MICROCLIMATIC LANDSCAPE DESIGN

Creating Thermal Comfort and Energy Efficiency

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Introduction

■ **MICROCLIMATE IS** the condition of the solar and terrestrial radiation, wind, air temperature, humidity, and precipitation in a small outdoor space.

In this book we will be introducing you to important components and characteristics of microclimate and helping you to understand how landscape design affects microclimate. One way to become familiar with the concepts is to begin with the "big picture" and work toward specific examples. This Introduction provides increasingly more detailed explanations of what the book is about, what the important issues are, and what you need to know for successful microclimatic landscape design. Once you have read and thought about them, you will have a framework within which to understand the details in the individual chapters of the book.

Your personal learning style may be to learn the details first, then add generalization until you can see the overall picture. In this case, you might prefer to read the Introduction after you read the rest of the book.

The following sections are written from the general to the specific, and are somewhat analogous to finding out information about a landscape. In familiarizing yourself with a landscape you might first look to satellite information to gain an overview and context of the site. Next you might review air photographs and maps that provide a more detailed look; then you could visit the site and drive around it for a "windshield survey," and, finally, walk through the landscape to understand it in more detail. With this overview of a site, you would then know what information you need in more detail, and what problem have to be resolved. Similarly, we will provide you with increasing more detailed discussions so that when you read the chapters they will fit into the overall picture.

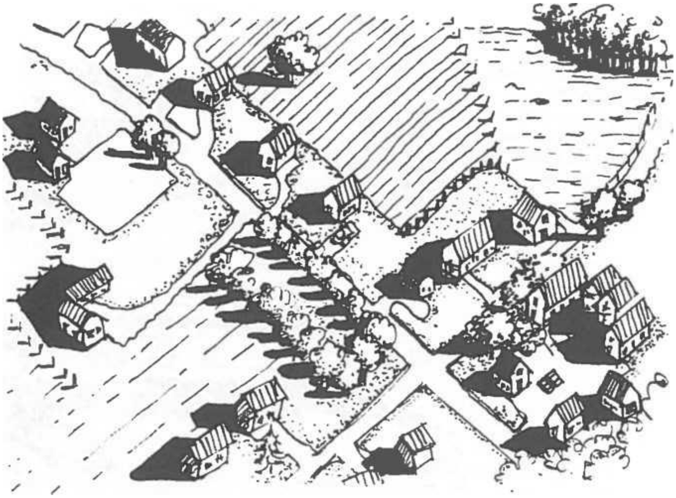
View from a Satellite

Microclimatic design requires (1) knowledge of prevailing climate conditions, (2) understanding of the ways in which objects in the landscape affect climate to create microclimates, and (3) methods for applying this knowledge, through landscape design, to create microclimates that are comfortable for people and minimize the energy use of buildings.

A view from a satellite provides an overview and a context within which to study an area. You can relate all future information you gain to this view.

View from an Airplane

The prevailing climate of an area interacts with objects in the landscape to create microclimates. Microclimatologists describe these interactions in terms of the effects on the air temperature, wind velocity, solar radiation, relative humidity, and so on. Landscape architects determine locations of objects in the landscape through design, and consequently can have a significant effect on microclimates. Microclimates in turn strongly influence the thermal comfort of people within a landscape, and can significantly affect the energy required to heat and/or cool buildings in the landscape. This book will provide you with an understanding of how different types of objects in the landscape affect each component of the microclimate. Further, it will suggest methods for using that information as you design landscapes to maximize human thermal comfort and energy efficiency.

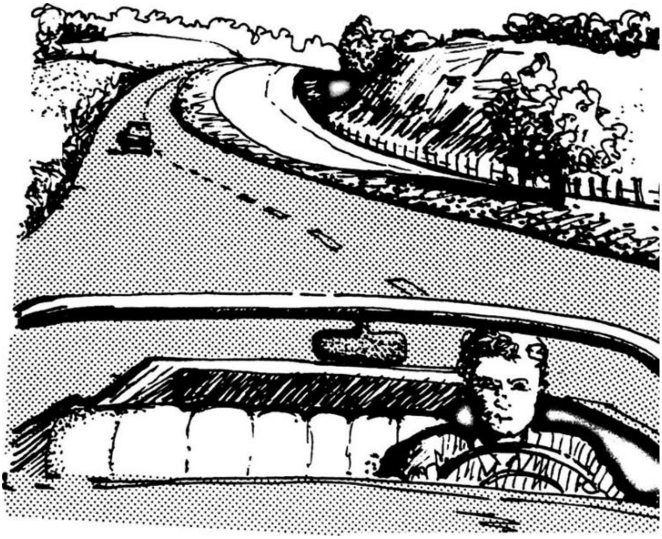


A view from an airplane provides a more detailed view. It shows relationships on-site and suggests how it all fits together.

View from the windshield of a Car

Microclimatic design requires two things: understanding and application. First you must have at least a conceptual understanding of how components of microclimate are modified by objects in the landscape. Some components, such as wind and solar radiation, can be significantly affected by objects in the landscape. Other components, such as air temperature and humidity, are most often not significantly affected by landscape. You must also understand how microclimate can affect the human use of a landscape, through a consideration of human thermal comfort and the energy use of buildings.

An understanding of microclimate begins with an understanding of the forces that drive the earth's atmospheric system. Atmospheric science can provide a good overview of the whole system and can explain how the energy from the sun and the movements of the earth drive all the weather and, consequently, the climates on the earth. This global view can be applied at a local level through a consideration of the interactions between the weather and components of the landscape such as trees, buildings, and ground covers.



A view from the windshield allows you to see things in three dimensions. The "big picture" begins to take shape, but you still see the landscape from afar, and it ~ passes by quite quickly.

Science typically analyzes (breaking down the subject into its components and examining methodically), then synthesizes (combining components), to achieve a clear understanding of the subject. This is the method typically used in microclimatology as well. A microclimate as a whole is incredibly complex and ever-changing, so the best way to understand it is through its component parts. These are typically landscape-modified components of the prevailing climate.

Another way of looking at microclimate is through the concept of an energy budget. Consider first another kind of budget. Most people must budget their finances to pay first for essentials like housing, food, and clothing. Whatever is left over, if any, is for savings or leisure activities. In the same way, the microclimate of a landscape can be modeled as a budget, but in this case, an energy budget. The site has a certain amount of energy available to it, normally in the form of solar radiation, and this is divided into different “streams” of energy. It can be used to heat the ground or to evaporate water, and whatever is left is used to heat the microclimate. The way that the energy is partitioned will strongly influence the microclimate. For example, if a landscape is very dry, no energy will go into evaporating water, so more energy is available to heat surfaces and/or the air. If it is wet, much energy goes into evaporation, so less is left for heating surfaces and the air.

The concept of an energy budget can also be applied to a person and to a building. In the case of a person, the available energy comes both from radiation and from metabolic energy (heat generated within the body). Energy losses as a function of the microclimate can be described with equations. When all the inputs and outputs of energy are summed, the resultant value will indicate whether a person would be thermally comfortable in a given landscape. If the budget is a large positive value, it would indicate that a person would be receiving much more energy than he or she would be able to get rid of, and would consequently be overheated and uncomfortably warm. The landscape could be redesigned to provide a microclimate that is more thermally comfortable.

Similarly, the energy budget of a house can indicate how much energy is required to maintain a constant internal temperature in a given landscape. Design of the microclimate can increase or decrease this energy requirement.

Once we have a basic understanding of the mechanics of microclimates, we can turn our attention to the objects in the landscape and how they affect the microclimate. The tools of the landscape architect will all affect the microclimate to one degree or another. It is important to know what will have a significant effect, and what won't make much difference.

The microclimatic components that can be most readily modified through landscape design are wind, radiation, and precipitation. In some circumstances other elements, namely air temperature and relative humidity, can be altered and can have an effect on human comfort or on the energy use of buildings, but we can normally best use our resources by focusing on wind and radiation. Precipitation in the form of rain can be important in human comfort, but can be dealt with through quite straightforward means (e.g., overhead structures). Snow can also be quite important; however, snow depends heavily on wind to move it around, so is most often dealt with through consideration of wind.

Most objects in the landscape, including the ground plane and all things on or over it, will affect wind and radiation. It is important to understand which of these effects will significantly alter the thermal comfort of people and/or the energy use of buildings. For example, the roughness of the ground surface will affect wind speed. A smooth ground surface will provide very little friction for wind and will allow it to maximize its speed. A rough ground cover will slow the wind by creating an increased drag. Although this difference in wind speed is measurable, it is not normally large enough to affect the thermal comfort of a person or the energy use of a building. So we can often ignore it. However, a continuous row of evergreen trees can create a reduction in wind speed, which can significantly affect the thermal comfort of a person and reduce the energy required to heat a building in cold seasons. Therefore we must use our design abilities so as to have the most impact.

Through illustrations of many of the processes and impacts of landscape objects on wind and radiation, you will be provided with a toolbox of information to apply to design. But you will also need a context within which to apply this information. There are frameworks and methods for incorporating microclimatic design into landscape design processes. Other techniques will use microclimatic design as a method of detailing or articulating designs once they are complete.

By evaluating examples and case studies that illustrate ideas, you will see both good and bad applications of microclimatic design, and you will gain an understanding of what to do and what not to do.

View on Foot

Chapter 1
Conceptual Framework

Whenever we are outdoors, we are experiencing microclimates. Our bodies interpret some microclimates as comfortable, others as uncomfortable, and consequently we are willing to spend more time in some landscapes than in others.

Microclimates, the result of interaction between prevailing climate and objects in the landscape, can be modified through design. Microclimate modification through vernacular design has a long history. Some examples of good microclimatic design from the past have survived, and we can analyze these to help us design today. They show

A view from on foot lets you see things up close. You can stop and examine them in more detail if you wish. Even individual plants can be identified.

that outdoor living areas to be used in more than one season should be oriented toward the south in the Northern Hemisphere (and vice versa in the Southern Hemisphere), and that overhanging structures should be provided to block the high summer sun while allowing the low winter sun to enter an area. Contemporary examples of good and bad microclimatic design also can be analyzed for valuable insight. Outdoor spaces to be used in cool or cold seasons should he sheltered from the wind, and failure to provide adequate shelter will result in limitations on use.

An important lesson to be learned from historical and contemporary examples is that no rule holds in all cases. You must consider the projected use and time of use of an area before making any design decisions about microclimate. The only general guideline that you can absolutely count on is that general guidelines don't always work.

Chapter 2
Atmospheric Systems

An understanding of microclimate begins with an understanding of weather. Weather, worldwide, is driven by solar energy and the rotation of the earth. Predictable weather systems result, and each system contains somewhat predictable weather characteristics. A basic understanding of the forces acting on the atmosphere will assist you in predicting the microclimatic effects of your design decisions.

The earth—sun relationship has two characteristics that significantly affect the weather. First, the earth is tilted in relation to the sun, so that the poles are virtually always tilted toward 'or away from the sun. This means that while one hemisphere is experiencing winter, the other is experiencing summer. Second, the earth is rotating on an axis running through the north and south poles. The atmosphere is not attached to the earth, but remains close to the earth because of gravity. While the earth rotates, the atmosphere is set in motion, and because this motion is not exactly the same as the motion of the earth, winds are provided. The tilt and the motion, then, drive the weather systems on earth.

The weather systems are studied through meteorology. When weather information for a whole year, or several years, is to be understood, it is described through climatology. This yields descriptors, such as mean annual temperature, prevailing winter winds, and soon. These are general characteristics that are regionally homogeneous.

Chapter 3 Microclimatology and Energy Budget

Weather systems and the resulting climates arc defined on a large, or macro, scale, whereby large areas of the earth's surface are affected by similar weather at any one time. The weather of an area, however, interacts with the various landscapes of that area, with unique results. That is, a weather system with a wind from the west at 25 kilometers per hour might be experienced as a wind from the north at 10 kilometers per hour in certain locations in that region. These differences between the prevailing conditions and the local conditions are extremely important in microclimatic design. It is these differences that we are attempting to achieve through design.

There are many ways of describing the effects of landscape on microclimate. One very effective way is through an energy budgeting process, that is, by keeping an account of the flow of energy into and through a landscape. This is done through equations or simply an understanding of the mechanisms. Energy received in a landscape is ultimately from the sun, and normally received as solar radiation. This radiation is apportioned in the landscape according to the characteristics of surfaces; the size, location, and orientation of objects; whether or not water is present; the size, type, and health of plants; and so on. Radiant energy can be stored in objects, used to evaporate water, be reradiated as terrestrial radiation, or used to heat the air. The relative proportion of energy used in each of these functions will strongly affect the microclimate.

Chapter 4 Human Thermal Comfort

The main reason for considering microclimate in landscape design is to create comfortable habitats for humans. Ultimately, a landscape will not be well used by people if it does not provide a thermally comfortable environment.

In considering the thermal comfort needs of people, the energy budget is again an appropriate method. The streams of energy toward and away from a person can be assessed and the resulting balance can provide an estimate of how comfortable a person would be in a certain microclimate. For example, a budget that has a large positive energy balance (more energy received than lost) suggests that a person would be overheated, while a large negative balance means that a person would be too cold. The objective, then, is to provide landscapes that interact with atmosphere creating microclimate in which people would have an energy budget balance near zero (not overheated and not underheated).

