating in the daytime and keep the night temperature at comfort level.

Surfaces should generally have medium colors. In areas most exposed to the sun a bright surface with high reflectivity is appropriate while in surfaces not exposed to the sun dark, absorptive surfaces are called for.

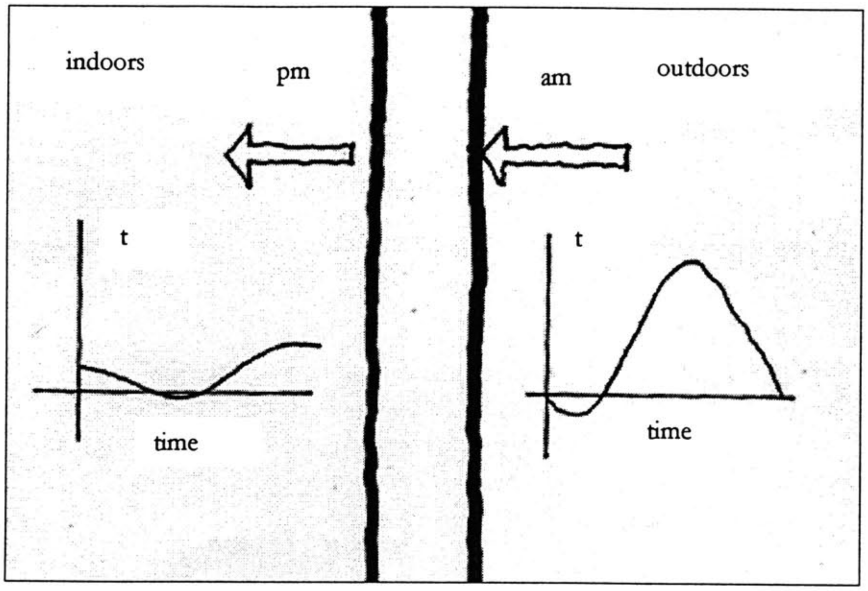



**Figure 6.16. Materials for walls. Thermal mass regulates ourdoor conditions**

## Openings and windows

Windows should be of medium size with openings on opposite walls for proper cross-ventilation during the humid period. On the west and north side walls should be small.

In order to utilize the heating effect of solar radiation, as many windows as possible should be placed facing south. However, excessive glazed areas on the south elevation can lead to heat loss at night. As a rule of thumb, not more than 50% of the south facade surface should be glazed.

Moreover, excessive glazing can lead to overheating. This can be counteracted by

- provision of adequate shading
- provision of ventilation
- sufficient heat storage capacity

## Roofs

The roof should provide protection from heat gain during the summer and heat loss in the winter. The roof should therefore have thermal insulation properties.

Usually a multilayered construction is required. The reflectivity and emissivity of the outer surface is then of minor importance.

The construction should have a medium heat storage capacity to balance temperature fluctuations between the daytime and evening hours, and also in case of sudden weather changes. This storage mass must be situated inside the insulation layer.

The construction should be airtight, the joints between the construction elements requiring special attention.

## 6.6. Illustration of application of guidelines

The second part of the chapter illustrates on a step by step basis the decisions taken in the design process. As in the first part of this chapter, the illustration covers decisions from a decreasing level of detail starting with site planning, building design and building component design.

While the design of all the stations in the first phase of Tren Urbano is nearly complete, in the second part of the chapter I will illustrate how these guidelines may be applied to one station, Hato Rey Centro. In order to effectively identify and differentiate how climate affects design, I will illustrate how the guidelines would be different if the same station with the same surroundings were situated in the other location whose climate I analyzed in chapter 2, Mexico City.

This part is intended to show design alternatives and briefly illustrate how to evaluate them. They are not intended as design proposals but as guidelines about how the recommendations of the previous chapters are applied in a specific context with a set of constraints and limitations.

### Hato Rey Nuevo Centro Plan

To illustrate the guidelines I chose a station area that is very helpful for this purpose because of its complexity, and relatively early stage of design. Hato Rey Centro Station is in the heart of the Golden Mile, a component of a late 1960s - early 1970s project to create a new financial center for San Juan and some mixed uses in surrounding areas. A canal housing squatters, Canal Ochoa, was cleared and old Martin Peña railroad yards and abandoned sugar cane fertilizing industries were 'urbanized' to accommodate this ambitious proposal. The Golden Mile is a one-mile strip delimited by two major arterial roads: Muñoz Rivera and Ponce de Leon Avenues.

The project has had moderate success in concentrating the financial activities of the city. There are still numerous plots of vacant land, serving such low value purposes as off-street parking. The new residential areas, called Nuevo Centro to the west of the Golden Mile, have developed along single-use, auto-oriented walk-up and elevator types catering to mid to high income populations. Little efforts have gone to making a pedestrian environment and linking the uses or allowing the mix of uses. Vegetation is scarce except for few unconnected exceptions.

Surrounding the Golden Mile to the east and southwest are old, consolidated grid neighborhoods. To the east is a low to mid-income area known as Las Monjas, and Martin Peña with a relatively good mix of uses. To the southwest is the Huycke neighborhood, a politically organized middle income neighborhood, also with a mix of uses.

Also surrounding the area to the north is a linear park, Parque Lineal, which connects to the Central Park of San Juan. Not far to the west is the biggest shopping center in Puerto Rico, Plaza Las Americas, which acts as a siphon for the area. The lack of mixed uses requires many to drive a mile to this shopping center for many daily activities.

### Hato Rey Centro Station

The area immediately surrounding the future train station presents the following features:

- an old shopping center (Metropolitan Center) about to be demolished and redeveloped and with the potential for joint development and linking it to the station.
- a well preserved public park that serves the Huycke neighborhood immediately adjacent to the future station.
- a major office tower with the potential to be linked to the station.
- a major bus transfer station across the street from the station and also potentially could be integrated to the design of the station.
- Polytechnic University

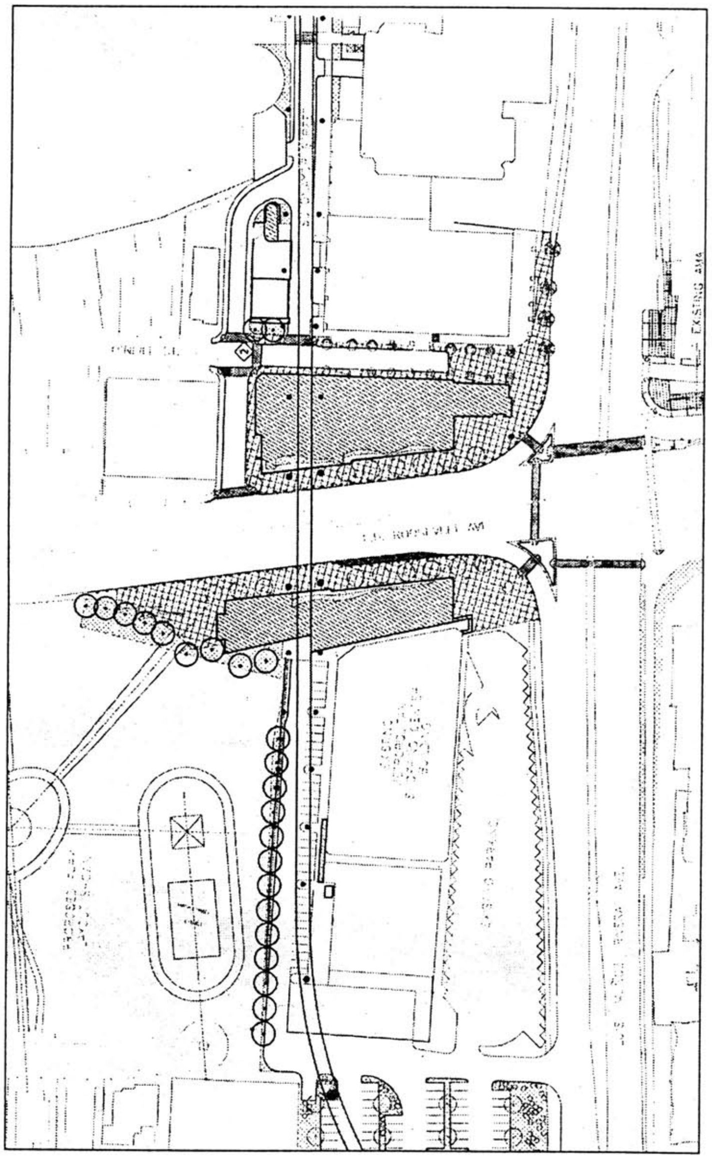


**Figure 6.17. Plan of Hato Rey Centro Station and surroundings.**

The station itself has the following characteristics as given:

- side platforms
- elevated
- joint development in and around the station building

**Assumptions**

I am assuming that the redevelopment of the shopping center will take place. To better illustrate site planning decisions, I propose design solutions at a very rough and approximate level for the redeveloped shopping center. Another approach is to take the existing building envelope as a given and design the station building and its relation to the shopping center in the most optimal way. Both these approaches are presented to enrich the illustration of guidelines given different context constraints.

## Illustrations

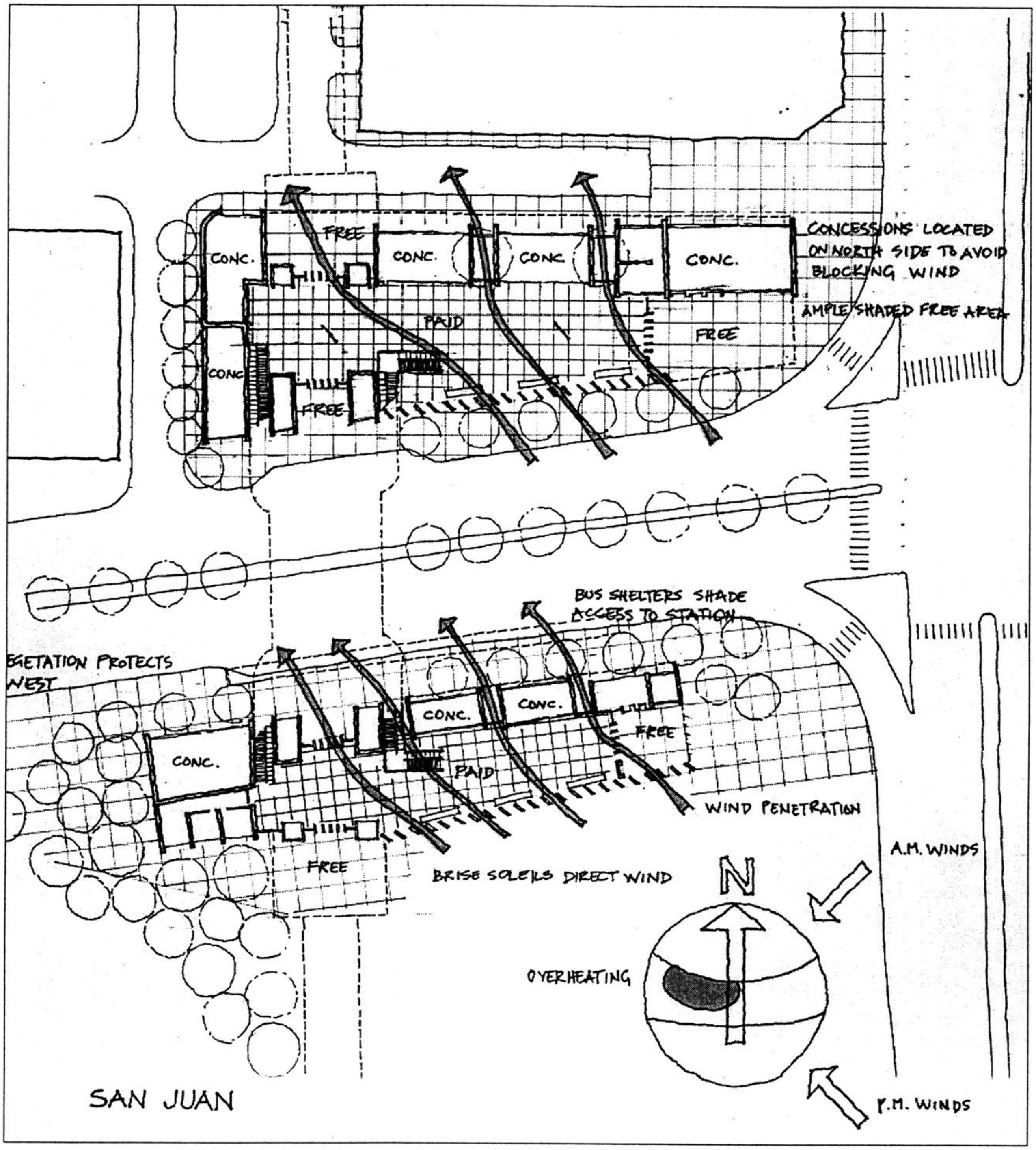



Figure 6.18. Illustration of a possible design proposal in San Juan.