Again, equations can be used to describe the energy budget of a person. However, some generalizations can also be made, in that some components of the microclimate can be modified only slightly through landscape design, while others can be significantly modified. Thus we can direct our efforts into designing for those elements, namely, radiation and wind, that can be modified and that have a large influence on thermal comfort. Air temperature and humidity can have a large influence on thermal comfort but cannot normally be modified very much through microclimatic design, so we can direct our efforts elsewhere.

Chapter 5 Energy Conservation in Buildings

Another important reason for considering microclimate in design is to minimize the energy use of buildings. This issue was extremely important in the 1970s during the so-called energy crisis and might again become very important in the future.

The landscape can significantly affect the energy use of buildings. As for a person, an energy budget can be determined for a building and the flows of energy described through equations. Again, the elements that can be most significantly modified by landscape and that strongly affect energy use are radiation and wind.

Chapter 6 Radiation Modification

As we now know, radiation can have a major effect on the thermal comfort of people and the energy use of buildings. There are many ways that radiation in a landscape can be modified. Radiation is normally discussed in terms of two types: solar radiation (emitted by the sun) and terrestrial radiation (emitted by objects on earth). First you need to understand how each of these types of radiation can be modified by objects in the landscape, and then you need to be able to evaluate a landscape to determine the prevailing radiation conditions (the inherent characteristics of the landscape).

Solar radiation is strongly affected by virtually every object in a landscape. Deciduous trees can provide a reduction in radiation during overheated summer periods as a result of interception by their leaves. These trees normally drop their leaves in winter thus allowing significantly more radiation to pass through during underheated periods.

They are therefore extremely valuable landscape elements. However, the difference in the effect on radiation between leafy and leafless periods is not the difference between 0% and 100%. Leaves substantial amounts of solar radiation (near infrared, invisible to the human eve) to pass through, and in winter twigs and branches can obstruct substantial amounts of radiation. Trees vary in their characteristics, but typically allow one-quarter of the sunshine through in summer and three-quarters through in winter. 'Ibis is still a significant difference, just not as much as intuition might suggest.

Most solar radiation normally travels in a straight line, so that the geometry of radiation is easily calculated. Thus a knowledge of sun angles and some simple trigonometry will provide excellent estimates of shadows cast by objects at various times of the year. Also, die amount of terrestrial radiation emitted is directly related to an object's temperature, so amounts of radiation are also readily determined.

Chapter 7
Wind Modification

Wind is the other component of a microclimate that can affect people and buildings and that can be significantly modified by objects in the landscape. Wind is extremely variable both in the direction from which it flows and in its speed. This is generally due to turbulence in the air, and turbulence is a function of the speed of the wind (the faster it is moving, the greater the turbulence) and the roughness of the underlying surface (the rougher the surface, the more turbulent is the wind).

Most objects in a landscape affect wind; some will reduce its velocity and redirect it, others will increase its speed. Wind is also influenced by the relative locations and orientations of objects. Whereas radiation can be described quite neatly through equations, wind still cannot be adequately described this way. There are basically two methods for understanding wind in a landscape. First, scale models are set up in wind tunnels or water flumes. The natural conditions are simulated as nearly as possible, and the wind speeds are measured across the landscape. This provides the opportunity to modify the landscape and "see" the resulting effect on the wind. The second method, which is more common and easier to use, but not as accurate or precise, is through empirical means: that is, using measurements of generalized situations and extending these data to other landscapes. For example, various researchers have taken careful measurements of winds around a single row windbreak of cedar trees. This information can be of considerable value in other landscapes where conditions are similar. The limitation of this method is that the conditions are seldom exactly the same, and some assumptions must be made.

Wind direction and speed often change with the time of day and with the seasons. Wind is generally strongest during the afternoon, and weakest in the very early morning. The prevailing direction of a wind can be illustrated through a wind rose (a diagram that shows the percentage of time a wind blows from each direction) or other graphic techniques. These often show a trend across seasons. For example, the winds in some northerly locations tend to be generally from the north in winter and more evenly distributed throughout the rest of the year. This type of information is valuable in locating winter windbreaks. You cannot generally design for all the wind in all conditions, but you can design for the majority of the time.

Chapter 8 Temperature, Humidity, and Precipitation Modification

Temperature and humidity both strongly affect the thermal comfort of people and the energy use in buildings. However, they normally cannot be modified significantly through landscape design. The atmosphere is such an efficient mixer that any temperature or humidity differences that might occur are normally dissipated very quickly.

There are some notable exceptions, though, that are worth exploring. If a microclimate can be disconnected or isolated from the prevailing atmospheric systems, then significant effects can be achieved. One example is "vest-pocket" parks in heavily urbanized areas such as Manhattan. These can be almost completely isolated from the prevailing conditions by tall buildings on all sides and a canopy of trees above. Similarly, walled gardens can be isolated and exhibit significant differences in temperature and humidity.

Precipitation can be modified through landscape design, but must be dealt with differently from radiation and wind, in that it seldom is considered part of the energy budget of a person or a building. Instead, it is often dealt with as an inconvenience to people in a landscape, and designed for in a very straightforward manner (i.e., with overhead structures).

Chapter 9 Integrating Microclimate Information in Design

Once a designer has a basic understanding of (1) the mechanisms that affect microclimate, (2) the effects that objects in the landscape can have on microclimate, and (3) the effects of microclimate on people and buildings in the landscape, this information can be used in designing new landscapes or modifying existing landscapes.

Energy budget information is valuable in understanding the mechanisms of energy flows in landscapes. It can also be useful in determining the relative merits of different surface treatments, the value of water features, windbreaks, overhead structures, and so on.

Energy budgets of people and buildings provide a mechanism for testing the effectiveness of microclimatic design before construction, as well as a method for postconstruction evaluation.

An understanding of radiation geometry and wind flows in landscapes, gained through illustrations and descriptions, can be readily applied in landscape design. This information is valuable at two levels: first, in determining the overall site characteristics and layout of elements; and second, in the detailed articulation of a particular microclimate that you want to create.

You also need to consider expected time of use and projected use of a landscape. This will allow you to decide specifically what microclimate is appropriate, and how best to use resources.

For example, suppose you are designing the location and orientation of certain tennis courts. If you start without knowing what the microclimatic requirements are, you will end up designing for all conditions. Normally, however, design problems have specific requirements. You could begin by analyzing **how people will use the courts** and then determining **when** the courts will be used.

First, people playing tennis will have a very high metabolic rate and therefore a high input of heat energy. This will strongly affect their thermal comfort. You might determine that there will be specific times of high use, probably spring, summer, and fall in northern latitudes and, if there are no lights, only during daylight hours. There might even be specific hours when most use occurs, such as predominantly during the evening at a condominium complex, or during the daytime at a school. You can use this information to design for use during a specific time of day and season of the year, without concern that the rest of the time the court is unbearably hot or cold. This limits the amount of information you require and focuses your efforts on design elements that will have the most impact.

The information you have gained sometimes fits neatly and conveniently into the landscape design or planning process. Other times it can be used most effectively through the enhancement of a design, or to assist in determining management procedures.

Summary

This book is intended to illustrate the pervasive influence of microclimate. It explains how microclimates are formed by the interaction between the prevailing weather and the physical environment, how they influence people, and how they can be modified through manipulation of landscape elements to create more comfortable, energy-efficient, and pleasant environments. It also discusses examples of appropriate and inappropriate microclimatic design from the past and present, and explains what went right or what went wrong. It explains conceptually how the atmosphere changes over time, how weather is created and can be predicted, and how microclimates are formed. Finally, concepts and details of microclimate modification and manipulation through landscape design are discussed.

The information in this book is presented at two levels: (1) a detailed explanation for a first time reading, and (2) highlighted **principles** and **concepts** to provide an overview for quick reference later. By reading only the highlighted areas you should be able to understand the overall context and intent of the book. By reading the detailed explanation you will be able to gain an understanding of microclimate information that you can use in design and planning. Rereading the highlights will remind you of a concept that you encountered previously.

When learning new information, it is often helpful to supplement reading with discussion. Each chapter includes a series of questions for you to think about, and to help you fix its concepts in your mind and extend your learning to real situations. This will ultimately assist you in applying the information to the myriad of individual problems that you encounter in your professional career.

The first set of questions, "Things to think about . . . ," are general questions to help you to see that through your own professional or life experiences, you already know quite a lot about design with microclimate.

Things to think about …

Before reading the rest of the book, think about the following questions. They may help you to draw on your present knowledge and intuition about microclimates. Consider them on your own or in a small discussion group. There are no right or wrong answers, but some answers are better than others.

1. **There is a wonderful new high-rise apartment in your community, and you are offered first choice of apartments. You are going to live in it over the summer, before leaving for college in the fall. Which apartment would you select and why? Did we mention that there is no air conditioning?**

2. **Imagine that the apartment complex is in the community where you are going to attend college. You again have first choice, and you will live there from September until April. Now which apartment would you select? Why?**

3. **Now you are married and have a baby just home from the hospital. You are going to live in the apartment for the foreseeable future. Which one would you select? Why?**

4. **It is midsummer, and very hot and sunny outdoors. You walk to work, and there are two routes you could take. One is along a roadway with no trees or other shade, the other is along a path through a city park, shaded by trees most of the way. Which one would you likely use more often? What if the roadway route was a little shorter? What if it was a lot shorter? How would you decide?**

5. **It is midwinter and quite cold and windy outdoors. You have been offered the opportunity to go skating at an outdoor rink. You watch the weather forecast. Under what conditions would you agree to go skating? Under what conditions would you decline the offer? Why?**

1

Conceptual Framework

■ **AN UNDERSTANDING** of microclimate can provide the tools for creating thermally comfortable habitats for people and energy-efficient landscapes for buildings.

Introduction

Weather is an integral part of our everyday lives. We live at the bottom of a vast sea of atmosphere that is constantly swirling about us, buffeting us with air and water molecules and bombarding us with radiation from the sun and our earthly environment. We listen to forecasts and try to estimate how the weather will affect our plans for the day, then select our clothing and arrange activities accordingly. Weather influences our choice of transportation, our thermal comfort, even the cost of heating our homes.

Weather is not experienced in the same way everywhere, of course, not even within a city or within a single park. You perceive that as you move through a landscape you experience **microclimates**, small areas where the weather "feels" different. Imagine walking down a city street on a windy winter day, leaning into the wind, your face numb with cold. You step quickly into a bus shelter where the air is calm, and at once you sense this as a much more comfortable microclimate.

Imagine now walking across a shadeless asphalt parking lot on a hot sunny day. You feel the oppressive heat and squint into the blinding light. You then walk into a park and under the shade of a large tree. You suddenly experience a very different microclimate.

You sense that it is much cooler and more comfortable among the trees.

As you can imagine, there are different microclimates virtually everywhere. All day long we pass from one to another. Some we linger in, as they make us feel good; others we hurry through because they make us uncomfortable. Our lives are inextricably linked to microclimates.

Definitions

To set the context there are a few definitions we should clarify. The earth's *atmosphere* is the gaseous bubble that completely surrounds the earth, held there by gravity. *Weather* is the condition of this atmospheric bubble at any given time and place, and is described by measures such as temperature, moisture, wind velocity, pressure, and radiation. The science that studies the instantaneous conditions of the atmosphere is *meteorology*. *Climatology*, on the other hand, is the science that describes the meteorological conditions that characteristically **prevail** over a period of time in a particular region.

To the terms *meteorology* and *climatology*, the prefixes *macro*- (large scale, kilometers to hundreds of kilometers), *meso*- (medium scale, tens of meters to kilometers), and *micro*- (small scale, meters to tens of meters) can be added. Thus, *micrometeorology* is the study of meteorological (instantaneous) conditions in a small area, and *microclimatology* describes the climate (prevailing conditions) of a small space, which can be quite different from the climate of the area as a whole. Both micrometeorology and microclimatology describe conditions within a small site as **modified** by landscape elements. In our earlier example, the atmospheric conditions in the bus shelter (microclimate) are significantly different from those in the open (climate).

Historical Context

The science of microclimatology has a fairly recent history. It has benefited greatly from computer advances that allow modeling of atmospheric environments through mathematical equations. However, *microclimate modification* has a long history. Probably since their beginning, people have been modifying their environments to create more comfortable outdoor places and to minimize the amount of energy required to heat their dwellings.

During prehistoric times people learned to seek out comfortable microclimates for homes. Very early examples of this are cave dwellings. This type of microclimate undoubtedly allowed people to live in areas where the climate would otherwise be inhospitable.

Throughout history people have created landscapes and gardens as pleasant retreats from sometimes harsh climates. They modified microclimates through designing their environments to suit their needs and desires. There was little formal science behind these designs, rather an empirical knowledge of the environment, developed over generations of observation and experimentation. There are examples in all the ancient civilizations: the walled gardens of Egypt, the Hanging Gardens of Babylon, the atrium houses of the Roman Empire. These all modified the microclimate, created comfortable outdoor living areas, and are examples of indigenous microclimatic design.

The exportation of European ideas and designs to much of the rest of the world during periods of exploration and colonization often led to the creation of structures and landscapes that were not indigenous but were, instead, in conflict with local climate. Compounding this effect was the relatively recent advent of inexpensive heating fuels, which brought about a loss of concern for construction appropriate to the local atmospheric environment. Buildings required large inputs of energy to maintain warmth, and the economic cost was artificially low.

Despite the efforts of many enlightened people, the tradition has continued, with the transportation of design styles and ideas throughout the world. Designs that are appropriate in one climatic environment are sometimes totally inappropriate in another. There are many examples of parks, plazas, gardens, houses, and landscapes that have inhospitable microclimates which we can analyze and learn from.

There are, of course, many architectural and landscape architectural features that are appropriate to their climatic environment. These can also be analyzed to determine why they work. Although the details cannot normally be transported elsewhere, the principles and concepts derived can often be used in other environments.

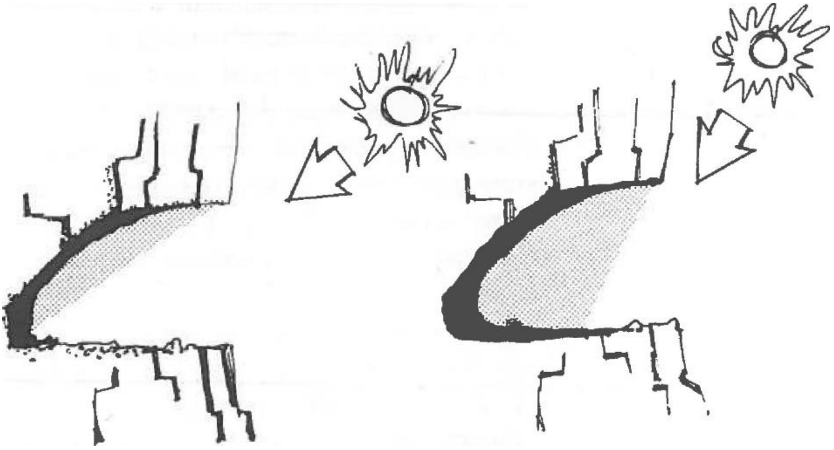
Examples of Microclimatically Appropriat

Historical Example

We first look at an example of a design that modifies an environment in a positive way, creating pleasant microclimates. The cliff dwellings of the Americas were villages built into the sides of cliffs, allowing substantial populations to survive in an otherwise very harsh environment. The climate was one of extreme temperature variations, high solar radiation loads, and very little available water. But inside the homes the air temperature varied only a small amount because of the insulating effect of the cliff walls. The sun was shaded from the dwellings by overhanging cliffs during the high heat loads of summer, but allowed unobstructed entry during winter when cool temperatures required extra heating (Figure 1.1). This was possible through an empirical knowledge of sun movements during different seasons. And while surface water disappeared quickly through evaporation in the open desert, the cool, shady environment of the cave allowed water to be saved. All in all, it was a brilliant use of knowledge about the environment.

Some simple concepts, derived from this example, can be of considerable value to us today.

- **Outdoor living areas to be used in more than one season generally should be oriented toward the south in the Northern Hemisphere.**



(a) Winter Sun

(b) Summer Sun

FIGURE 1.1. *Some caves inhabited by early civilizations were oriented in such a way that they allowed solar entry during wintertime (a), but obstructed solar access in summer (b). This helped to keep the dwellings cool during hot summers, and warm during cold winters.*

Whenever possible, as a very general rule, orient living environments toward the south to allow the warmth of the sun to enter the space during cool periods.

■ Provide overhanging structures above south-facing areas that will block the sun in summer and allow its entry in winter.

The sun appears higher in the sky in summer, so an overhang will not allow solar radiation to enter south-facing areas. The sun appears lower in the sky in winter, so the overhang does not obstruct solar radiation, which can then enter and warm the interior of the area.

■ There is much to be learned by analyzing what others have done.

Whenever you have the opportunity, observe the interaction of a landscape with climate, and analyze the resultant microclimate. This will assist you in learning how to design.

Many approaches to microclimatic design have been continued through tradition and empirical knowledge in contemporary landscape architectural design

One example comes from the campus of the authors' own university, where the majority of students are present from September until April (fall, winter, and spring). Facilities intended to accommodate student use are geared primarily to these seasons.

Contemporary Example

A small sitting space has been provided by a bench outside the door of an academic building (see Figure 1.2). This space is well used year round as a thermally comfortable place to sit. In summer it is shady and cool. In spring, fall, and winter it is sunny and warm, with little wind. It is what many people would call a "sun catch." These are simple concepts and a simple and effective microclimatic design.

Examples of Microclimatically Inappropriate Design

It is difficult to find historical examples of design that were inappropriate to the environment, because they would not have survived the test of time. Particularly uncomfortable microclimates would likely have been abandoned or demolished. There are, however, many contemporary landscapes that have very uncomfortable or otherwise unpleasant microclimates.

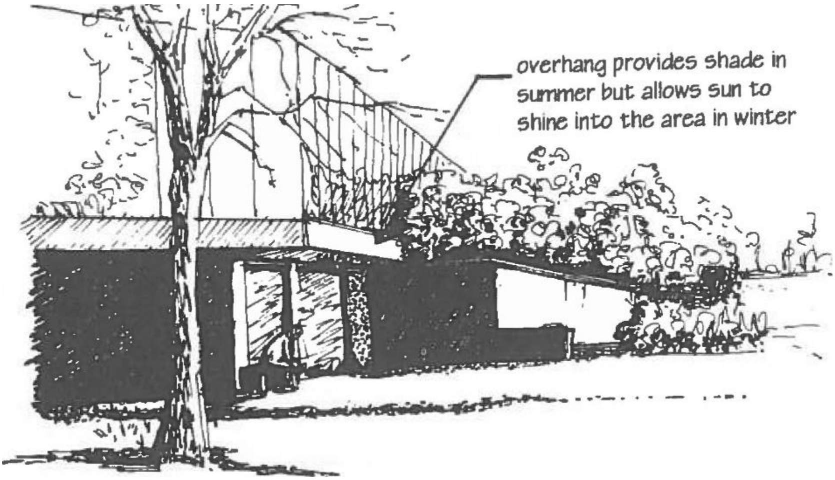


FIGURE 1.2. This sitting area outside a building has been sited so as to provide a shady seat during hot weather, but a sunny place during the cool seasons.

We use, as an example, another sitting area from our university campus. This one was built next to a major walkway, between a residence cafeteria and the main University Center. The sitting area is a very good spot in which to "see and be seen." It has several tiers of seats and is arranged in a semicircle around a deciduous tree. It would appear to be an appropriate facility for that location (see Figure 1.3). It has, however, an extremely uncomfortable microclimate and is seldom used by anyone at any time.

The main error in design was in orienting the open side of the semicircle to the north. This means that the sun never shines on the

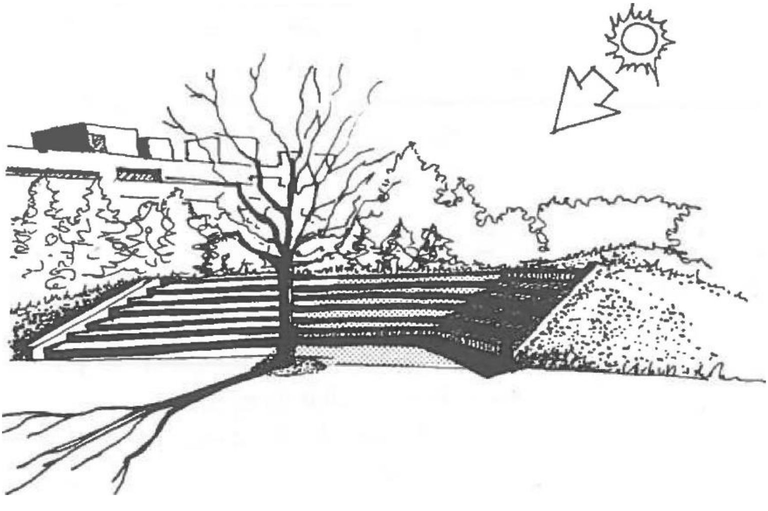


FIGURE 1.3. A sitting area that has many good features is seldom used by anyone, as the microclimate is inappropriate at nearly all times. During winter, spring, and fall the sun does not shine into the area and the wind blows through, whereas during the summer the sun shines on the backs of people's heads. It is oriented in the wrong direction.

seats. People sitting there would, at most, have sun on the backs of their heads and necks. The tree casts a shadow that seldom falls on the seats.

A typical cold-season day would be bright and sunny, and the wind would be from the north. On these days, when people might like to be outdoors, the cold wind blows directly into the area and cools anyone sitting there.

■ Outdoor spaces to be used in cool or cold seasons should be sheltered from the prevailing winds.

When outdoor areas are expected to be used in any season other than summer, provide shelter from the wind. The prevailing wind describes the direction from which wind blows more often than any other.

■ You can learn as much from examples of inappropriate microclimatic design as you can from appropriate microclimatic design.

Just as you observe and analyze good design, try to experience and analyze why some designs create uncomfortable microclimates. Then you will know what not to do in your design.

A much more acceptable solution for this sitting area would have been to orient it exactly the opposite way, and plant shrubs along the top tier to deflect the wind over the heads of the people (Figure 1.4)

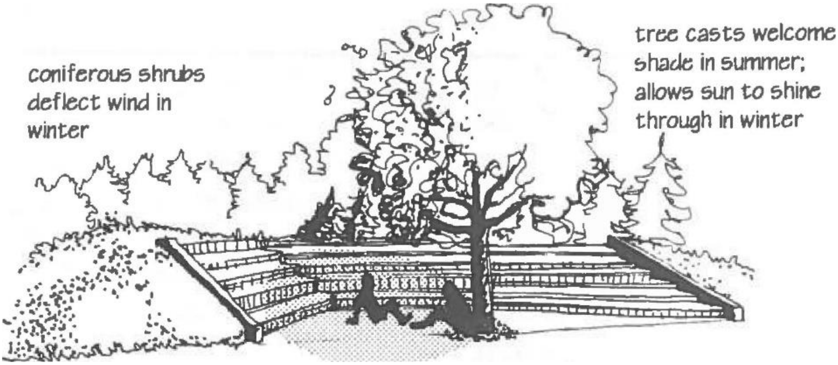


FIGURE 1.4. The sitting area shown in Figure 1.3 could have been designed to be more microclimatically appropriate. It should have been oriented toward the south, with some additional vegetation to deflect the cold winter winds over the top.

Exceptions to the Rules

There are always exceptions to any rule. Take, for example, the concept of orienting outdoor living spaces toward the south. Imagine an outdoor area that is to be used exclusively as a breakfast patio. It might be much more appropriate to orient it toward the east to receive morning sun.

Consider also an area that is to be used as an outdoor pub near a university. The main time of use would be late in the afternoon and into the evening. It might be more appropriately oriented toward the west to receive afternoon sun.

■ **Consider the projected use of an area before making any decisions about microclimate.**

Provide a comfortable microclimate for projected uses and for a specific time of use. The microclimate at other times is usually of much less concern.

Another example may be a family planning a new deck for their house. They might ask your advice on where to locate it. You might be likely to say with confidence, "orient it toward the south." However, a deck on the south side of a home can be a disaster if it is built without any overhead structure, vegetation to screen it, or windbreak. It might be much too hot on sunny summer days, much too cold and windy on most winter days, and probably too cool during fall and spring as well. There is more to the siting of decks than you have gained thus far in this chapter.

Finally, consider the principle of sheltering outdoor areas from prevailing winds during cool seasons. Suppose that someone wanted to use an area for parking a car and walking into the house. If you suggested reducing the wind in this area, you might provide a comfortable winter microclimate, but you might also be creating an opportune place for snow to accumulate. This could create an ongoing snow removal problem for the owner. Considering the small amount of time that people would actually be in the area, you might decide instead to design it to be very windy, thus keeping it clear of snow. The discomfort of the cold would be a small price to pay to have a clear driveway and parking area.

■ **General guidelines don’t always work.**

Always think about what you are trying to accomplish and use guidelines with caution.

Summary

This chapter has introduced some basic ideas about microclimate and landscape design. You now have some concepts and principles that you can use in creating landscapes. However, you also know that they must be used with caution. As you read this book, you will begin to build on this knowledge and learn when to use the rules and when to consider the exceptions.

Things to think about …

Here are sortie ideas and questions to think about. Remember, they don't really have right or wrong answers, although some answers are more appropriate than others. Work through them on your own or as part of a discussion group. They will help you to think about the information in this chapter in relation to other typical design problems. We hope you will come back to these questions after reading other sections in the book to see how your skills and confidence have grown.

1. **Suppose you are given the assignment of designing an outdoor courtyard that will have chairs and tables for use by diners. What are some of the issues regarding the space and the projected activities you will need to know in order to design the microclimate adequately? What solutions would you suggest to your client?**

2. **A friend asks you to determine the best location for a vegetable garden in her backyard. What information would you gather about this job, and what would be the main determinants of the location?**

3. **You are given the job of deciding the location of a tennis court in a large city park. What information do you need about the site and about the projected use that will be helpful in decision making? Are there any other facilities that the players or spectators require?**

4. **Imagine that you are considering spending next Saturday at a provincial or state park. As the weekend approaches, what information are you interested in acquiring, and why? How important are the physical facilities of the park relative to the weather forecast?**

5. **You are given the job of designing a deck for Mr. and Mrs. A's backyard (where Mrs. A can watch her husband work in the garden). Mr. A has been to the library and has photocopied all the climate summaries for the past five years. He has mean annual temperature, prevailing wind direction and speed, relative humidity, precipitation—all pertinent information. How would you use this information? He also has the weather forecast for the next five days. How would you use this information?**

2

Atmospheric Systems

Introduction

A casual observer may see the daily changes of wind and sky as a chaotic parade. But we shall see that there is grand-scale organization to the atmospheric machine, which allows us to identify repeated sequences from the weather parade. These sequences can inform our daily decisions, and their accumulation over weeks and years forms the macroclimate of a region. The play of local physical features on the macroclimate generates the microclimates for which we must design.