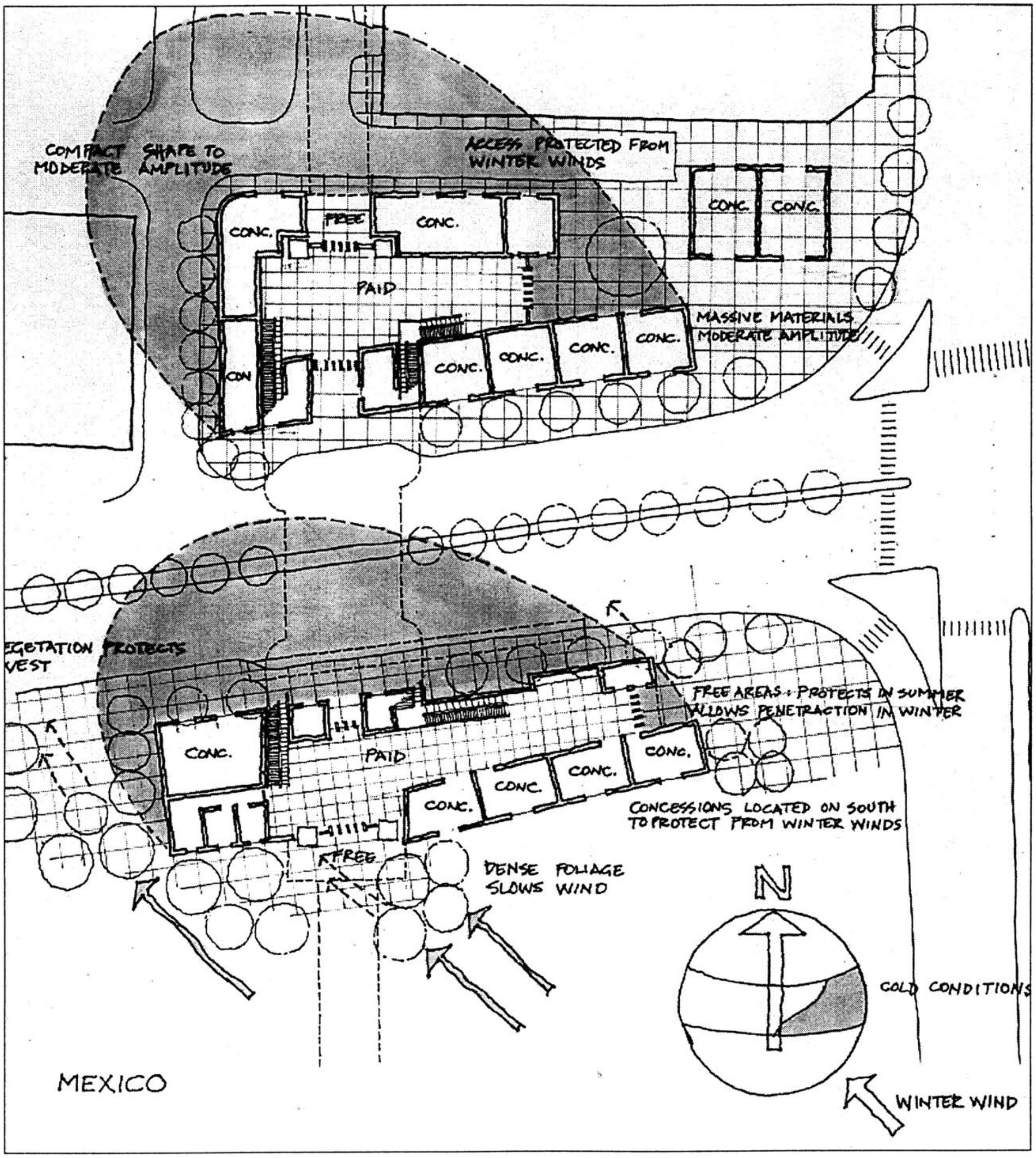



**Figure 6.19. Illustration of a possible design proposal for Mexico City.**

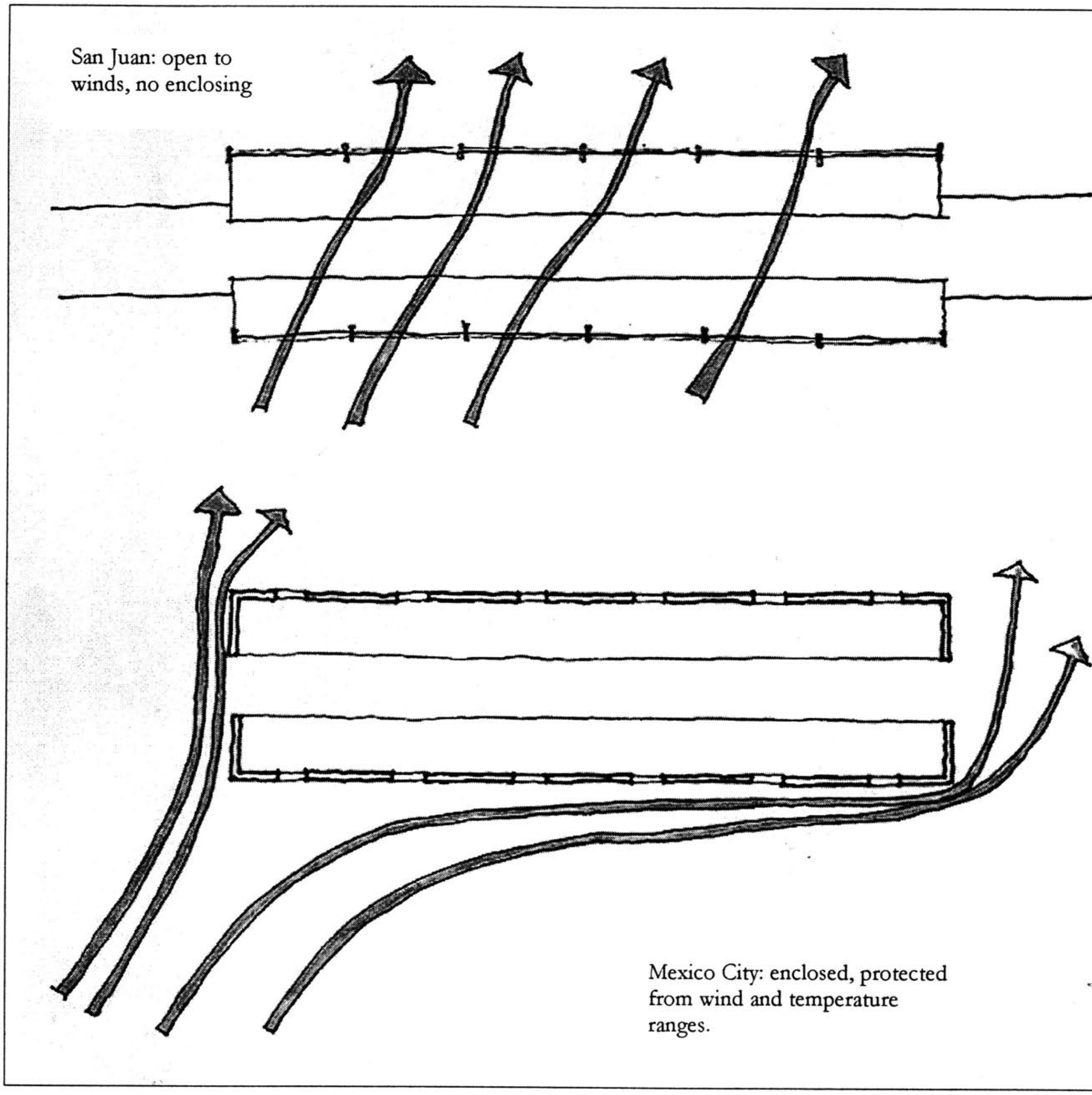



**Figure 6.20. Platform area: open to winds in San Juan and protected from winds in Mexico City. Different use of materials regulates outdoor conditions**