Solar Energy: The Power Behind the Weather

■ **Two very large-scale features of the earth, its shape and its tilted rotation, modulate the way that solar energy powers the global weather machine.**

Imagine holding a basketball in one hand and a flashlight in the other, to simulate the earth and sun (Figure 2.1). If the flashlight is held with the beam shining straight at the ball's "equator" (Figure 2.1a), a round patch of light will illuminate the "tropical regions" of our model earth. If the flashlight is tipped slightly so it illuminates a "pole" of the ball, the patch of light will change to an oval (Figure 2.1b). There is the same total energy in the beam in both cases, but the oval patch looks dimmer than the circle because the energy is spread over a larger area. In a similar fashion, the poles of the earth are illuminated with less solar

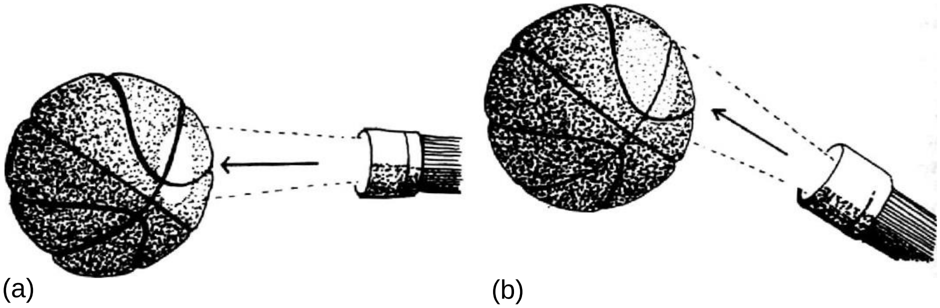


FIGURE 2.1. A basketball can be used to model the shape of the earth. A flashlight beam directed onto the ball is similar to sunlight reaching the earth. When the light is directed at the middle of the ball (the equator) the intensity of light is high (a). However, when the light is directed to a pole, the light is spread over a larger area and the intensity of light is lower (b).

power than the equator.

At the top of the atmosphere, perpendicular to the sun's beam, the available power is similar to 14 100-watt light bulbs mounted on a 1-square-meter board (1,400 w/m2). Since the earth's spherical shape smears the beam over greater areas as we move from the equator to the poles, this power is reduced to about 1,000 watts at 40° latitude and 250 watts at the 80th parallel. The atmosphere is not a good absorber of sunshine, so much of the power strikes the earth's surface.

■ The atmosphere is heated from below.

There is a surplus of power in the tropics and a chilling deficit toward the poles. As we later discuss in more detail, these gradients in heating promote the development of large-scale wind systems.

Imagine a second experiment in which our props are a grape skewered through from pole to pole by a toothpick, and a lamp sitting in the center of a table (Figure 2.2). If we sit the south pole of the toothpick on the table (position a) and tilt the north pole away from the light about one-quarter the distance from vertical to horizontal (actual tilt is about 23° off vertical), we've modeled the situation on the longest summer day in the Southern Hemisphere or the shortest winter day in the Northern Hemisphere (the solstice, near December 21).

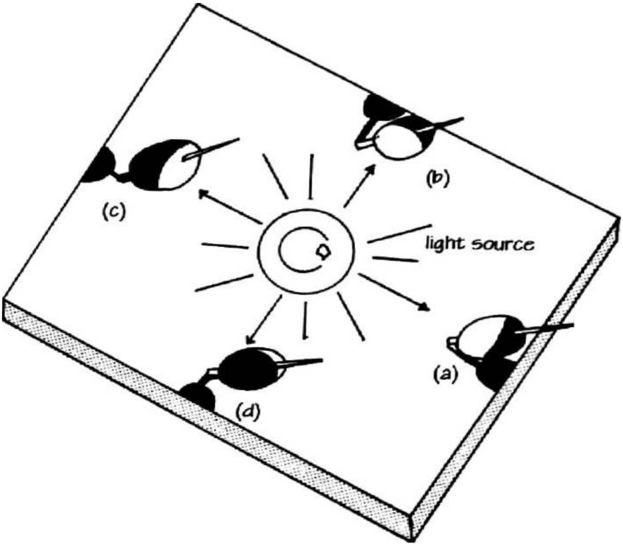


FIGURE 2.2. A grape on a toothpick moving around a light in the middle of a table can simulate the movements of the earth around the sun. In position (a) the earth is tilted away from the sun, representing the winter period in the Northern Hemisphere. As the grape moves around the light it represents (b) spring, (c) summer, and (d) fall in the Northern Hemisphere. The amount of solar energy received at different locations drives the weather systems on earth.

On this date the sun shines directly on the Tropic of Cancer (about 23° south latitude). If we spin the grape on its toothpick to simulate the daily rotation of the earth, we see that tropical and midlatitude locations have day and night, while the south pole is always lighted and the north pole is always dark Uneven heating is most evident in the Northern (winter) Hemisphere. We suspect that this might accentuate the atmospheric mixing, and indeed **the vigor of large-scale wind systems is greater in winter than in summer.**

Now circle one-quarter of the way around the table, keeping the toothpick tilted with the north end **always pointed at the same wall** (position b). This simulates the time of the equinox (near March 21), when the sun is directly over the equator, both poles are barely illuminated, and rotation of the toothpick shows that **all locations have equal day and night.**

If we then circle halfway around the table, still pointing the tilted toothpick at the same wall (position c), we arrive at the longest summer day in the Northern Hemisphere (near June 21). The north pole is in continuous sunshine, but the south pole is dark. The energy deficit from equator to pole is most severe in the Southern Hemisphere, so the southern wind systems are in the full fury of winter. Moving to the next quarter of the table (position d) simulates the second equinox (about September 23). We can close the seasonal circle by returning to the solstice, where we began at about December 21.

■ The earth's travel around the sun on a tilted axis gives us the seasons, always leaving us with a greater energy deficit from pole to equator in the winter hemisphere. Winter temperatures are, therefore, colder and the winter wind systems are stronger. Because the earth's path is precisely known, we can accurately predict the sun's position on any given day. The daily and annual cycles of sun and climate, caused by the shape and the tilt of the earth, are tightly linked. Good landscape design works in harmony with these cycles.

Air Masses

We have noted that the atmosphere is mainly heated from the ground upward. Vertical motions, revealed by bubbling clouds, stir the heat through a layer that extends about 10 kilometers above the ground. This region is called the troposphere (from the Greek for "turning sphere"), where the average temperature **decreases** with elevation. It contains three-quarters of the atmosphere's mass, so much of the earth's aeolian envelope is within easy reach of human influence. "Weather" is confined to the troposphere, because more than 90% of the world's water vapor exists in this layer, where it undergoes the phase changes from gas to liquid or solid that we experience as clouds and precipitation.

Energy deficits at the poles allow the "blobs" (or masses) of air in these regions to become cold, and they sit like two gigantic inverted bowls of cold blue Jell-O over the top and bottom of the earth. Imagine the warm air that spills out of the tropics as red cherry juice, splashing against the Jell-O in midlatitudes (Figure 2.3). The interface between the juice and the Jell-O is the main global "front," so named because it is indeed a battle zone where the warm and cold air masses struggle to push each other aside. This front is sometimes sharp and sometimes diffuse. It generally moves farther south in the winter hemisphere as the cold air mass expands in size, and then retreats farther north in summer. Later in this chapter we examine the weather at these fronts in more detail.

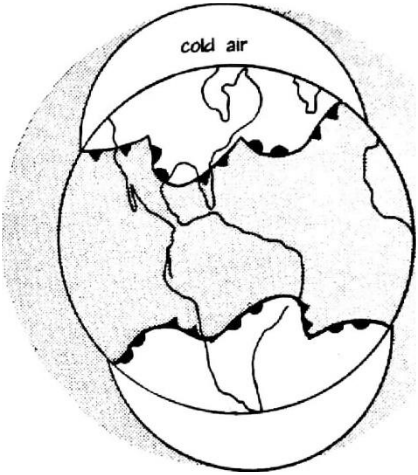


FIGURE 2.3. Cold air pools at the poles and can be thought of as a cap of cold air. Warmer air predominates everywhere else. The interface between cold and warm air is the main global "front" (bold line, with symbols explained later in the chapter).

■ We can summarize the existence of air masses and fronts as follows. Heating differentials between the poles and the equator produce gigantic caps of cold air over polar regions, and sources of warm air in low latitudes. These polar and tropical air masses continually joust along their Interface. This battle zone is the main global weather "front" and Is responsible for the unending variety of weather in middle latitudes.

Global Stirring

Just as uneven swirls of cream in your coffee coax you to stir, the uneven horizontal distribution of atmospheric heat promotes grand-scale mixing, particularly in midlatitudes where the cold and warm air masses push against each other. The giant atmospheric eddies are more random in their motion than the precise track of the sun, so we cannot forecast the weather as well as we can map out seasons and shadows. But there is a degree of organization that allows us to see recurring sequences in midlatitude weather. If we can explain these sequences, then we have some predictive capability and therefore have enhanced our design skills.

We can see the atmospheric eddies on satellite weather reports as massive swirls of cloud that may be 1,000 to 3,000 kilometers in diameter. On weather maps they are delineated and tracked by drawing lines called *isobars*, which join together points on the ground with equal

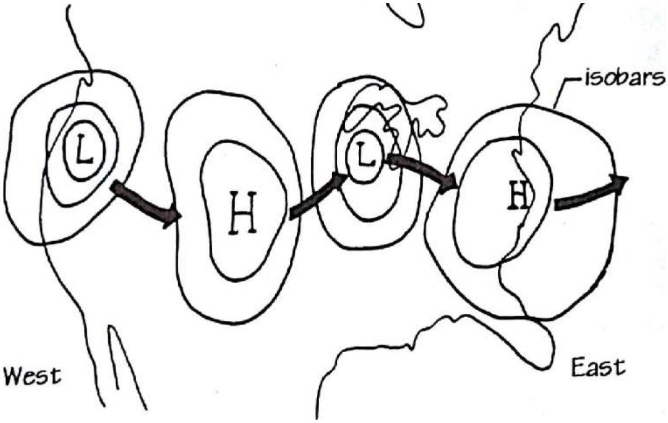


FIGURE 2.4. Weather systems travel from west to east. Solid lines are isobars, which delineate high- and low-pressure systems. Sold arrows show the directions in which these systems are traveling.

(*iso*) barometric (*bar*) readings. The resulting pressure patterns form distorted bull's-eyes, which are marked as having relatively low (L) or high (H) pressure at their centers. High- and low-pressure centers often string from east to west in an alternating sequence, and unsettled weather is more often associated with low pressure than with high pressure. Check this on your home barometer—the low end of the scale will be labeled "Stormy" while the high pressure weather is called "Fair." And when we look at several weather maps in sequence, we find that these eddies are usually **traveling from west to east** (Figure 2.4). Eddies in the lower troposphere drift eastward because they are carried along by the strong river of winds from the west (the jet stream) that blows in the upper half of the troposphere.

To begin to understand why these relationships hold, we'll look at typical pressure systems in a little more detail. In particular, we examine, the associated wind patterns.

Low and High Pressure Cells

Figure 2.5a shows the wind pattern for a stylized low-pressure system. Air moves in a gigantic, counterclockwise, inward-spiraling pinwheel. Intuition might suggest that air should flow directly into a hub of low pressure like the spokes of a wheel, but this expectation is modified by the spinning of the earth. An oversimplified but helpful analogy can be illustrated thus: Fill a laundry tub with water and spin it for a while until the drag of the walls on the water creates a rotating current. Then pull the plug, and the flow will become an inward spiral. (If you want to know more about the effect of the earth's rotation on winds, look up the

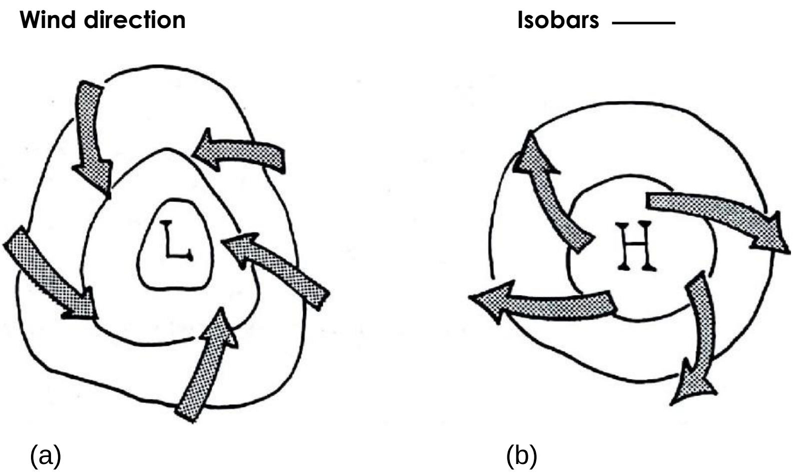


FIGURE 2.5. (a) A typical wind pattern for a low-pressure system has the winds spiraling inward toward the middle in a counterclockwise pattern (Northern Hemisphere). (b) The typical wind pattern for a high-pressure system has winds spiraling outward, away from the middle, in a clockwise pattern (Northern Hemisphere).

name "Coriolis" in any introductory weather book. This engineer and mathematician (1792-1843) is credited with explaining how winds are affected by the spin of our planet.)