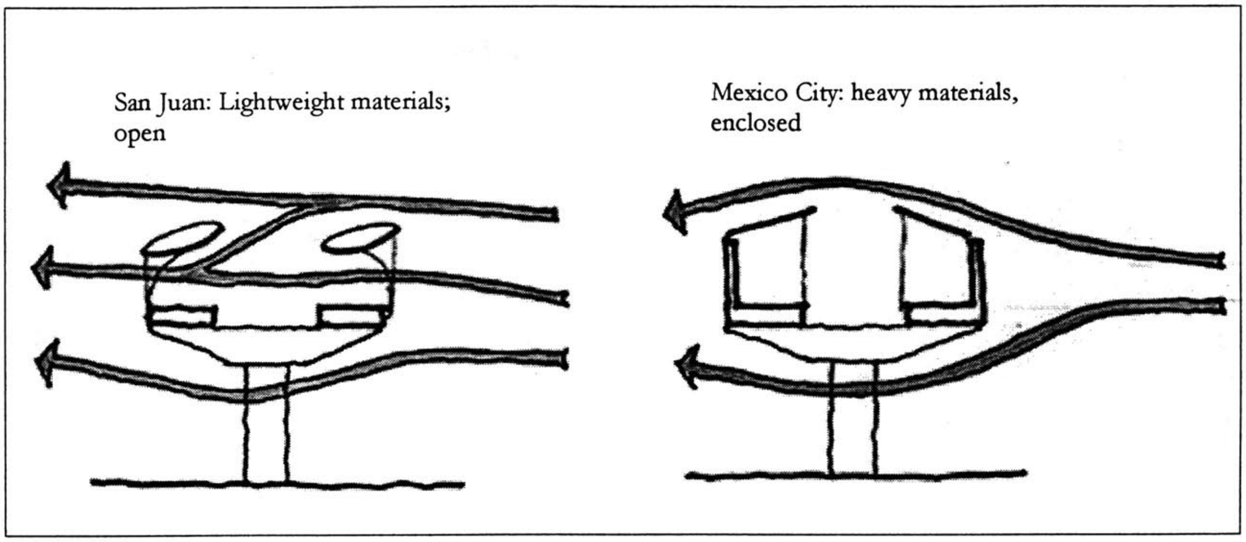



**Figure 6.21. Roof design manipulates wind. Materials regulate indoors conditions.**

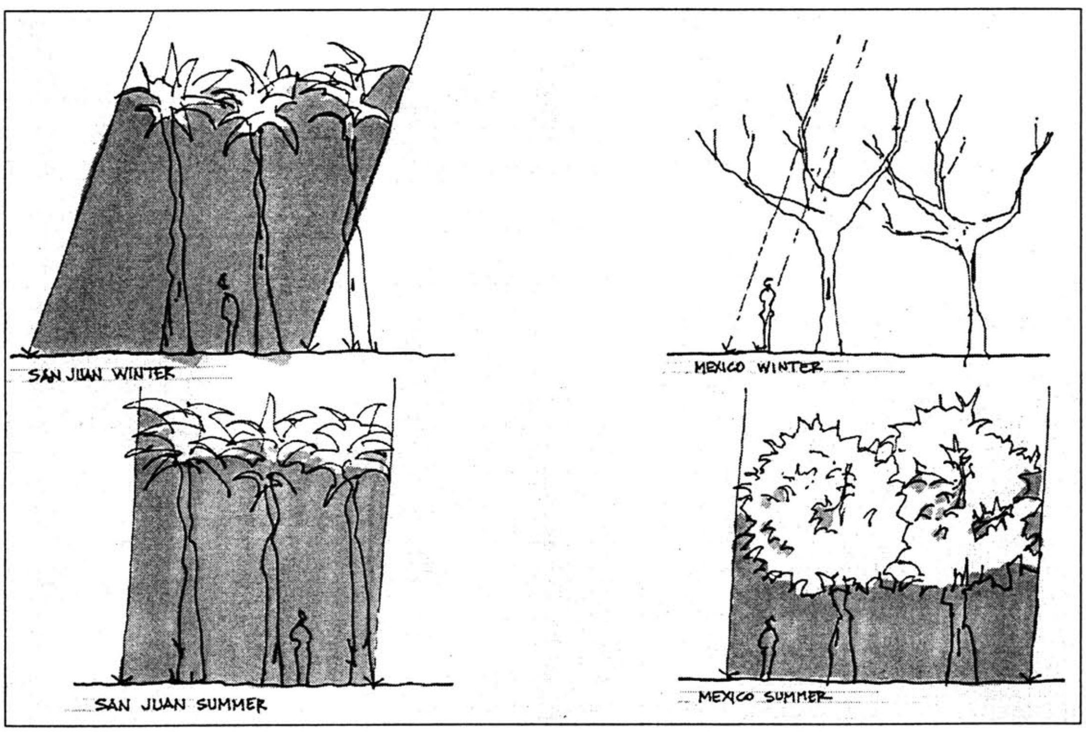



**Figure 6.22. Choice of vegetation: evergreen responds to stable conditions in San Juan (left) and deciduous responds to varying conditions in Mexico (right)**

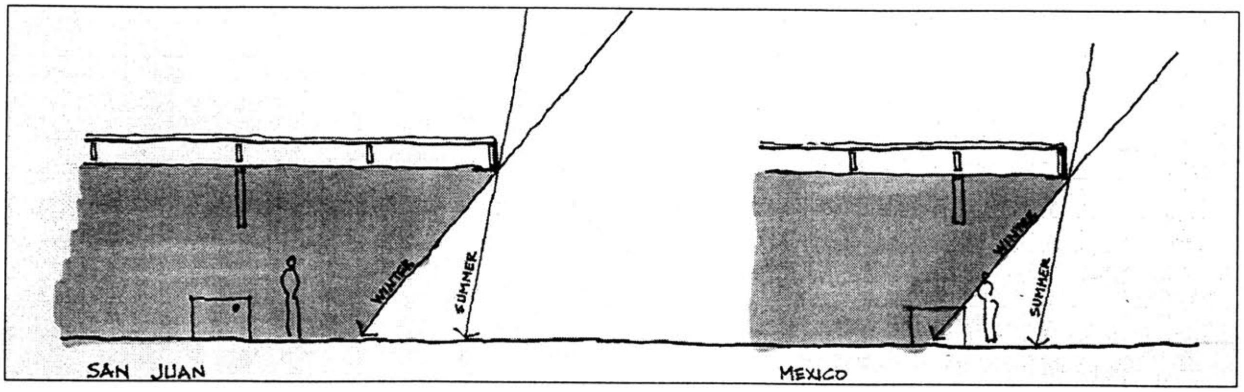



**Figure 6.23. Design of components to protect from sun throughout the year in San Juan (left) and differentiate between seasons in Mexico (right)**

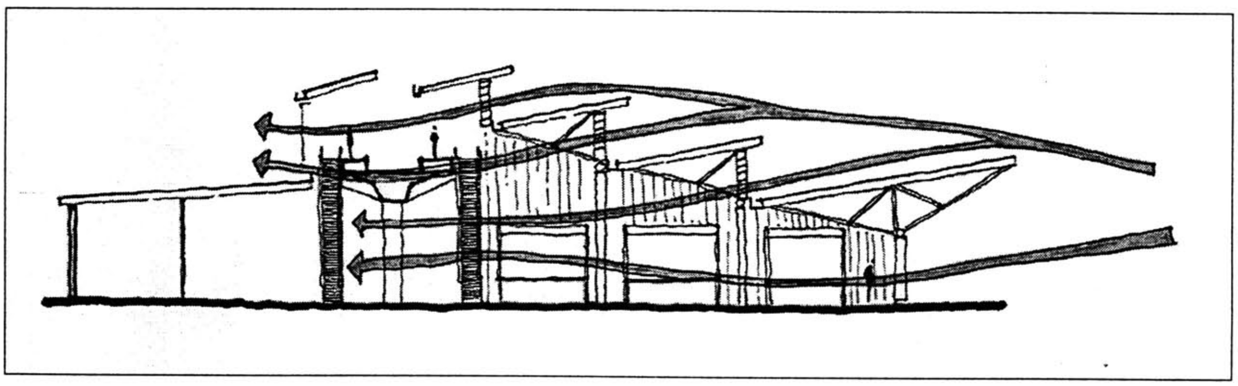


**Figure 6.24. Section in San Juan. Roofs capture wind. Lightweight materials.**

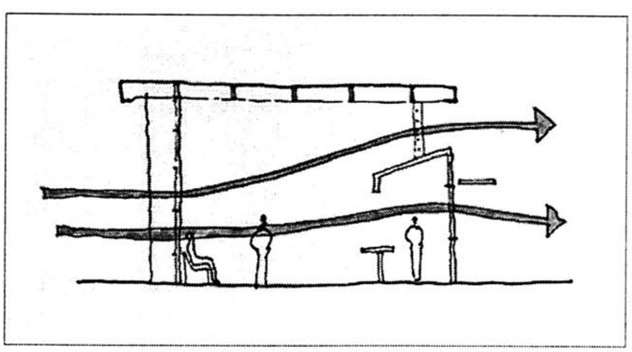


**Figure 6.25. Cross section San Juan.**

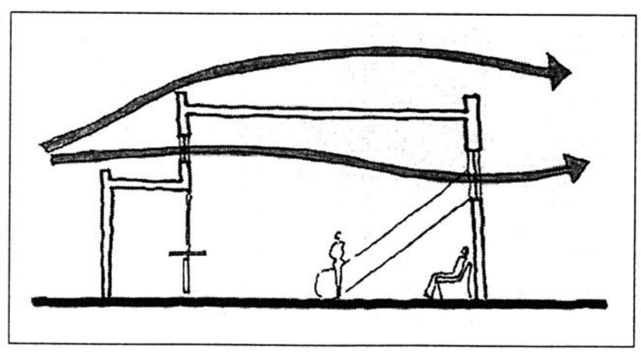


**Figure 6.26. Cross section Mexico City.**

# 7. CONSTRAINTS/OBSTACLES

This chapter identifies the potential problems, obstacles, constraints and conflicts that stand in the way of implementing the design guidelines drawn in the previous chapters and begins to suggest ways of overcoming these.

There are two main categories of obstacles: the specifically bioclimatic or design related conflicts and the institutional conflicts.

The main issues arising out of institutional conflicts relate to the unique contractual arrangement adopted for the construction of Tren Urbano as described in Chapter 1. Other institutional conflicts include institutional capacity and enforcement. These issues in themselves constitute the subject of what could be a lengthy thesis. I will draw some basic conclusions leaving this as an area for future research.

## 7.1. Bioclimatic design internal conflicts

Some of the design guidelines contradict each other as was seen in the previous chapters. The resolution of these conflicts is an important aspect of this thesis, as the idealized conditions are hardly ever found in practice.

A detailed analysis of each site in Tren Urbano is impossible. This section draws general conflicts that are likely to appear in the use of the guidelines

### a) Driving rain (can be horizontal with strong wind) -wind capture (captured to fullest extent possible)

In San Juan winds can get extremely fast. Coupled with rain, this could produce driving rain, that is, rain in a predominantly horizontal direction. This is in conflict with the need to capture winds: capturing winds requires minimum obstacles, while protection from driving rain requires some sort of obstacle. One possible solution is to use a double set of louvers, whose first set keeps the rain out and whose second set redirects the wind so that it is felt at the human level.

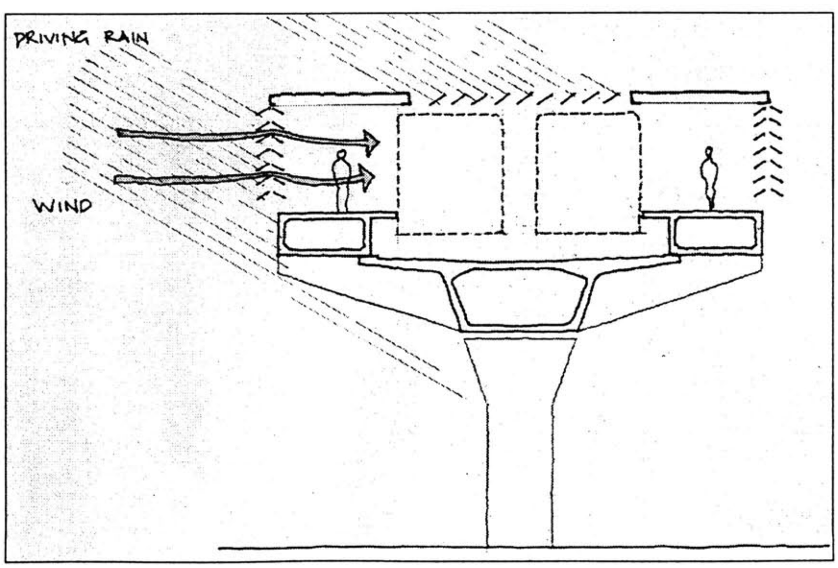



**Figure 7.1.Driving rain – wind capture conflict**

**b) Solar protection (orientation n-s) – wind capture (orientation ne–se)**

As mentioned in the guidelines, the optimum orientation for sun protection is north - south, that is, with the long axis oriented along the east-west axis. This is because the sun coming from the east and west is more horizontal than that from the north and south, which can be protected by a small roof overhang. Moreover, being more horizontal makes the rays more intense since they are more perpendicular to the surface.