What becomes of the air that makes its way toward lower pressure? It cannot escape through the ground or disappear, so the inward spiraling must also have a slow drift upward. Whenever air drifts upward it encounters ever-lowering pressure, and therefore expands. Expansion is a cooling process, and eventually this cooling results in condensation which produces clouds and precipitation. Here we have discovered a fundamental rule of meteorology:

- **Unsettled weather is associated with regions of rising air.**

Figure 2.5b also shows the typical **outward and clockwise** wind pattern for a high-pressure region. If air is constantly spiraling out of a region of high pressure near the ground, where does this air come from? You have guessed by now that this pressure system must be accompanied by a slow downward drift of air, which results in compression because the pressure increases as the ground is approached. Compression produces slight warming, which discourages condensation and suppresses cloudiness.

■ Low pressure regions are typically stormy, because the inward spiraling near the ground induces upward motions. These lead to expansion, cooling, condensation, and precipitation as the air rises to higher altitudes. On the other hand, high pressure regions are typically more settled, because the air descends into an outward spiral near the ground and the associated sinking suppresses the buildup of clouds.

Winds and Weather Fronts

We understand why a falling barometer is associated with deteriorating weather. Put in the context of the model we have just developed, a falling barometer means that a low-pressure, inward-spiraling whirlpool is approaching from the west. Convergence near the ground is causing upward vertical motions, and these motions are leading to cooling, condensation, cloud, and precipitation. Conversely, downward motions are associated with a rising barometer, as a high-pressure cell approaches, and the result is a suppression of clouds and a period of fair weather. This means that:

■ The direction and speed of pressure changes, called the pressure tendency, is more important as a weather forecasting tool than the actual value of the pressure.

However, careful study shows that the pressure tendency often does not slide up and down smoothly, particularly when a vigorous low-pressure cell churns through a region. In such a well-developed system, rapidly **falling** pressures signal its arrival, but a quick shift from cool easterly to warmer southerly winds (winds are always named by the. direction **from** where they blow) often takes the steam out of the pressure tendency. The pressure tendency later regains its strength and rapidly **increases**, but only after a notable shift from warm southerlies to cold northwesterlies. These coordinated shifts in wind, pressure, and temperature are tangible evidence that **fronts** between cold and air masses are passing. Earlier we suggested that this stirring of cold southward and warm air northward is the main function of the great atmospheric eddies, so lets examine the interplay of fronts with winds and weather

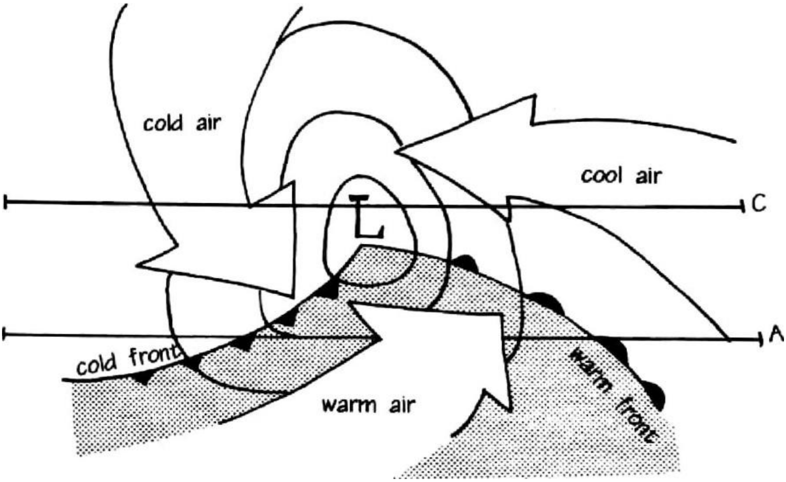


FIGURE 2.6(a). There are typically three airstreams associated with a low-pressure cell: the cool easterlies, the warm southerlies, and the cold northerlies. The warm and cold streams are separated by a 'cold front," the warm and cool streams by a "warm front." Lines A-L3 and C-D are two possible pathways through this storm that are discussed in the text.

more closely.

The winds near the ground in a typical low-pressure cell can be seen as three airstreams (Figure 2.6a). A **cool airstream** rides in on the easterlies ahead of the cell's center, accompanied by vigorous pressure falls. A **warm airstream**, with weak pressure tendencies, flows up from the south. Moving west of the cell, we find strong rising pressures bursting in from the northwest on the wings of a **cold airstream**.

Recall that we have modeled the main global air masses as cold, inverted bowls of blue Jell--O sitting over polar regions and pressing against warmer tropical air. Figure 2.6a is an enlarged and more detailed view of one of the waves shown on the edge of the cold air mass in Figure 2.3. The cold airstream west of a low-pressure cell pulls a fresh, chilly blob of polar air out of the northwest and drives it against the west flank of the warm airstream (Figure 2.6b). The temperature difference between these two streams is large, so the dense, heavier polar air wedges under the tropical air. Enhanced vertical lifting occurs along this collision zone, usually resulting in a band of heavy showers, or even thunderstorms. As this zone crosses from west to east, there is a quick wind shift into the cold airstream, so it is called a **cold front**.

The east winds of the cool airstream in advance of a low-pressure

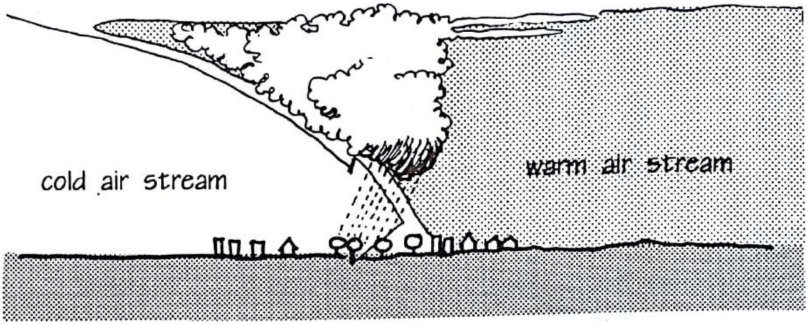


FIGURE 2.6(b). An elevational view of a typical cold front illustrates that the cold air pushes under the warmer air, forcing it upward and causing condensation, cloudiness, and often precipitation.

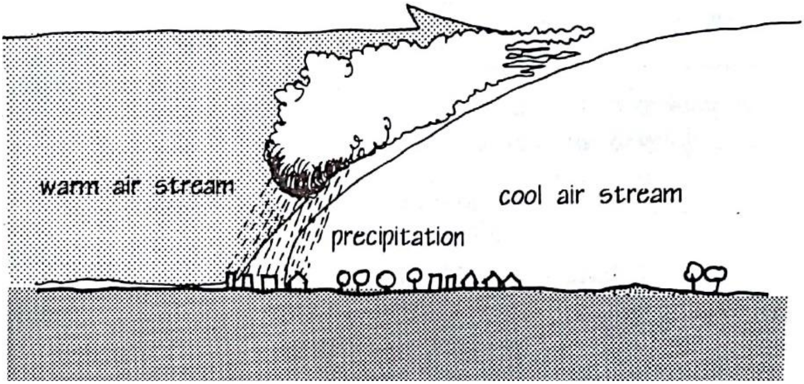


FIGURE 2.6(c). An elevational view of a typical warm front illustrates that the warm air pushes up and over the cold air. This can also cause condensation, clouds, and precipitation, although this is not likely to be as violent as weather associated with a cold front.

cell do not tap the depths of the polar air. Therefore, when the warm airstream attacks the south flank of the cool airstream ahead of a low-pressure cell, only sometimes is there sufficient temperature contrast to form a front (Figure 2.6c). If the contrast is strong enough, the warm air will slide up over the cool, and this lifting will provide additional clouds and precipitation. The zone where the flow shifts from the cool to the warm airstream is called a **warm front**.

A strong low pressure cell may collide the warm airstream vigorously with both the cold air west of the cell and the cool air to the east. In this case, the enhanced cloud and precipitation caused by both fronts will be clearly visible on satellite images (see Figure 2.7).

High-pressure areas, with their **outward spiraling** winds, push air mass borders away from their centers. A high-pressure cell is typically tucked into the burst of polar air behind a strong cyclone. From that location, the eastern half of this cell feeds the cold airstream of the cyclone to the east, while its western half blends into the cool airstream

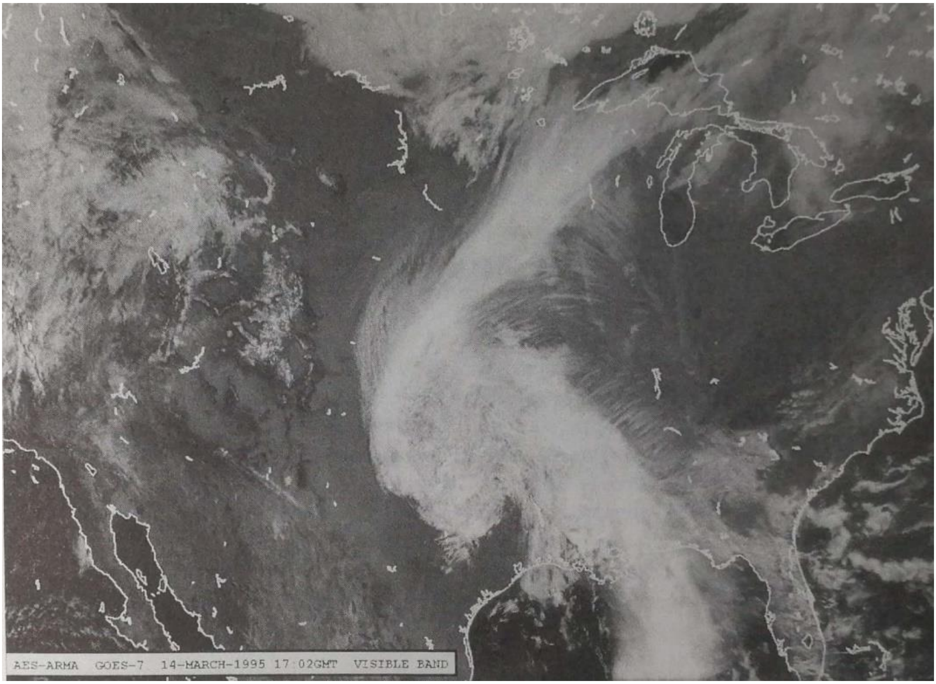


FIGURE 2.7. The satellite photo above shows cloud patterns over a large area of North America (used with permission of Atmospheric Environment Service, Canada, and NASA). At right, an interpretation of the weather systems associated with these clouds illustrates that the clouds are associated with cold and warm fronts.

of the next cyclone to the west.

We now can create a holistic overview of how large-scale low- and high-pressure eddies, and associated collisions between polar and tropical air masses along fronts, create the ever-changing parade of weather that is typical of latitudes beyond the tropics on our globe (Figure 2.8).

■ **Low pressure regions are typically stormy, because the inward spiral The spherical shape of the earth and its tilted axis create differential heating that produces cold air masses at the poles and warm air masses in the tropics. All fluid systems with temperature gradients develop some stirring mechanisms that attempt to smooth out such gradients. In the atmosphere, these mechanisms are the large, traveling high- and low-pressure cells of the lower troposphere. These cells never succeed in smoothing out the pole-to-equator temperature differences, but their unending attempts provide a fascinating variety of weather. They are guided in their strength and motion by the vast west-to-east river of air that flows in the upper half of the troposphere. Therefore we watch for changes in the weather to approach from the west.**

High-pressure regions are characterized by sinking air, which reduces the formation of clouds. The sinking air spirals outward near the surface, pushing air mass borders away from their

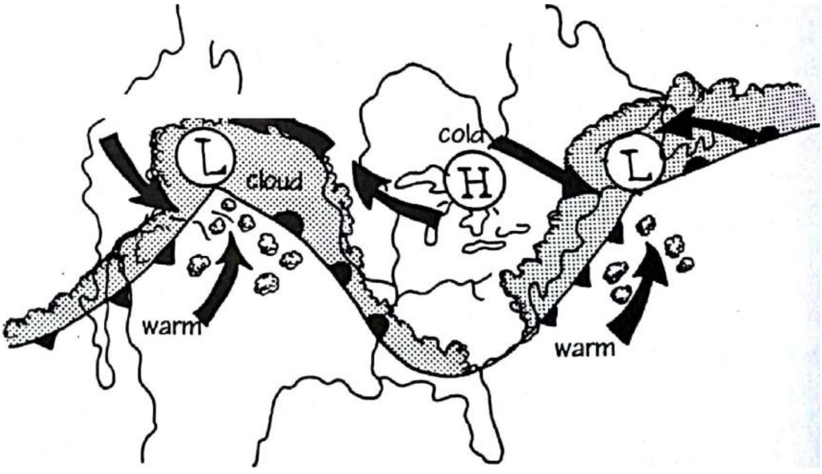


FIGURE 2.8. The satellite photo Synthesis of the concepts of fronts, low- and high-pressure cells, airstreams, and associated areas of cold cool cloudiness. These systems and their associated variety of weather are marching from west to east across the map.

centers. inward motion Induces strong collisions between polar and tropical air in the heart of the cell. Warm tropical air from the south is attacked on its western flank by a cold polar airstream from the northwest; and the resulting aggravated lifting of the warm air produces heavy weather along a cold frontal zone that extends behind the cell center. Another zone of aggravated weather may develop along a warm front extending ahead of the cell center if the warm airstream collides strongly with the cool easterly winds that typically precede the lowest pressure.

As a cell of low pressure with well developed cold and warm fronts moves by to the north of your location, the resulting sequence of weather events can be seen by following along the line A-B in Figure 2.6a. Easterly winds of the cool airstream at A will be accompanied by increasing cloud and a falling barometer. Precipitation is likely as the warm front approaches (Figure 2.6c), but this will diminish or cease as the warm front passes and you note a shift to warm southerly winds. After a period in the warm airstream, the cold front will approach with its band of heavy weather (Figure 2.6b). Then the cold airstream will bluster from the northwest and the pressure will rise quickly. As the low-pressure cell moves eastward and is replaced by higher pressure, the weather will settle after position B is reached.

If the low-pressure cell moves by to the south of your location, you will experience the weather along the line C-D in Figure 2.6a. Clouds and precipitation will develop in the cool easterly airstream as the system approaches. Gradually the wind will back around to the northwest as the cold airstream arrives at your location, but you will never enjoy the warm air mass that is confined south of the fronts. Finally, higher pressure will settle the weather again west of position D.

The sequences of weather described in the previous two paragraphs occur again and again over time, sometimes boldly and sometimes only subtly. With a little practice your eye will detect the bold and the subtle, just as a trained musical ear can pick out recurring themes in a symphony. For anyone involved with activities in the landscape, it is helpful to have this framework for understanding weather. Designs can recognize the challenge of cold fronts, field surveys can be carried out in

Greater comfort, and opening ceremonies for your latest landscape masterpiece can be planned with more confidence. But most important, this framework allows you to greatly enhance your use of climatic data, which are often very important in landscape design.

Climate: The Sum of Many Weather Sequences

Preceding sections have described how weather systems pass in an orderly pattern that alternates from low to high pressure and back again. Despite the order in these patterns, they are not entirely predictable because they change speed and intensity with time. It is an easier task to sum up the weather that has occurred over a period of time to form a set of climatic data. The official time period for such summations is 30 years, and these 30-year averages should be updated every decade.

Table 2.1 shows some typical temperature data from three stations spread widely over the latitude zone where the pressure whirlpools do their mixing.

We can read between the lines of these data to see applications of important principles already described. First, more powerful solar energy is available to warm the atmosphere as the sun moves into the northern hemisphere in summer, so average temperatures arc warmest in summer, of course. Second, in summer the cold air mass shrinks in size and the frontal mixing zone moves farther north. So our most southerly station, Houston, remains for long periods of time in tropical air with no interruptions from outbursts of cold air, leaving this location with the warmest average temperatures of our three examples. Third, in winter the cold air mass expands southward and deepens its chill,

TABLE 2.1
Typical air temperature data from three stations widely spaced over the latitude zone affected by frontal systems: Houston, Texas; Winnipeg, Manitoba; Yellowknife, Northwest Territories.

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Houston	12	13	17	21	24	27	28	29	26	22	19	12	21
Winnipeg	-19	-16	-8	3	11	17	20	18	12	6	-5	-14	2
Yellowknife	-29	-25	-19	-7	5	13	16	14	7	-2	-14	-24	-5

because solar radiation has weakened or disappeared in northern latitudes. Yellowknife is almost continuously locked in the cold Jell-O, and Winnipeg also experiences a severe winter as fresh cold outburst behind storms frequently supply the region with frigid days. Houston experiences fewer incursions of cold polar air streams and therefore has the mildest winters of the three stations.

We can also see our airstream concepts at work in a set of climatic wind data. Table 2.2 shows such data for a midlatitude Ontario weather station. Looking at the average annual data, which pool together all months of the year, we see that the most frequent wind directions are from the southwest, west, and northwest. Hence we say that midlatitude stations lie in the wind belt called the "westerlies." Thinking back to our division of day-to-day winds into three airstreams, this station normally spends more than two-thirds of its time in the warm or cold airstreams. Since these streams come primarily from the compass directions that lie between southwest and northwest, corresponding behavior in the annual wind data is understood. If we looked at monthly data, we would see that the Ontario station experiences more frequent northwesterly winds in January but more frequent southwesterly winds in July, reflecting more visits from cold airstreams in winter and warm airstreams in summer. Although this behavior is sometimes assumed for all midlatitude stations in design work, care should be taken to look at each individual case, where special effects such as the proximity to water bodies may create unique situations.

TABLE 2.2
Thirty-year wind frequency data (percent of time) for all wind directions; during only January; and conditional data for only January winds over 10 m/s at a midlatitude Ontario station

	N	NE	E	SE	S	SW	W	NW	Calm
Yearly Average	6	4	10	11	11	16	17	14	11
January Average	5	3	9	9	12	17	24	18	3
Winter Winds > 10m/s	2	1	24	2	8	19	31	13	0

Conditional Climatic Data

Although the standard data allow us to see the integrated effects of the great global pressure systems and their airstreams, and of the sun's precise march from Cancer to Capricorn with the seasons, such overall averages are usually not the best climatic data for landscape design. We generally need climatic data that meet some special conditions dictated by the particular nature of the design problem.

■ **Such conditional climatology is often not available in standard volumes of climatic data. You may need to request special information from your meteorological colleagues.**

The need for conditional climatic data may be illustrated with a design problem that involves control of blowing snow in winter. Table 2.2 shows the 30-year average wind direction data **for all wind speeds** during January, typical of published climatic normals. These data suggest a need of protection from wind from the west. But when we realize that snow blows only when the wind is strong, and therefore request a set of average wind-direction data, under the **condition** that the wind **speed** exceeds **10** meters per second (m/s) (third line in Table 2.2), we discover a new design challenge. These conditional data show us we must protect against **both** strong westerly outbursts of cold air behind low cells **and** strong attacks of cool airstreams from the east in advance of winter storms. The requirement for protection from the east is not revealed in the standard data.

Suppose we are designing an outdoor patio to be used in high summer. Our goal is to keep this space comfortable on hot days, so we might ask for the following conditional climatic data. What are the afternoon wind directions only for days when the daily maximum temperature is warmer than the average maximum temperature for the design month? We do **not** want to block the cooling effect of wind flow from directions revealed in this analysis. We might anticipate in advance that these are days when the location is in a warm airstream from the southwest, but good design demands that the wind regime for each specific site be checked. Influences such as lakes, valleys or elevation may modify the regional airflow.

As another example, consider the task of extending the use of a park in the fall season by suitable landscape design. We would ask for wind directions when temperatures are **below** normal and skies are **cloudy.**

This would allow protection from cold airstream outbursts, and therefore prolong use of the space by enhancing human comfort in this season. Such **conditional climatology** is critical to good landscape design, but is often not the same as the average climatology for a region.

- **Landscape design problems often require the specific enhancement or suppression of the weather conditions associated with one or two of the three airstreams that accompany traveling low- and high-pressure cells. However, traditional climatic data average together the weather conditions over many arrivals and departures of all three airstreams, thus diluting the impact of critical weather events. For optimum results, landscape planners need to formulate requests for conditional climatic data stating the particular weather conditions that challenge the design most severely. The frequency of various wind directions may be required, for example, only when certain conditions of temperature are met. Very often, such conditional climatology will direct the landscape planner toward different and more successful designs than are suggested by the traditional climatic data.**

Things to think about . . .

1. **Suppose a child asks you, “How can people forecast the weather?” What would you answer?**

2. **You are on a canoe trip in a remote area. The people you are traveling with know that you have read this book, and now they expect you to act as weather forecaster for the trip.**
   —You set up camp under increasing cloudiness and a wind that is freshening from the east. Your campmates ask what to expect in the morning.
   —Later, as you are paddling along in your canoe, the atmosphere is warm and humid. The western skyline becomes dark and you hear the rumble of thunder. What are your immediate plans? What do you expect the weather to be like tomorrow?

3. **Think back to the bus shelter that you visited in your mind's eye during Chapter 1. What weather system, wind direction, air temperature,**

pressure tendency, etc. was affecting your area? Where else in the landscape do you think you might find a pleasant place to hide out for a while? Describe the landscape elements in terms of location and orientation.

4. **Suggest the conditional climatic data you would request for the following projects:**
   —Designing an outdoor amphitheater
   —Improving an open-air bus transfer area
   —Landscaping around a swimming pool.

3

Microclimatology and Energy Budgets

■ **WHEN THE CLIMATE** of a region interacts with the local landscape, a unique microclimate is created. This microclimate can be analyzed in terms of its energy budgets in order to understand how the flows of energy can be modified through landscape design.

We now understand how many visits of large, traveling pressure systems combine to produce regional-scale macroclimates. The macroclimate of an area, however, interacts with the local landscape to create an unique result. Differences between a regional macroclimate and a local microclimate are extremely important in landscape design. Macroclimates are the stuff from which we will create managed microclimates.

Your objective in this chapter is to understand how a macroclimate interacts with landscape elements. Then you will have the confidence necessary to skillfully manipulate microclimates to meet target criteria through design.

We will learn that:

■Energy is the key commodity in microclimate analysis.

Introduction

- **Local microclimate depends primarily on the way solar energy is consumed by (1) convection into the air, (2) evaporation, or (3) heating of the objects at a microsite.**

We can't destroy unwanted energy at will, but:

- **We have the ability to block or transmit radiant energy, and to adjust the partitioning of this energy among its consumers.**

These are powerful methods for purposeful microclimatic manipulation.

- **We are most capable of changing radiation, wind, and energy partitioning at a site. We are least able to change temperature and humidity, because wind is remarkably efficient at mixing air heat and moisture.**

If you marched through a varying summer landscape with temperature and humidity sensors at hand—over an open lawn, under a majestic old shade tree, and across a sizzling parking lot—you would find that the vast differences in the "feel" of each microclimate would overwhelm the small differences you observe between temperature and humidity at each microsite. It's the differences in energy and wind that really matter here, so our limited ability to manipulate temperature and humidity is not a serious handicap.

Of course, we can also manipulate the local precipitation by covering the location. But this alteration could not be considered in isolation, because it would change the radiation and wind environments as well. The elements of microclimate intermingle. **Energy** is the spoon that stirs these elements together in harmony and leads to successful microclimatic landscape design.

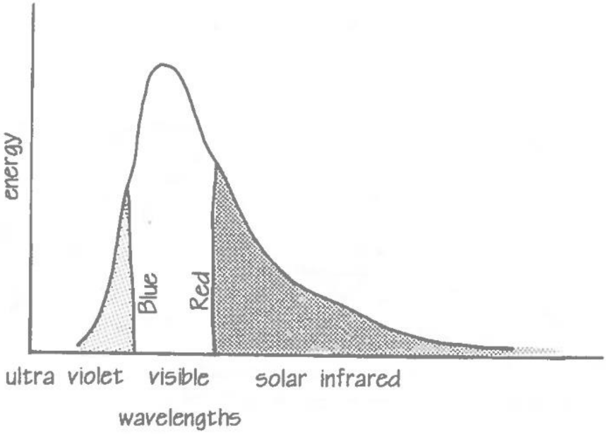
Solar Radiation

Incoming Solar Power

The power that drives the microclimate engine is solar radiation. Solar energy arrives in a roughly bell-shaped distribution over a range of wavelengths that are conveniently divided into three packages (see Figure 3.1).

The first package consists of **ultraviolet** photons, with wavelengths that are too short for our eyes to see. Many of these

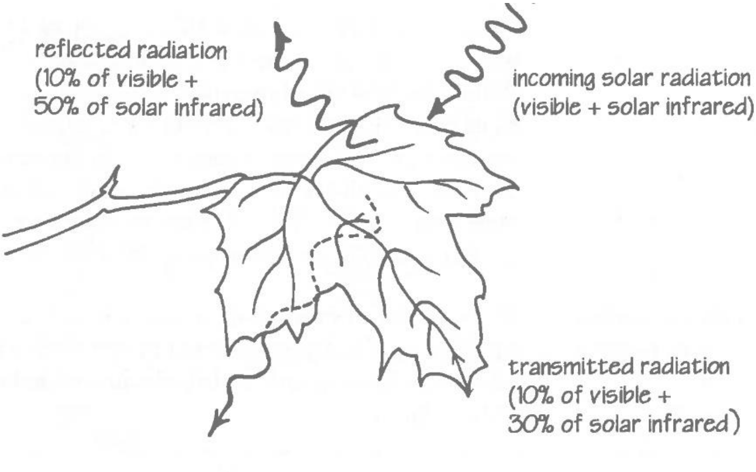
FIGURE 3.1. The satellite photo Synthesis of the Solar energy arrives in a variety of wavelengths, from very short ultraviolet wavelengths to relatively longer solar infrared wavelengths. The distribution of energy across all the wavelengths is illustrated in this graph.



photons are consumed by the production of needed ozone in the stratosphere. The reduction in ozone in the stratosphere, resulting from human intervention with chemicals such as chlorofluorocarbons, has increased the amount of this radiation reaching the earth's surface. Since it is potentially damaging to skin and eyes, its removal by shading may be one design objective for some sites.

Most of the solar energy falls into the two remaining packages, which are about equal in size. The first is the **visible** energy that we use to see, and that plants utilize in photosynthesis. The second is beyond the red end of the visible spectrum, and so is called **solar** infrared. Leaves cannot use this energy for growth, so they reject it by reflection or transmission (see Figure 3.2).