Orientation for winds on the other hand, calls for different orientations from that of the sun. In San Juan, winds in the morning tend to be from the sea (northeast, sea breezes) and winds in the afternoon tend to be from the southeast (land breezes). In order to optimize orientation, we must look at the temperature at the times these winds occur to capture the wind at the most disadvantaged period where wind capture will be most important. As we saw in the climatic analysis temperatures are highest in the afternoon. Therefore priority, in terms of wind, should be given to capturing afternoon winds, which calls for a building whose long axis is orientes along the northeast - soutwest axis.

Taking both sun and wind into account yields an orientation somewhere between the optimal sun and optimal afternoon wind orientation, that is somewhere between having the long axis along the east-west and the northeast-southwest axis. It should be noted that often a site is restricted in its possibility to orient the building as desired, and in these cases the use of wind deflectors to capture wind may be used though the results are not going to be as effective.

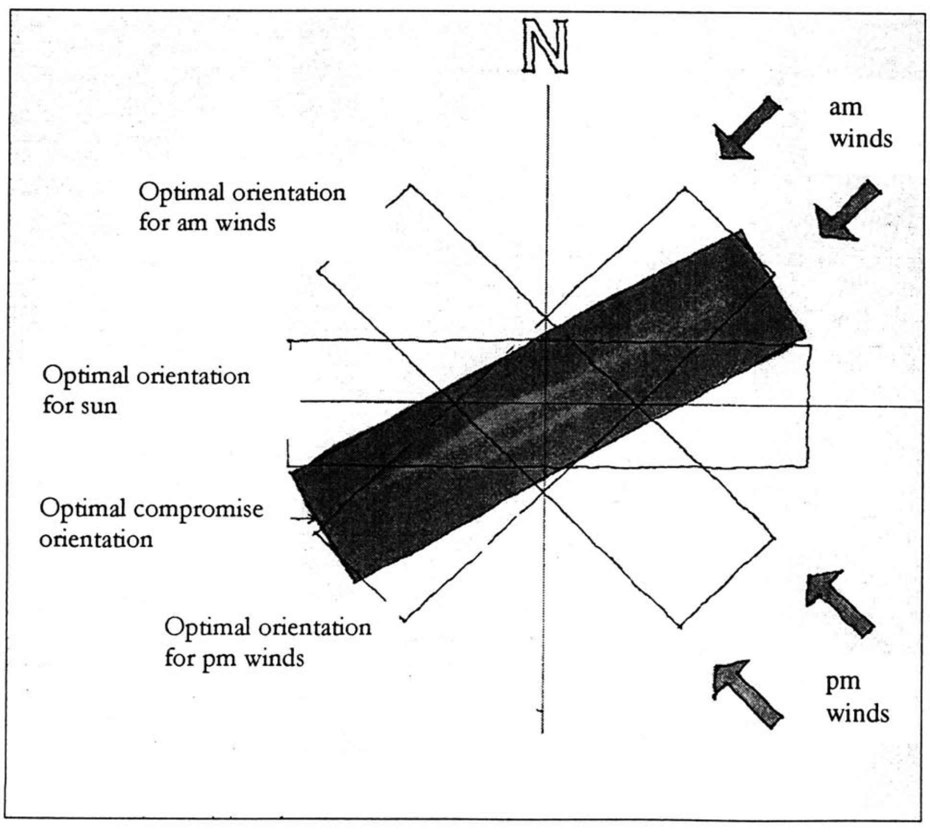



**Figure 7.2. Sun orientation vs. wind orientation conflict.**

**c) Views, or attractors/flows – optimal climatic orientation**

Often a building's location and orientation are predetermined by factors such as passenger flows, attractions, development, etc. These may conflict with bioclimatic guidelines. When this is the case, the functional considerations should prevail but some remediative measures can be taken to improve performance. If a building must be oriented west, very careful attention must be paid to the openings and use of glass. Protecting openings facing west requires the use of vertical shading devices as a horizontal device would be too long.

**d) Solar protection form vegetation (dense foliage) – wind penetration (no obstructions)**

Vegetation plays a key role in creating a comfortable shaded outdoor space. There is however a tradeoff between vegetation with dense foliage, which could potentially provide better shading but block airflow, and a taller tree with less dense foliage. Tall trees with dense high foliage and a long thin trunk with no foliage at human level, such as palm trees, which produce a canopy effect, are optimal.

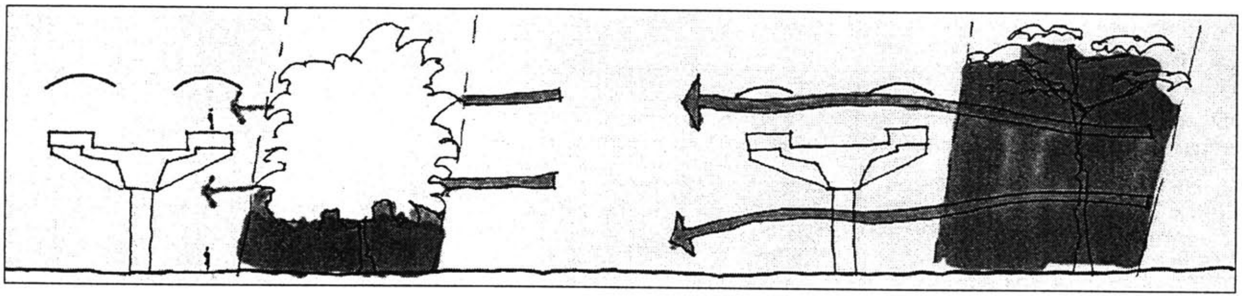


**Figure 7.3. Vegetation – sun protection tradeoff. Tall trees with high foliage allow better airflow but do not refresh as much as trees of more dense foliage.**

**e) Connotation of materials (glass, steel) – climatically desirable materials**

Certain materials have come to represent qualities that are not responsive to climate. Glass is associated with progress and its indiscriminate use is extremely counterproductive, particularly in roofs, in a warm humid island climate such as San Juan's. This is a cultural conflict that is not the scope of this work but widespread and needs to be overcome by education of designers and developers and perhaps through incorporation of thermal test requirements in building codes.

**f) Noise protection - wind capture**

Protection from noise has two dimensions. Protection of noise from the surroundings of buildings and protection from noise generated within a building. Buildings in warm humid climates tend to be of lightweight construction making it hard to protect from outside noise other than by skilful use of absorbent surfaces. Yet to protect the outside from noises generated by the train a noise barrier would be necessary as close as possible to the source (train), which is in conflict with the need to avoid any obstacle to the wind.

**g) Daylight - rain and sun protection**

Another conflict arises out of the need to protect from the sun and rain and the desire to capture daylight. This problem is not very acute in San Juan because daylight tends to be diffuse and excessive light is mentally associated with warmth while reduced lighting with coolness. Direct sunlight is excluded for thermal reasons. The sky is bright, could provide sufficient light, but its luminance would also cause glare. As, however, sky luminance near the horizon is much lower than at higher angles, a view of 15° from the horizon may be permissible.

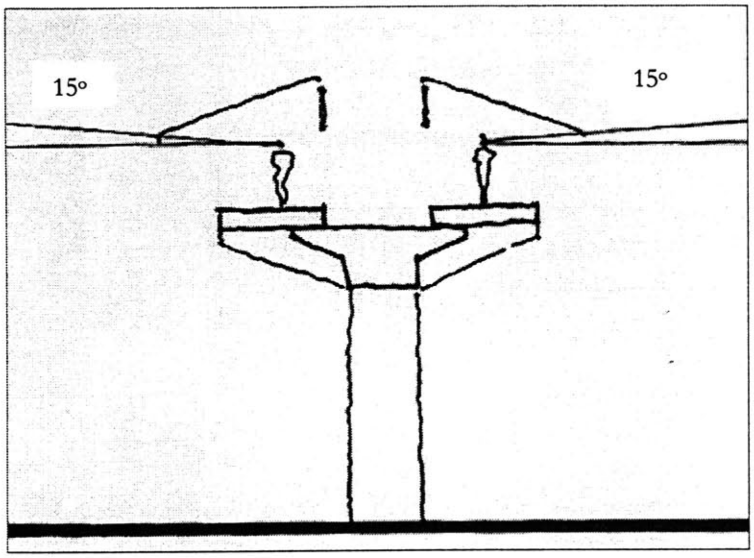



**Figure 7.4. Daylight – glare/sun protection.**

## h) Site development constraints

One of the most obvious constraints to using climate responsive guidelines is that posed by existing conditions of sites and their built environment. A wind that appears in the climatic data may not be available due to obstructing buildings or topography.