FIGURE 3.2. Leaves absorb and use a large portion of the visible solar radiation, but reflect and transmit a large portion of the invisible solar infrared radiation.



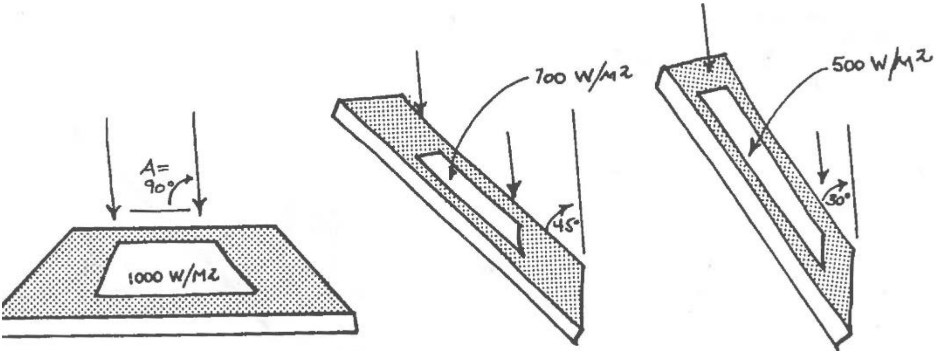


FIGURE 3.3. The formal relationship between the energy received on a surface held directly toward the sun (direct beam) and a surface tilted at some other angle (tilted beam) is:
Tilted beam energy = [Direct beam energy] x [sine of angle A].

Since leaves typically transmit about 10% of the visible sunshine and about half the solar infrared, there is still about 25% of the sun's total energy available under a single layer of leaves. Multiple leaf layers will reduce the transmission, of course, but there is always more solar radiation available under a tree than your eyes tell you.

We can clearly adjust the incoming solar energy by shading, but also by adjusting the angle between the sun's beam and the intercepting surface. We previously used this concept to explain the difference between solar energy received near the equator and at the poles. Remember how the illumination weakened as we tilted the flashlight so its beam changed from a circle to an ellipse? About 1,000 watts of sunshine can strike one square meter facing directly to the sun on a clear day, but tilt the surface to a 45° angle and only 700 watts hit the same square meter. Tilt it further, to make an angle of only 30° with the beam, and the energy drops to 500 watts (see Figure 3.3).

Reflection and Net Solar Radiation

The reflection of solar radiation by leaves can be generalized by defining the fraction of sunshine reflected by any surface as its "albedo." This talent for reflection varies widely over natural and artificial surfaces (see Table 3.1).

TABLE 3.1

Albedos, Emissivities, and Thermal Conductivities of Elements Often Found in the Landscape

	Albedo (%)	Emissivity (%)	Thermal Admittance $(J/m^2 s^{1/2} K)$
Soils	5-75	90-98	
Moist dark cultivated	5-15		
Moist gray	10-20		
Dry sandy	25-35	84-91	
Wet Sandy	20-30		
Dry sand dune	30-75		
Dry soil			600
Wet soil			2500
Vegetation	5-30	90-99	
Grass	20-30	90-95	
Green fields	3-15		
Wheat	15-25		
Meadows	10-30		
Chaparral	15-20		
Brown grassland	25-30		
Woods	5-20		
Deciduous forest	10-20		
Coniferous forest	5-16	97-98	
Swamp forest	12	97-99	
Water	5-95	92-97	1500
Water (high sun angle)	5	92-97	
Water (low sun angle)	95	92-97	
Snow (fresh)	70-95	99	130
Snow (old)	40-70	82	600
Urban Surfaces			
Asphalt	5-15	95	
Concrete	10-50	71-90	
Brick	20-50	90-92	950
Stone	20-35	85-95	
Tar and gravel roof	8-18	92	
Tile roof	10-35	90	
Slate roof	10	90	
Thatch roof	15-20		
Corrugated iron	10-16	13-28	
White paint	5040	85-95	
Red, brown, green paint	20-35	85-95	
Black paint	2-15	90-98	
Air			
Still			5
Turbulent			400

Water viewed from above (5%) and new snow (95%) are extensive natural surfaces that lie at opposite ends of the albedo scale. Viewed at low angles, however, the albedo of water increases dramatically (95%), as you know from squinting across a glistening lake. All varieties of albedo are available to the landscape designer willing to incorporate some artificial components, from bright white paint (up to 90%) to buff brick (20-50%) or asphalt (as low as 5%).

To understand the contribution of solar power to the microclimate of a design site, we need to consider the incoming sunshine and the reflection in unison. We realize that it is the amount of radiation we **keep** at the site that is important. This is simply the difference between the intercepted and reflected radiation, or the **net** solar radiation. If we express albedo as a decimal rather than a percentage (e.g., 60% is expressed as 0.6):

$$\begin{aligned}\text{Net solar} &= \text{Intercepted solar} - \text{Reflected solar}\\ &= (1 - \text{albedo}) \times \text{Intercepted solar}.\end{aligned}$$

For example, suppose we have intercepted 500 watts of sunshine on a surface. If its albedo is 80% (quite highly reflective), we will keep only 100 W. But with a dark absorber whose albedo might be 20%, the net solar power would be 400 W. Four times more power is kept by the darker surface. Even though the incoming sunshine is dictated by cloudiness, we still have a vast capability to adjust the **net** solar radiation.

■ We are most capable of changing radiation, wind, and energy partitioning One task for a landscape designer is to manage the net amount of solar power that Is captured at a site. This can be done by:

1. **Admitting or blocking the solar beam**
2. **Adjusting the angle between the sun's beam and objects in the design space**
3. **Choosing the solar reflectivity (albedo) of objects in the design space**

These principles will be put into practice in Chapter 7.

Terrestrial Radiation

At longer wavelengths than solar energy, there is another package of radiation that is invisible to our eyes but very important to the microclimate at a site. This is the terrestrial radiation, which is **emitted** by all objects on the earth's surface, by clouds, and by the sky itself.

If we show, side by side, the solar power captured by the earth and the terrestrial radiation emitted, we note that the area under the two curves is about equal and there is almost no overlap between the curves (Figure 3.4).

Solar power peaks at a wavelength about 20 times shorter than terrestrial emissions, so we may safely deal with the two energy regimes quite separately. The solar and terrestrial packages are often named "shortwave" and "longwave" radiation, respectively. When the areas under the two curves are identical, the earth's average temperature remains fixed.

It may be surprising that all terrestrial objects—the trees, the sky, this book, and you, too—**emit** energy. This is because all terrestrial molecules are in constant motion, acting like minute vibrating radio antennae that broadcast in far infrared wavelengths. Their broadcast strength is controlled by temperature, so you notice longwave radiation most when you feel it arriving from a hot object such as the top of a crackling wood stove.

More than a century ago, Stefan and Boltzmann, Austrian physicists who made important contributions to the theory of radiation and gases in the latter half of the nineteenth century, told us that the energy–temperature relationship should obey the following law when temperature (7) is in celsius degrees:

$$\text{Energy} = S \text{ x } (T + 273)^4.$$

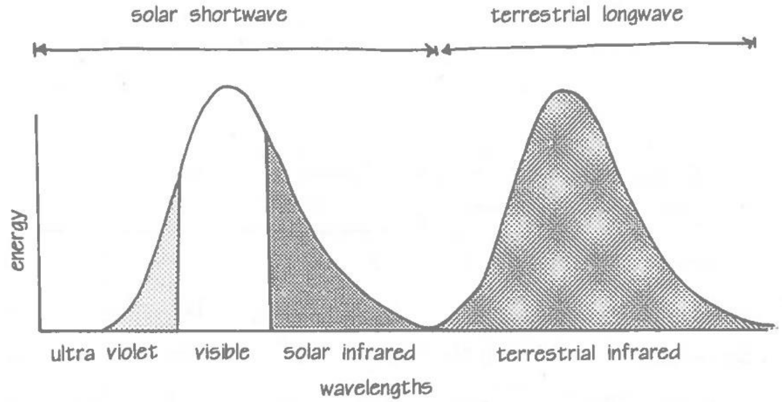


FIGURE 3.4.
The solar (shortwave) radiation received by the earth and the terrestrial (longwave) radiation emitted by the earth. There is virtually no overlap between the Wavelengths of these two types of radiation, so we can consider them separately.

This recipe yields energy in watts per square meter if we use the linking number S as 5.67 x 10^{-8}, so we can estimate how much energy, say, a tree or a brick wall at 30°C is emitting as follows:

$$\text{Energy} = (5.67 \times 10^{-8}) \times (30 + 273)^4 = 478 \text{ W/m}^2.$$

So a nearby wall might add nearly 500 W/m^2 of longwave energy to the roughly 1,000 W/m^2 of shortwave energy we would expect to arrive in the sun's beam. It's clear that terrestrial longwave energy must figure in our quest to manipulate microclimates.

The Stephan-Boltzmann recipe gives the theoretically maximum possible energy emission rate, which must be tempered slightly to match real life. The answer derived from their equation should be multiplied by a correction factor called the "emissivity," but the second column in Table 3.1 shows that this factor is always greater than 0.9 for things of interest in landscape design anyway. So when we're happy with estimates within 10% of reality, the uncorrected equation we have used is usually just fine. One important exception is the sky, whose emissivity changes with temperature. Table 3.2 shows sky emissivities and longwave emissions for selected temperatures.

■ **All terrestrial objects emit radiation at a rate controlled by their temperature. This radiation falls at long infrared wavelengths that do not overlap with solar energy.**

TABLE 3.2
Sky Emissivities and Terrestrial Radiation Emissions for Selected Air Temperatures

Temperature (°C)	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**
Surface emissions (W/m^2)	**316**	**340**	**364**	**391**	**419**	**448**	**479**	**511**
Winnipeg	**0.72**	**0.75**	**0.77**	**0.80**	**0.82**	**0.85**	**0.87**	**0.90**
Yellowknife	**228**	**254**	**280**	**313**	**344**	**381**	**417**	**460**

Combining and Manipulating Absorbed Solar and Terrestrial Radiation

Earlier, we realized that the **net** solar radiation was the shortwave energy actually absorbed by an object. We can now expand this idea to include both solar and terrestrial contributions. The total energy absorbed by an object is the sum of the net solar radiation **plus** the intercepted longwave radiation from the sky and other surroundings.

$$\text{Total radiation absorbed} = (1 - \text{albedo}) \times (\text{incoming solar}) + \text{intercepted longwave radiation.}$$

There is no longwave equivalent of "albedo" in our equation, because reflection hardly occurs for terrestrial radiation, even though reflection is very important for solar radiation.

To illustrate these ideas, consider a simple object—a dark gray (albedo = 0.30), smooth, horizontal surface such as an asphalt parking lot. It's a warm and sunny afternoon, with a temperature of 30°C, and 800 W/m^2 of solar energy striking the pavement. From Table 3.2, the longwave sky radiation at 30°C is 417 W/m^2, so:

$$\text{Total radiation absorbed} = (1 - 0.3) \times 800\ \text{W/m}^2 + 417\ \text{W/m}^2 = 977\ \text{W/m}^2.$$

Despite some solar reflection, there is still more **total** radiation absorbed than the original full 800-watt power of the sun on this day. No wonder we can "fry eggs" on a sunny parking lot!

Suppose we could shade this surface with mature trees that allow only 20% (or 160 W/m^2) of the sunshine to dapple through, and we could pick a lighter colored material like concrete (albedo = 70%). Assuming the leaves in the lower canopy of the trees are near the air temperature of 30°C, according to the Stefan-Boltzmann recipe they are emitting 478 W/m^2. They will replace the sky as the source of longwave radiation intercepted by our surface. Now:

$$\text{Total radiation absorbed} = (1 - 0.7) \times 160\ \text{W/m}^2 + 478\ \text{W/m}^2 = 526\ \text{W/m}^2.$$

Our intervention has been quite impressive. We do have a great deal of control over the radiation regime at a site by adjusting shade and albedo. We have almost halved the absorbed radiation, but we still have more than 500 watts, the equivalent of a toaster, plugged into each square meter. Wouldn't this environment still get warmer and warmer with time? We must expand our thinking to include energy **consumers** as well as energy suppliers.

■ We can manipulate the total radiation absorbed at a site by shading, or by changing the solar reflectivity (albedo) of objects. Shading may cause a moderate increase in the amount of terrestrial longwave energy received, because the sky is a poorer emitter than trees or buildings. However, this extra longwave gain is usually overwhelmed by the large decrease achieved in sunshine, so the total absorbed radiation is significantly reduced.

Consumers, Suppliers, and the Energy Budget

In matters of finance, income supplies money while necessities and frivolities consume it. A stable financial environment requires that the **monetary budget** is balanced. A stable microclimatic environment requires that the **energy budget** is balanced;

$$\text{Energy Supplied} - \text{Energy Consumed} = 0.$$

The balance reflected in this simple but powerful statement is the Holy Grail of microclimatology. What, then, are some energy consumers at a site that could balance the radiant energy surplus we have already described and manipulated? We'll discover the consumers by returning to the unshaded asphalt parking lot.