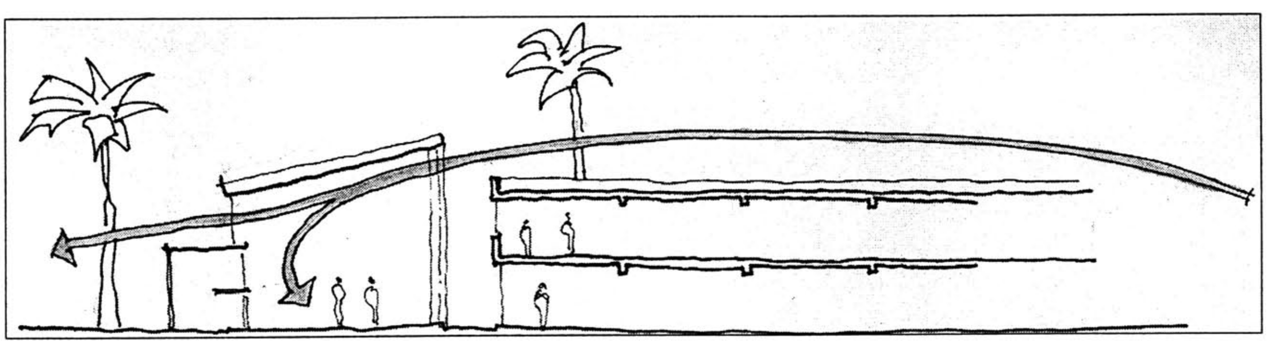


**Figure 7.5. Use of section to solve development conflicts.**

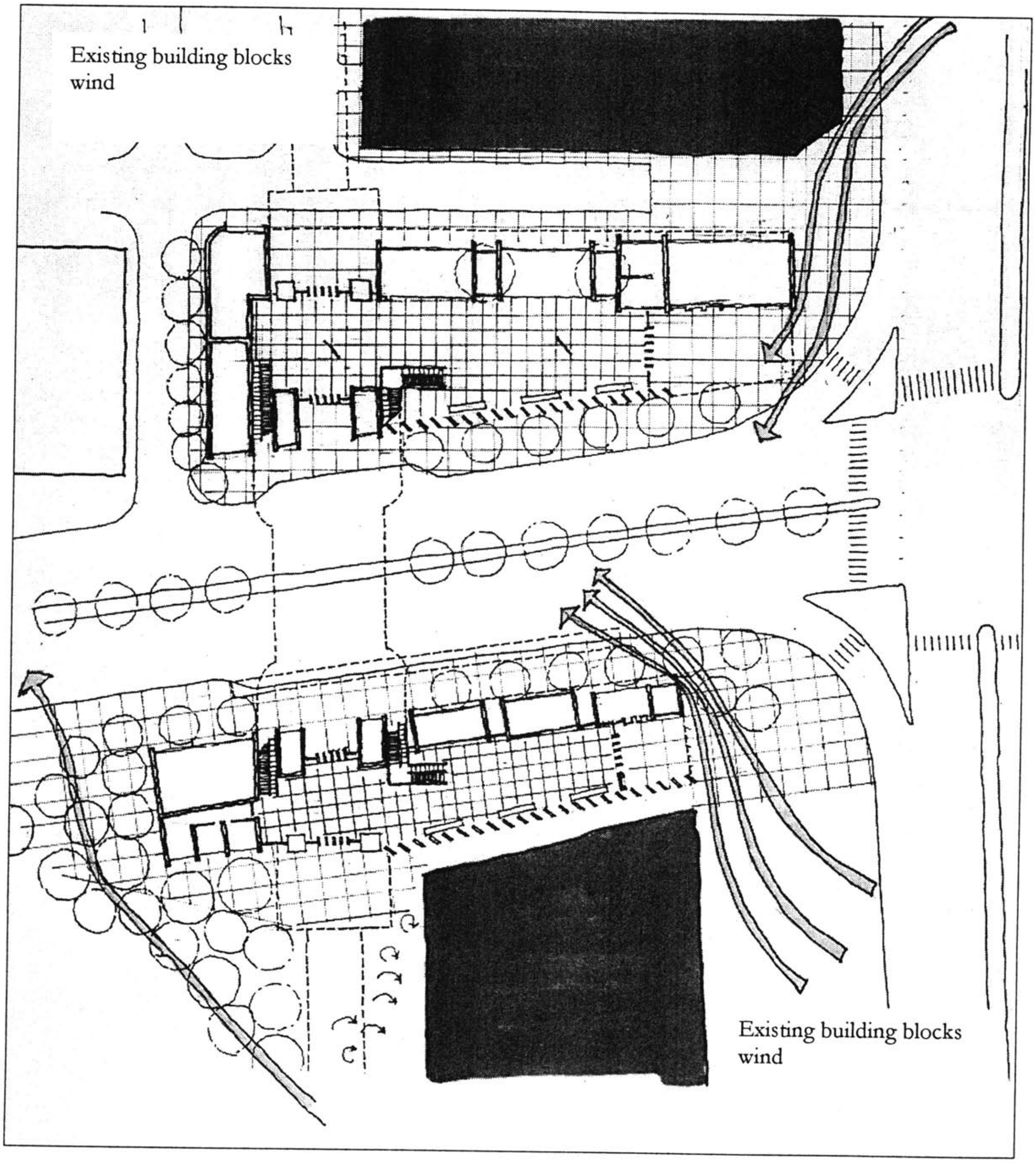



**Figure 7.6. Site development constraints**

## 7.2. Institutional conflicts, implementation

Implementation of design guidelines is a complex issue. Many hurdles must be overcome for implementation to work. Some of the most commonly mentioned problems are lack of institutional capacity to implement, inadequate incentives, politization of guideline management/ evaluation. This is an area for future study, especially given the unique contractual arrangement under which Tren Urbano is being built. I discuss three possible directions: an incentive-based mechanism for motivating guideline compliance, a mandatory and gradually more stringent implementation scenario and the inclusion of climate responsive design in architecture curricula.

### 7.2.1. Incentive-based

One strategy that is often used to implement desired outcome is to install an incentive-based system of bonuses for those who make use of the guidelines. This is commonly done in design review processes where, without legal power to enforce changes, it is hard to set standards of desired outcomes. Discretion is left to a body that decides whether a proposal fulfills the standards that are hard to quantify.

The central question is how to produce the right incentives so that contractors naturally adopt them, without undue cost. In essence, the object is to evaluate costs and benefits to offer the right incentives to legitimate what you would like to impose by making it voluntary.

Two common problems arise. First, political pressures to be granted bonuses, without necessarily abiding by the criteria, are common and sometimes override the object of obtaining good design. Second the selection of the people to evaluate the proposal and decide on its merits is also subject to pressure. Moreover, it may be that people to evaluate the proposals from a bioclimatic perspective are not available.

In the case of bioclimatic design guidelines, evaluation is relatively easier than plain design review, which is done using more discretionary criteria such as aesthetics. However, the prospects of pressures and the lack of experience with this practice indicate that this may not be the optimal arrangement. This, however, is not conclusive and should be the subject of future research.

### 7.2.2. Mandatory

The contractual arrangement of the first phase of Tren Urbano is as follows: Tren Urbano Office decides on alignment, location of stations, general planning and design criteria. Tren Urbano then goes out for bid for the civil work of separate parts of the alignment, under a design-build arrangement. System-wide communications, trackwork, trains and operations are also put to bid on a design-build-operate turnkey contract.

Under existing contractual conditions all design documents are divided into two categories. The design build contractor must fulfill category 1 documents, and the Tren Urbano Office can demand compliance. These usually include safety and operative considerations. Category 2 documents require the design build contractor to meet the intent of the drawings but allows flexibility in methods to fulfill the intent. Tren Urbano has no legal right to demand changes where functionality is accomplished by different means. The intention of establishing category 2 details is that they are the less critically important from the owner's point of view.

Setting stringent bioclimatic design standards in category 1 format from the start may backfire. Many designers, including local designers, are not accustomed to using these tools. A more reasonable approach may be to demand that basic studies with respect to solar access, ventilation, and other criteria be presented along with bid documents. This requirement will start to modify attitude towards bioclimatic design and establish a set of criteria as part of the design build contract documents.

### 7.2.3. Education

Another potentially effective strategy of implementing design guidelines is the inclusion of these concepts in the curricula of all architecture universities. This may be met with some resistance by the institutions whose agendas are driven by other considerations. The architectural sciences and technology programs within architecture schools need to be strengthened. Often architecture schools struggle to differentiate themselves from engineering schools. Such polarization of this issue requires attention.

Inclusion in curricula can follow two paths: inclusion and integration of bioclimatic design concepts in studio classes, or creating separate courses on bioclimatic design. Presumably the first insures students are exposed to the issues as the studios are mandatory, and it may be hard to make the newly created course mandatory. However, inclusion of bioclimatic concepts in studios will require that professors be prepared to teach and review this subject. The literature mentioned in this thesis and the bibliography provides substantial material for creation of courses and research on this topic.

One idea that must be instilled in the education of architecture is that of life-cycle costing. More often than not cost saving refers exclusively to initial capital investment cost. Maintenance and operating costs are often neglected. Skilful climate responsive design can reduce these costs considerably. In a sign of educational inertia it is commonly believed that the use of passive means implies a large initial investment when this is not the case.

# 8. CONCLUSIONS

This thesis described the concept of climate-responsive design, its methodology and framework. It also identified various reasons for which the application of bioclimatic design guidelines can be of particular interest and use in the context of transit station design and design of immediate surroundings in a warm-humid island climate such as that of San Juan, Puerto Rico. The main reasons are:

- the natural shape of stations, which is long and narrow, allows the building not to store heat.
- the fact that many of the stations will be elevated, favoring wind capture.
- the climatic conditions throughout the year are relatively comfortable.
- the potential for a city like San Juan, where climate responsive design is not disseminated and where there is considerable ground for improvement.
- the immediate need to tackle environmental problems in a city increasingly congested.

It also became clear that certain hurdles must be overcome for these recommendations to be implemented. Two sets of hurdles were identified: internal conflicts within design guidelines and implementation/institutional/social obstacles.

The first set can be dealt with using discretion in making design decisions: when conflicts internal to guidelines arise, the designer should weigh all the indicators and variables to come up with a compromise solution as was shown in previous chapters. This is not a hurdle yet: there is no widespread dissemination of climate-responsive design and therefore these conflicts, which require greater study, still need to be identified and refined in practice.

Institutional hurdles can be seen at two levels. In the short run, the issue is to implement guidelines for the Tren Urbano project extensions. This presents challenges due to the unique contractual arrangement employed for the construction of Tren Urbano. Who should enforce? Who should set standards? Or should standards be set? Should there be an incentive-based system in order to motivate designers to consider climate?

In the long run, the practice of climate-responsive design should be required for all major infrastructure and design projects. There are various options for doing this. Initially standards may be set low to gradually build them up as the architecture and engineering professions incorporate the concepts into their curricula and a pool of qualified designers can practice and evaluate design proposals. Dissemination in school and professional organizations is a necessary step. Gradual incorporation of climate responsive-design concepts into building and planning codes is also a necessary step.

Yet, from the author's perspective, the single most important hurdle is social acceptance. Recent urban expansion trends in San Juan have followed the single-family, low density suburbanization pattern so predominant in the United States. Coupled with a considerable shortage of public transportation, this has created a dependence on private automobiles which has created important environmental problems. Congestion is out of control and road expansion has come at the expense of natural resources. Puerto Rico must take advantage of the challenges and opportunities offered by the construction of this major transportation investment.

## APPENDIX 1 – CLIMATE CLASSIFICATION

### 1. Warm-humid climates

#### 1.1. Warm humid climate

Warm humid climates are found in a belt near the equator extending to about 15°N and S. There is very little seasonal variation throughout the year the only punctuation being that of periods with more or less rain and the occurrence of gusty winds and electric storms.

**Air temperature** in the shade reaches a mean maximum during the day of between 27 and 32°C, but occasionally it may exceed the latter value. At night the mean temperature varies between 21 and 27°C. Both the diurnal and annual temperature ranges are quite narrow.

**Humidity**, i.e. RH, remains high at about 75% for most of the time, but it may vary from 55% to almost 100%. Vapor pressure is steady in the region of 2500 to 3000 $N/m^2$.

**Precipitation** is high throughout the year generally becoming more intense for several consecutive months. Annual rainfall can vary from 2000 to 5000 mm and may exceed 500 mm in one month, the wettest month. During severe storms rain may fall at the rate of 100 mm/h for short periods.

**Sky conditions** are fairly cloudy throughout the year. Cloud cover varies between 60 and 90%. Skies can be bright, a luminance of 7000 $cd/m^2$ or even more when it is thinly overcast or when the sum illuminates white cumulus clouds without itself being obscured. When heavily overcast the sky is dull 850 $cd/m^2$ or less[1].

**Solar radiation** is partly reflected and partly scattered by the cloud blanket or the high vapor content of the atmosphere, therefore the radiation reaching the ground is diffuse but strong and can cause painful sky glare. Cloud and vapor content also reduces outgoing radiation from the earth and sea to the night sky, thus the accumulated heat is not readily dissipated.

**Wind velocities** are typically low, calm periods are frequent, but strong winds can occur during rain squalls. Gusts of 30 m/s have been reported. There are usually one or two dominant directions.

**Vegetation** grows quickly due to frequent rains and high temperatures and it is difficult to control. The soils are generally poor for agriculture. The subsoil water table is usually high and the ground may be waterlogged. Little light is reflected from the ground.

#### 1.2. Warm-humid island climate

Islands within the equatorial belt and in the trade winds zone belong to this climate type. Typical examples are the Caribbean, the Philippines and other island groups in the Pacific Ocean. Seasonal variations are negligible.

**Air temperature** in the shade reaches a day time mean maximum between 29 and 32°C and rarely rises above skin temperature. Night time mean minima can be as low as 18°C, but it is normally

[1]Candela = unit of intensity of light source.

between this figure and 24°C. The diurnal range is more than 8°C and the annual range is only about 14°C.

**Humidity** varies between 55% and almost 100%, the vapor pressure being between 1750 and 2500 $N/m^2$.

**Precipitation** is high 1250 to 1800 mm per annum and 200 to 250 mm in the wettest month. Up to 250 mm may fall in a single storm of a few hours' duration. Spray is driven nearly horizontally on windward coasts.

**Sky conditions** are normally clear or filled with white broken clouds of high brightness except during storms when the skies are dark and dull. Clear blue skies are of low luminance, between 1700 and 2500 $cd/m^2$.

**Solar radiation** is strong and mainly direct with a very small diffuse component when the sky is clear, but varies with the cloud cover.

**Winds** the predominant trade wind blows at a steady 6 to 7 m/s and provides relief from heat and humidity. Much higher velocities occur during cyclones.

**Vegetation** is less luxuriant and of a lighter green color than in the warm humid zones. It varies with the rainfall. Sunlight reflected from light colored coral, sand, sea and rock can be very bright.

## 2. Hot-dry climates

### 2.1. Hot dry desert climate

These two climates occur in the two belts at latitudes between 15 and 30° north and south of the equator.

Two marked seasons occur: a hot and a somewhat cooler period.

**Air temperature** in the shade rises quickly after sunrise to day time mean maximum of 43 to 49°C. During the cool season the mean maximum temperature ranges from 27 to 32°C. Night-time mean minima are between 24 and 30°C in the hot season and between 10 and 18°C in the cool season. The diurnal range is very great, 17 to 22°C.

**Humidity** varies from 10 to 55% and the vapor pressure is normally between 750 and 1500 $N/m^2$.

**Precipitation** is slight and variable throughout the year from 50 to 155 mm per annum. Flash storms may occur over limited areas with as much as 500 mm rain in a few hours but some regions may not have any rain for several years.

**Sky conditions** are normally clear. Clouds are few due to the low humidity of the air. The sky is usually dark blue, with a luminance of 1700 to 2500 $cd/m^2$, and further darkened during dust or sand storms to 850 $cd/m^2$ or even less. Towards the end of the hot period, dust suspended in the air may create a white haze, with a luminance of 3500 to 10000 $cd/m^2$, which produces a diffuse light and a painful glare.

**Solar radiation** is direct and strong during the day but the absence of cloud permits easy release of the heat stored during the day-time in the form of long-wave radiation towards the cold night sky. Diffuse radiation is only present during dust haze periods.

**Winds** are usually local. The heating of air over the hot ground causes a temperature inversion, and as the lower warm air mass breaks through the higher cooler air, local whirlwinds are often created. Winds are hot carrying dust and sand and often develop into dust storms.

**Vegetation** is sparse and difficult to maintain because of the lack of rain and low humidities. The soil is usually dusty and very dry. Soils dry quickly after rain and would be fertile if irrigated. The subsoil water table is very low.

### 2.2. Hot dry maritime desert climate

Maritime desert climates occur in the same latitude as the hot-dry desert climates, where the sea adjoins a large land mass.

There are two seasons: a hot one and a somewhat cooler one.

**Temperature** in the shade reaches a day-time mean maximum of about 38°C, but in the cool season remains between 21 and 26°C. The night-time mean minimum temperatures of the hot season range from 24 to 30°C and of the cool season from 10 to 18°C. The diurnal mean temperature range varies between 9 and 12°C, the larger diurnal variation occurring during the cool season.

**Humidity** is steadily high between 50 and 90% with vapor pressures of 1500 to 2500 $N/m^2$, as the strong solar radiation causes strong evaporation from the sea. The moisture is, however, not precipitated but remains suspended in the air creating intensely uncomfortable conditions.

**Precipitation**, as in other desert regions, is very low.

**Sky conditions** are as for hot dry desert climates but a little more clouds may appear in the form of a thin, transparent haze, which is likely to cause a glare.

**Solar radiation** is strong, with a higher diffuse component than in desert climates due to the thin clouds and suspended moisture.

**Winds** are mostly local, coastal winds, caused by the unequal heating and cooling of land and sea surfaces. These tend to blow off the sea towards the land during the day and in the reverse direction during the night.

**Vegetation** is sparse not more than some dry grass. The ground and rocks are brown or red; it is dry and dusty throughout the year. Ground glare can be intense.

## 3. Composite Climates

### 3.1. Composite or monsoon climate

These climates usually occur in large land masses near the Tropics of Cancer and Capricorn, which are sufficiently far form the equator to experience marked seasonal changes in solar radiation and wind direction.

Two seasons occur normally. Approximately two thirds of the year is hot-dry and the other third is warm-humid. Localities further north or south often have a third season best described as cool-dry.

**Air temperatures** in the shade reach a day-time maximum of 32-43°C in the hot-dry season, 27-32°C in the warm-humid season and up to 27°C in the cool-dry season. Night-time mean minima are in the 21-27°C range in the hot-dry season, 24-27°C in the warm-humid season and 4-10°C in the cool-dry season. Lastly, diurnal ranges are in the range of 11-22°C in the hot-dry season, 3-6°C in the warm-humid season and 11-22°C in the cool-dry season.

**Humidity** is low throughout the dry periods at 20 to 55%, with a vapor pressure of 1300 to 1600 $N/m^2$. During the wet period it rises to 55 to 95%, with a vapor pressure of 2000 to 2500 $N/m^2$.

**Precipitation**: the monsoon rains are intense and prolonged; occasionally 25 to 38 mm can fall in an hour. Annual rainfall varies from 500 to 1300 mm with 200 to 250 mm in the wettest month. There is little or no rain during the dry season.

**Sky conditions** markedly vary with the seasons. The sky is heavily overcast and dull during the monsoons and clear with a dark blue color in the dry seasons. Towards the end of the hot-dry season the sky becomes brighter with frequent dust haze. The intensity of the sky glare varies accordingly.

**Solar radiation** alternates between conditions found in the warm-humid and hot-dry desert climates.

**Winds** are hot and dusty during the dry period. Directional changes in the prevailing winds at the beginning of the warm-humid season bring rain-clouds and humid air from the sea. Monsoon winds are fairly strong and steady.

**Vegetation**, which is sparse -characteristic of hot-dry regions with brown and red barren ground - changes rapidly and dramatically with the rain. Plants grow quickly. In the cooler period vegetation covers the ground, but diminishes as the temperature rises. The soil is damp during the rain but it dries out quickly. In the dry season strong ground glare may be experienced.

### 3.2. Tropical upland climate

Mountainous regions and plateaux more than 900 to 1200 m above sea-level experience such climates, between the two 20°C isotherms.

Seasonal variations are small in upland climates near the Equator, but when further away from the equator the seasons follow those of the nearby lowlands.

**Air temperature** in the shade decreases with altitude. At an altitude of 1800 m above sea-level the day-time mean maxima may range from 24 to 30°C and the night-time mean maxima are around 10 to 13°C. At some locations it may fall below 4°C and ground frost is not uncommon. The diurnal range is great. The annual range depends on latitude. At the Equator it is slight but at the Tropics of Cancer and Capricorn it may be 11 to 20°C.

**Humidity** varies between 45 and 99% and the vapor pressure between 800 and 1600 $N/m^2$.

**Precipitation** is variable, but rarely less than 1000 mm. Rain often falls in heavy concentrated showers, reaching an intensity of 80 mm per hour.

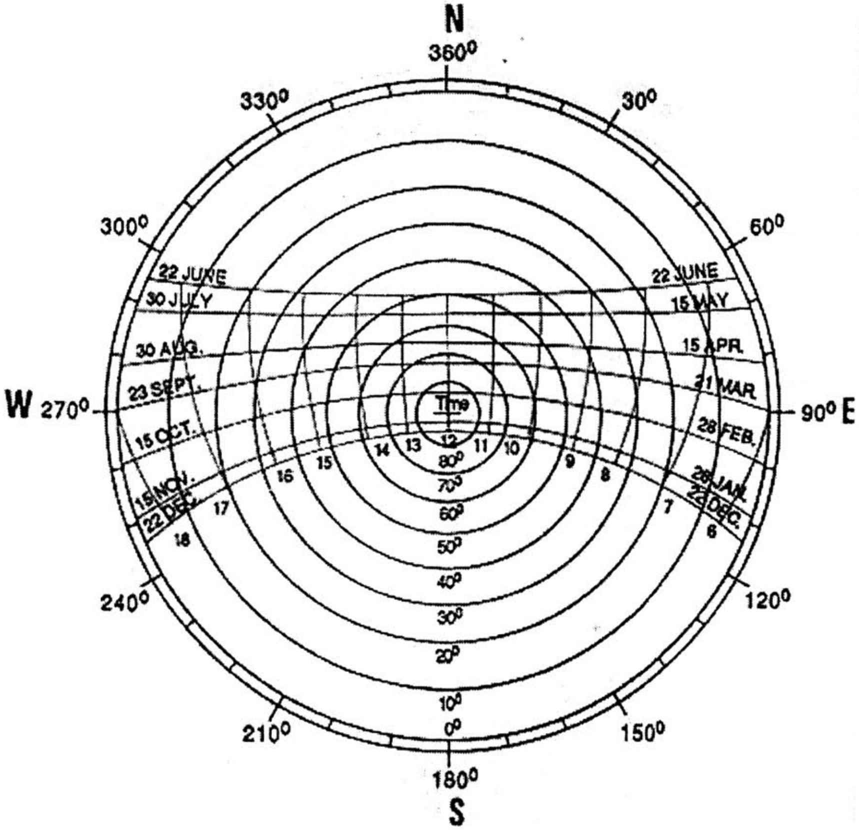
**Sky conditions** are normally clear or partly cloudy to the extent of about 40%. During the monsoon rains the sky is overcast - and the clouds are heavy and low.

**Solar radiation** is strong and direct during the clear periods, stronger than at the same latitude but at sea-level. Ultra-violet radiation especially is stronger than at lower altitudes. It becomes more diffuse as cloud coverage increases.

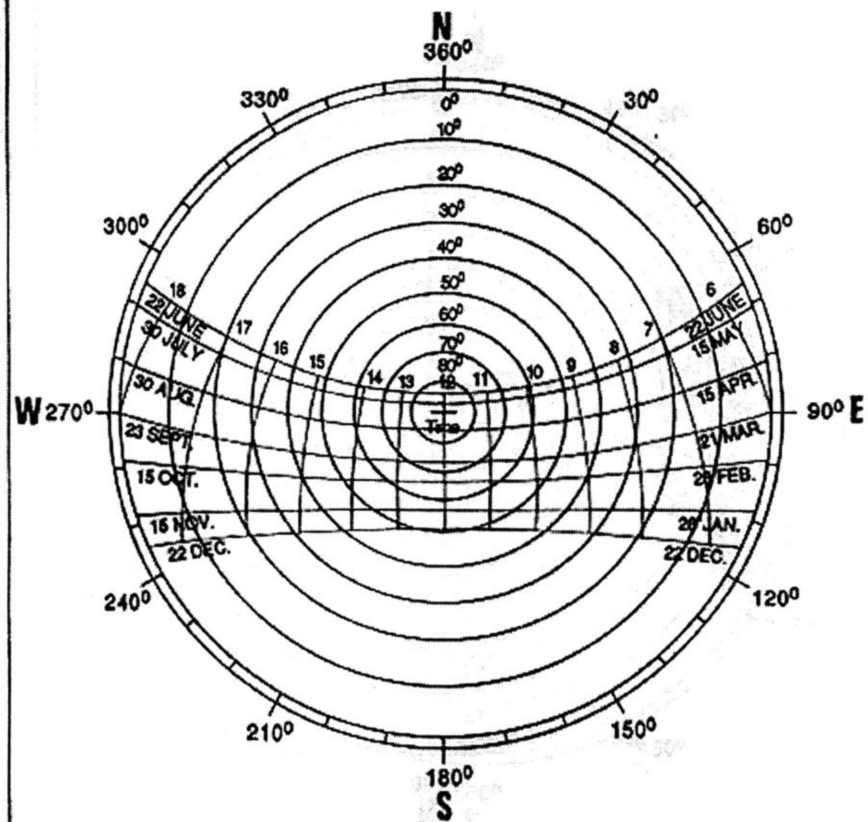
**Winds** are variable, predominantly north-east and south-easterlies, but may be drastically deflected by local geography. Wind velocity rarely exceeds 15 m/s.

**Vegetation** is green although not very luxuriant during the wet season but it may wither in the dry season. The soil may be damp in the rains but dries quickly.

LATITUDE 16° SOUTH




LATITUDE 16° NORTH



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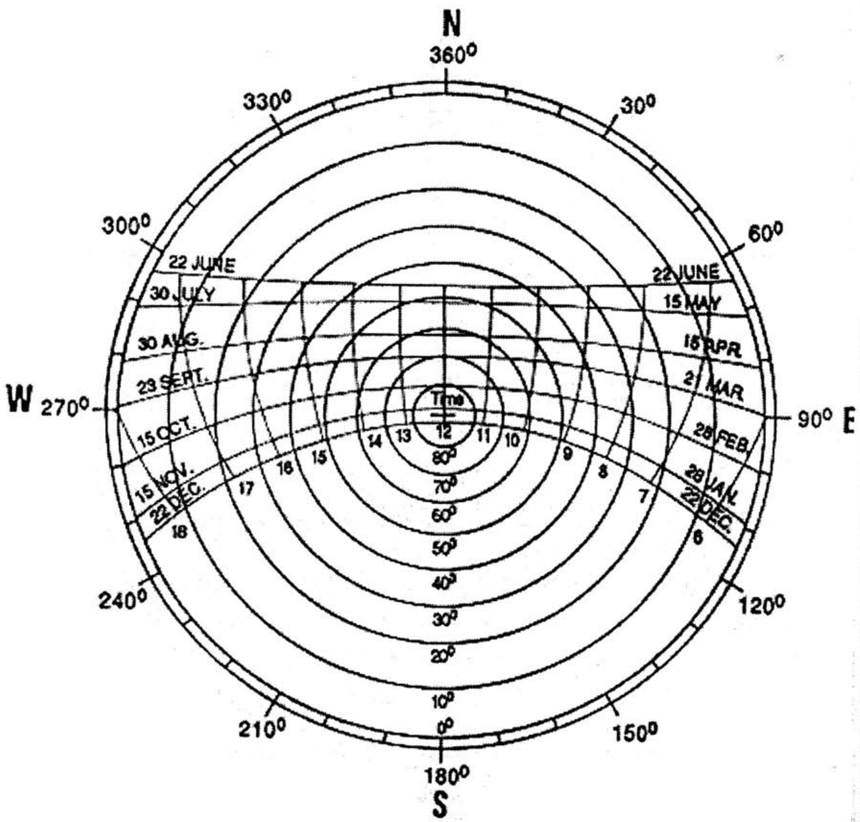
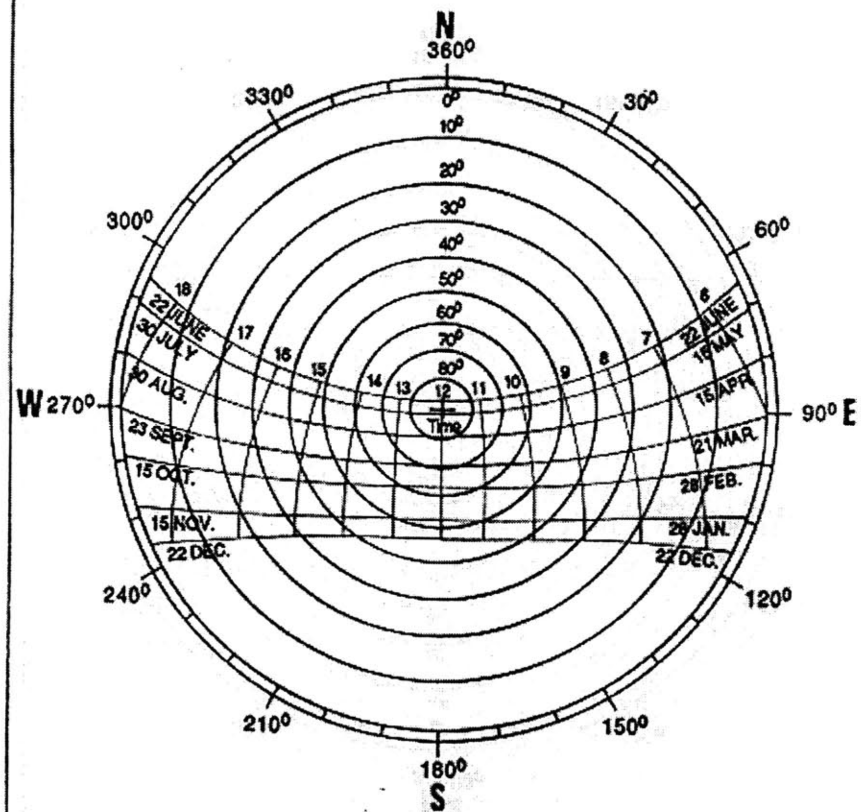
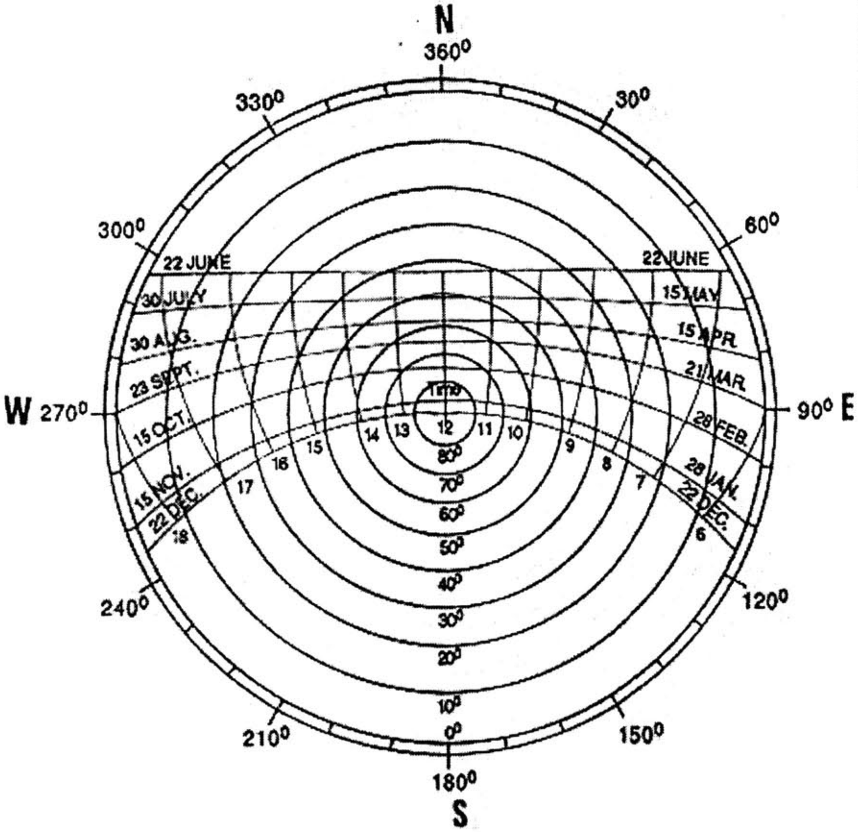


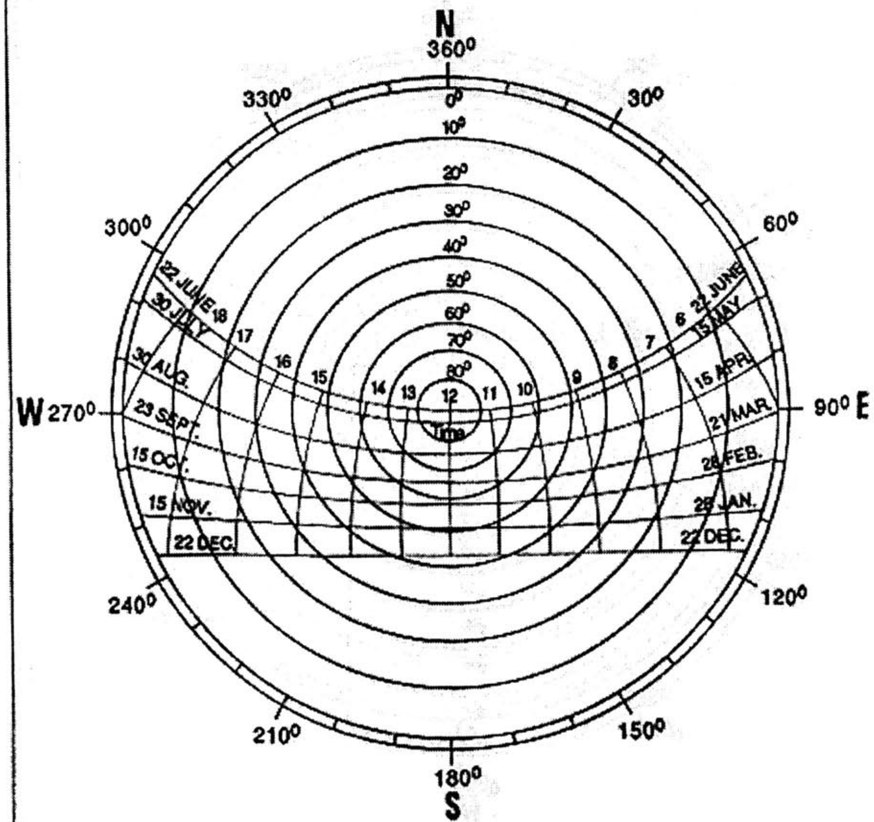

LATITUDE 20° NORTH



LATITUDE 24° SOUTH




LATITUDE 24° NORTH



## APPENDIX 3 – THERMAL PROPERTIES OF METERIALS

### Density, thermal conductivity, specific heat

| | | Density kg/$m^3$ | Thermal conductivity (k) W/mK | Specific heat ( Q ) Wh/kgK |
|---|---|---|---|---|
| a) | **Natural stone and earth (moist)** | | | |
| | Granite, marble | 2800 | 3.5 | 0.26 |
| | Sandstone, limestone | 2600 | 2.3 | 0.22 |
| | Sand | 1700-2000 | 1.4 | |
| | Earth | 1800 | 2.1 | |
| b) | **Sand and earth (dry)** | | | |
| | Sand, gravel (loose filling) | 1800-2000 | 0.7 | 0.22 |
| | Clay massive (adobe) | 1000-2000 | 0.2-1.0 | 0.23 |
| c) | **Concrete** | | | |
| | Solid concrete (RCC) | 2400 | 1.8 | 0.33 |
| | Gas concrete | 1000-1700 | 0.3-1.0 | |
| d) | **Plaster** | | | |
| | Cement plaster | 2200 | 1.4 | 0.3 |
| | Lime-cement plaster | 1800 | 1.0 | |
| | Gypsum plaster | 1200 | 0.6 | 0.26 |
| e) | **Timber** | | | |
| | Softwood | 450-500 | 0.15 | 0.55-0.66 |
| | Hardwood | 600-800 | 0.18-0.22 | 0.55-0.66 |
| f) | **Boards** | | | |
| | Gypsum | 1000 | 0.40 | 0.22 |
| | Asbestos cement | 1700-2000 | 0.48 | 0.24 |
| | Woodwool, cement bound | 700 | 0.12 | 0.42 |
| | Wood fibre, hard | 800 | 0.17 | 0.7 |
| | Wood fibre, porous | 200-400 | 0.06 | 0.7 |
| | Wood chips | 650 | 0.11 | 0.75 |
| | Plywood | 600 | 0.44 | 0.75 |

## APPENDIX 3 (CONT.)

| | | Density kg/m$^3$ | Thermal conductivity (k) W/mK | Specific heat ( Q ) Wh/kg |
|---|---|---|---|---|
| g) | **Masonry** | | | |
| | Hollow brick | 1200 | 0.47 | 0.26 |
| | Solid brick | 1800 | 0.8 | 0.26 |
| | Cement stone | 2000 | 1.1 | 0.3 |
| | Gas concrete | 500-700 | 0.16-0.21 | 0.3 |
| h) | **Insulation materials** | | | |
| | Mineral wool, glass wool | 20-120 | 0.04 | 0.17 |
| | Slag wool | 30-70 | 0.06 | 0.17 |
| | Grass board | 200-300 | 0.06 | 0.17 |
| | Coconut matting | 50-200 | 0.05 | 0.17 |
| | Hemp mat | 50-200 | 0.05 | 0.17 |
| | Cork board extruded | 110-140 | 0.04 | 0.42 |
| | Cork coarse | 80-160 | 0.06 | 0.42 |
| | Foamglass | < 125 | 0.045 | 0.22 |
| | Perlite with pressed fibre | 170-200 | 0.06 | 0.17 |
| | Polystyrene extruded | 20-40 | 0.04 | 0.39 |
| i) | **Various materials** | | | |
| | Steel | 7850 | 60 | 0.13 |
| | Copper | 9000 | 348 | 0.1 |
| | Aluminium | 2700 | 200 | 0.26 |
| | Glass | 2500 | 0.81 | 0.22 |
| | Water 10°C | 1000 | 0.58 | 1.16 |
| | Ice | 820-920 | 2.23 | |
| | Snow 0°C | 100 | 0.05 | |
| | Air (theoretical case of still air) | 1.2 | 0.02 | 0.28 |

## Thermal transmittance (U-value), time-lag values and solar heat gain factor

### a) Homogeneous materials

| | Thickness in cm | Time lag ( O ) hours | Solar heat gain factor (SHF) % |
|---|---|---|---|
| Stone | 20 | 5.5 | |
| | 30 | 8 | |
| | 40 | 10.5 | |
| | 60 | 15.5 | |
| Sand | 30 | 13.4 | |
| Solid concrete | 5 | 1.1 | |
| | 10 | 2.5 | |
| | 15 | 3.8 | 9 |
| | 20 | 5.1 | |
| | 30 | 7.8 | 7 |
| | | 40 | 10.2 |
| Solid brick | 10 | 2.3 | |
| | 20 | 5.5 | 10 |
| | 30 | 8.5 | |
| | 40 | 12 | |
| Stabilized soil, mud | 10 | 2.4 | |
| | 15 | 4.0 | |
| | 20 | 5.2 | |
| | 30 | 8.1 | |
| Wood | 1.5 | 0.2 | |
| | 2.5 | 0.45 | |
| | 5 | 1.3 | |
| | 10 | 3.0 | |
| | 30 | 17.4 | |
| Aluminium sheet (new) | | 0.5 | 10 |
| Corrugated galvanized iron sheet (new) | | 0.5 | 20 |
| Corrugated galvanized iron sheet (rusty) | | 0.5 | 34 |
| Corrugated asbestos cement sheet (ACC) | | 0.5 | 16 |
| Insulating board | 1.5 | 0.1 | |
| | 2.5 | 0.23 | |
| | 5 | 0.77 | |
| | 10 | 2.7 | |
| | 15 | 5 | |

b) **Roof constructions**

| | Transmittance (U) W/m²K | Time lag (O) hours | Solar heat gain factor (SHF) % |
|---|---|---|---|
| Thin sheets without ceiling (Alu, CGI, ACC) | 8 - 9 | 0.5 | see above |
| Alu sheet + cavity + asbestos sheet ceiling | 1.9 | 1 | 4.5 |
| ditto + 50 mm fibre glass in cavity | 1.3 | 1 | 3 |
| Rusty CGI sheet + cavity + thin sheet ceiling | 1.9 | 1 | 8 |
| ditto + 50 mm fibre glass in cavity | 1.3 | 1 | 5 |
| Concrete slab, 300 mm | 2.5 | 9.2 | 7 |
| Concrete slab, 150 mm | 3.3 | 4 | 9 |
| ditto + 50 mm woodwool slab internally | 1.13 | 4.5 | 3 |
| ditto + external and internal insulation | 0.75 | 13.5 | 2 |
| ditto + whitewashed externally | 3.3 | 4 | 4 |
| ditto + 50 mm woodwool + whitewashed ext. | 1.13 | 4.5 | 1.5 |
| ditto + ext. and int. insul.. + whitewashed ext. | 0.75 | 13.5 | 1 |

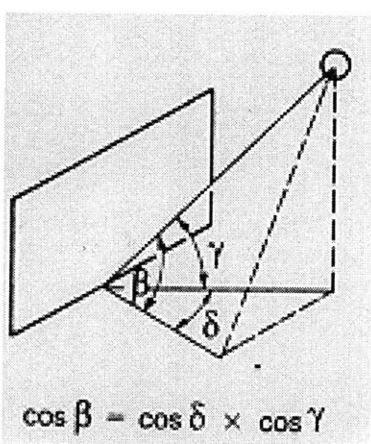
c) **Wall constructions**

| | Transmittance (U) W/m²K | Time lag (O) hours | Solar heat gain factor (SHF) % |
|---|---|---|---|
| Hollow concrete block, 250 mm, rendered on both sides | 1.7 | 11 | 5 |
| ditto + whitewashed externally | 1.7 | 11 | 2 |
| Window with single glazing | 4 | 0 | 85 |
| Open window | - | 0 | 100 |
| Solid brick wall, 230 mm | 2.7 | 8 | 10 |
| ditto + whitewashed externally | 2.7 | 8 | 3.5 |
| Brick wall 280 mm incl. 50 mm cavity | 1.7 | 10.5 | 6 |
| ditto + whitewashed externally | 1.7 | 10.5 | 2 |
| Corrugated asbestos cement sheet | 8 | 0.5 | 16 |
| ditto + 50 mm woodwool slab + cavity | 1.2 | 0.5 | 2.5 |

## APPENDIX 4 – SOLAR ANGLES

| Time of day | Summer = 6/21 (1) vertical angle (γ) | (2) horizontal angle (δ) (0 = south) | Winter = 12/21 (1) vertical angle (γ) | (2) horizontal angle (δ) (0 = south) | Spring/Autumn 3, 9/21 (1) vertical angle (γ) | (2) horizontal angle (δ) (0 = south) |
|---|---|---|---|---|---|---|
| 5 | -5.656 | 62.892 | -20.586 | 71.126 | -14.208 | 85.140 |
| 6 | 7.269 | 67.592 | -7.269 | 67.592 | 0.000 | 90.000 |
| 7 | 20.586 | 71.126 | 5.656 | 62.892 | 14.208 | 85.140 |
| 8 | 34.150 | 73.673 | 17.957 | 56.602 | 28.305 | 79.619 |
| 9 | 47.857 | 75.113 | 29.237 | 47.999 | 42.111 | 72.396 |
| 10 | 61.604 | 74.619 | 38.802 | 36.042 | 55.212 | 61.207 |
| 11 | 75.141 | 67.757 | 45.521 | 19.802 | 66.350 | 40.180 |
| 12 | 85.000 | 0.000 | 48.000 | 0.000 | 71.500 | 0.000 |
| 13 | 75.141 | 67.757 | 45.521 | 19.802 | 66.350 | 40.180 |
| 14 | 61.604 | 74.619 | 38.802 | 36.042 | 55.212 | 61.207 |
| 15 | 47.857 | 75.113 | 29.237 | 47.999 | 42.111 | 72.396 |
| 16 | 34.150 | 73.673 | 17.957 | 56.602 | 28.305 | 79.619 |
| 17 | 20.586 | 71.126 | 5.656 | 62.892 | 14.208 | 85.140 |
| 18 | 7.269 | 67.592 | -7.269 | 67.592 | 0.000 | 90.000 |
| 19 | -5.656 | 62.892 | -20.586 | 71.126 | -14.208 | 85.140 |

Negative solar height means the sun has not risen at the time.




Solar angles.

## Reflectivity and emissivity of materials

| | Surface | % Reflectivity of solar radiation (6'000°C) | % Emissivity of thermal radiation (10 to 40°C) |
|---|---|---|---|
| a) | **Natural materials** | | |
| | Sand, white | 59 | |
| | White marble | 54 | 95 |
| | Limestone | 43 | 95 |
| | Wood, pine | 40 | 95 |
| | Grass | 20 | |
| | Sand, grey | 18 | |
| b) | **Concrete and masonry walling** | | |
| | Cream brick | 50 - 70 | 40 - 60 |
| | Yellow and buff brick, stone | 30 - 50 | 85 - 95 |
| | Concrete | 35 - 45 | |
| | Red brick, stone | 25 - 45 | 85 - 95 |
| | Asbestos cement, aged 1 year | 29 | 95 |
| c) | **Paints** | | |
| | Whitewash | 80 | |
| | White lead paint, light grey | 71 | 89 |
| | Light green paint | 50 | 92 |
| | Medium grey, yellow | 45 | 92 |
| | Aluminium paint | 45 | 55 |
| | Dark color ( brown, grey, red) | 35 | 92 |
| | Deep dark brown, dark red, dark green | 10 | 92 |
| | Black, non-metallic | 2 - 15 | 90 - 98 |
| | Black, matt | 3 | 95 |
| d) | **Metal** | | |
| | Silver polished | 93 | 2 |
| | Polished aluminium, chromium | 60 - 90 | 2 - 8 |
| | Bright aluminium, gilt, bronze | 50 - 70 | 40 - 60 |
| | Polished brass, copper | 50 - 70 | 2 - 5 |
| | Dull brass, aluminium | 35 - 60 | 20 - 30 |
| | Aluminium anodized | 33 | 92 |
| | Galvanized iron, aged (oxidized) | 10 | 28 |
| e) | **Plaster** | | |
| | White | 80 | 97 |
| | Orange | 45 | 97 |
| | Light green | 40 | 97 |
| | Light brown | 35 | 97 |
| | Brown | 32 | 97 |
| | Dark brown | 17 | 97 |

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