The first consumer, **longwave emission,** awaits our application of the Stefan-Boltzmann recipe to the pavement itself. This equation demands that the parking lot, like all objects, will emit longwave radiation according to its surface temperature. Imagine for a minute that longwave emission is the only willing consumer. The surface temperature will escalate, pumping up the energy used by outgoing longwave radiation (according to Stefan-Boltzmann) until this use is consuming all the incoming radiation. The temperature will stabilize as the budget eases into balance. We can estimate what the surface temperature would become under this "one consumer" scenario if we recall from our earlier example that the total radiant energy being supplied to the pavement is 977 W/m^2. Our "one consumer" energy budget is:

$$\text{Radiant energy supplied} - \text{Longwave emitted} = 0$$

$$960\ \text{W/m}^2 - (5.67 \times 10^{-8}) \times (T_{\text{surface}} + 273)^4 = 0.$$

Solving this equation for the asphalt surface temperature, $T_{surface}$, we find that the pavement would stabilize at the sizzling temperature of 89°C! Even though parking lots do feel like pizza ovens on a sunny day, this is an unreasonably high temperature value. In reality, there must be more consumers to share the energy supplied by radiation.

A second consumer is **conduction.** Energy will be carried down through the asphalt and stored in the substrate below. In some design problems we may wish to accentuate this consumer pathway as much as possible. For example, we might arrange to pour energy into a massive brick wall in a courtyard during the day so that this heat can later be returned for the comfort of outdoor evening diners, or for the nighttime protection of cold-sensitive plants. We can manipulate this energy pathway by adjusting the thermal admittance of materials at our design site (see Table 3.1). High admittance will enhance energy consumption by conduction, leaving less energy to be dissipated by longwave emissions.

■ Here we have discovered another powerful design tool that is available to modify a microclimate. It concerns the partitioning of the supplied energy among potential consumers. If you enhance one of the consuming energy flows, less energy must flow through the remaining consumers, and conversely, if you restrict any of the consuming energy flows, more energy must flow through the remaining consumers.

Our parking lot will not really reach 89°C, because longwave emissions do not have to carry the whole flow of energy consumption alone. The energy budget has now expanded to:

Radiant energy supplied — Longwave emitted — Conduction = 0,

and there are still more consumers to add to the list.

Evaporation is another possible, and very potent, energy consumer. Your intuition and experience confirm that flooding our parking lot with a fire hose would quickly take the sting out of the surface temperature! Once we have discussed all the consumers, we'll put their typical magnitudes side by side for comparison on several typical surfaces. We'll see that evaporation ranks high as a consumer, **provided**

water is available, of course. If your object is to dissipate excess daytime energy at a design site, elements such as a pond or water-wall can combine aesthetic appeal with a voracious energy appetite. We can now add another term to our energy budget:

Radiant energy supplied – Longwave radiation emitted
– Conduction – Evaporation = 0.

Let's put what we know so far about energy budgets to work on the following question: 'Why does a summer beach burn my feet, even though the sand has a high albedo?" The whiteness of sand does help to keep it cool by decreasing the net solar radiation (a black sand would be even hotter), but the explanation of the burning heat lies with the consumers. lithe sand is dry, then evaporation can't participate in the energy budget. Lack of moisture also leaves the pore spaces between grains of sand full of still air, which has very poor thermal conductivity, so conduction is only a feeble energy consumer. The **partitioning principle** is at work here. Two consumers are severely restricted, so most of the energy consumption is shunted through longwave emissions. The surface can achieve strong longwave losses only by heating up (much as in our earlier parking lot example), so the sand stabilizes at a toe-toasting temperature. At the shoreline, where waves **wet** the sand, the energy partitioning is quite different. Here, evaporation and conduction can now vigorously consume energy, so longwave emissions and the accompanying surface sand temperature are comfortably lower.

The energy consumption story is not complete for the sand and other landscapes until we add a final consumer to our budget—**convection**, the transfer of energy from objects into the overlying air by the wind. When a surface is heated, the air next to it will become warm and rise away in the wind, removing some energy. This consumer provides a linkage between the microclimate at a local site and the macroclimatic temperature and wind provided by the traveling global weather systems.

Removal of energy by convection responds to two factors: the amount of mixing or "turbulence" that is occurring in the air, and the temperature difference between the surface ($T_{surface}$) and the air (T_{air}). We can write:

$$\text{Convection} = (\text{Mixing factor}) \times (T_{surface} - T_{air}).$$

A hot cup of coffee provides a helpful analogy. The coffee cools fastest when the temperature difference between it and the surrounding air is greatest, and cooling can be encouraged by stirring. In the atmosphere, mixing is enhanced by strong winds and rough surfaces that swirl the air into vigorous local turbulence.

Most of the surface-to-air temperature differences associated with convection occur within the first meter of an object, or even the first centimeter, depending on the size and roughness of the object. Therefore, **the effect of a surface on ambient temperature decreases quickly with increasing distance away from that surface.** Beyond this shallow layer, the temperature and atmospheric humidity are mainly controlled by the current macroscale air mass.

Since the surfaces of the asphalt parking lot and the dry sandy beach we have discussed were very warm relative to the prevailing macroscale air mass, convection would be an important energy consumer. Convection would take some share of energy consumption away from longwave emissions, so although the surface temperature would still be toasty, it would not need to be as high as the 89°C value we computed when longwave loss was the sole consumer. When we want convection to help us remove as much energy as possible from site, our design should take care **not** to block the wind and thereby weaken the mixing factor. In some design problems it may be practical to tumble the wind over a purposefully roughened surface, thereby encouraging more mixing and stronger convection.

We now have completed the set of energy consumers and can write a final version of the energy budget (Figure 3.5):

Radiant energy supplied – Longwave radiation emitted
– Conduction – Evaporation – Convection = 0.

■ The "energy budget" is a fundamental concept that lies at the core of microclimatology. The microclimate at a site will adjust until there is a balance between the radiant energy supplied and the energy removed by all consumers. The four major available consumers are longwave radiation by objects at the site, conduction of heat into objects, evaporation of water, and convection of heat from objects into the air by wind. As this concept has been developed piece by piece, we have seen that

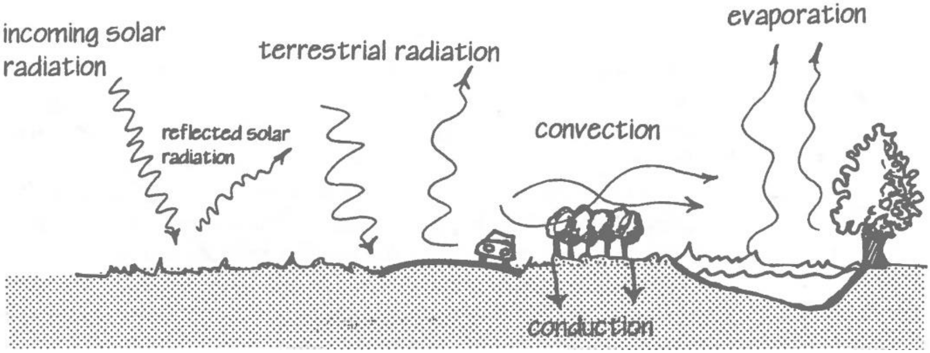


FIGURE 3.5. An energy budget of any surface considers all the flows of energy toward and away from the surface. It is useful to consider the magnitudes of the flows through each avenue. For example, if there is no water available for evaporation, then the energy must be shared among the remaining streams of energy.

a number of opportunities exist to manipulate the partitioning of energy between the carious terms in the energy budget, and therefore to design a target microclimate.

Evening and Nighttime

Landscape design for evening or nighttime use may sometimes be required. The evening energy budget has mysterious traits; some daytime energy consumers can transform into energy suppliers after the sun goes down.

Consider a flat, open turf surface under clear skies just before sunset. The day has been cool, and the current air mass and grass surface temperatures are both about 5°C. But when the sun slips below the horizon, the only radiant energy supplier becomes the longwave radiation from the sky. Table 3.2 shows that this sky will supply only 254 W/m2 of radiant energy, whereas Stefan-Boltzmann say the 5°C grass must be losing 340W/m^2 of longwave energy itself. This leaves the first two terms of our budget with a deficit, and no energy suppliers to balance the budget. This approach may work in some government offices, but not in microclimatology. A microclimate will adjust until a stable state is achieved.

Here are the processes that occur to bring the turf's energy budget into balance. First, the stomata! pores of on the grass leaves close, stopping evaporation. Because of the radiant energy deficit, the turf will be forced to cool until its temperature is less than the temperature of the overlying air mass, and less than the temperature of the soil reservoir, which has filled with conducted heat during the day. Now heat can flow **down** to the turf from the warmer air, and **up** to the turf from the warmer soil. **Nighttime convection and conduction have transformed from consumers to suppliers.** We may see frost on the grass at sunrise even though the back porch thermometer has never gone below freezing, because the turf stabilized at a nighttime surface temperature that was cooler than the macroscale air mass.

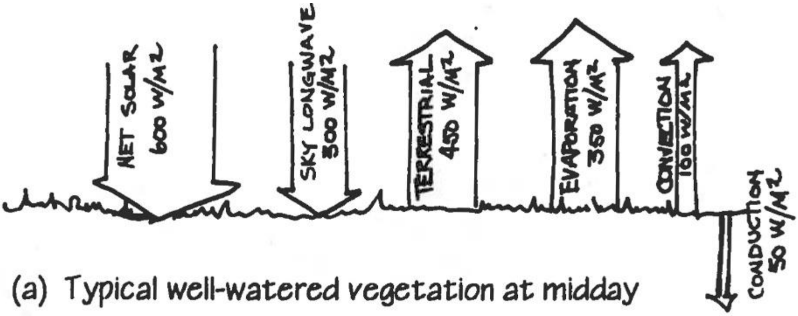
Summary

Working within the framework of an energy budget can help us to design site microclimates that meet target specifications. An energy budget considers the major suppliers and consumers of energy at a site: absorbed shortwave and longwave radiation from the sun, sky, and objects overhead; conduction into site objects; evaporation; and convection of heat from site objects into the wind. **A stable microclimate is achieved only when the energy suppliers and consumers are balanced.** Figure 3.6 shows the energy budget components for several noon and evening situations often encountered at landscape sites.

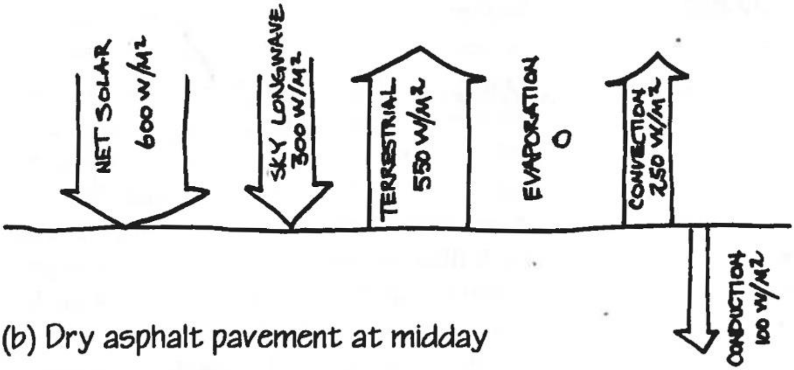
We can strongly influence the incoming shortwave and longwave radiation by adding shade. Shade will **decrease** the intercepted solar power, but **will increase** the incoming longwave radiation, since trees and other shading objects are better emitters of longwave energy than the sky. The net result is still a decrease in total radiant energy input. We can also influence the effect of solar radiation by changing the amount of reflection that occurs, through appropriate choices of object albedos.

In addition, we can manipulate the **partitioning** of energy among the various consumers. If some consumers are enhanced/restricted, then less/more energy must flow through the other consumers. For example, objects are forced to emit longwave energy according to their temperature, and the partitioning principle says we can increase this consumption by shutting down energy pipelines to other budget components. If we choose to restrict conduction into substrates and to prevent evaporation, surface temperatures of site components will rise, because stronger longwave losses must occur.

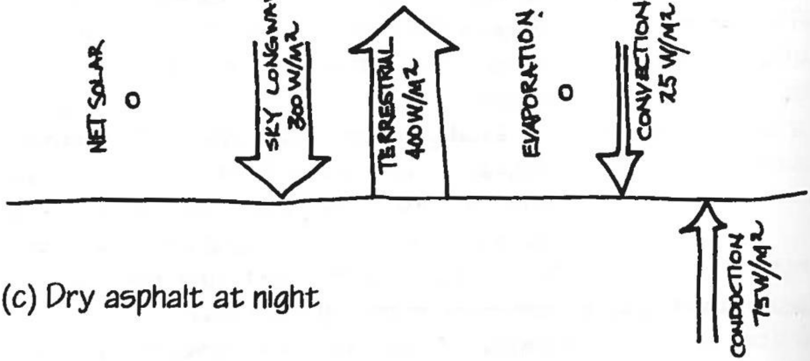
FIGURE 3.5. These graphs illustrate typical partitioning of energy over different landscape surfaces at noon and during the evening. Note the relative magnitudes of the energy flows through the various channels depicted as the width of the arrows.



(a) Typical well-watered vegetation at midday



(b) Dry asphalt pavement at midday



(c) Dry asphalt at night

Conversely, we could choose substrates with high thermal conductivities that carry energy away to deeper reservoirs. We may wish to bring this heat back for later use to keep a rock garden free of early fall frost, or to heat a solar house on a cloudy day. We might also lock up energy in the invisible evaporation of water, which is a potent consumer. Either of these partitionings can lower surface temperatures (and, therefore, longwave emissions) if this is our objective.

Finally, we can influence the rate at which energy is convected into the air by modifying the wind or surface roughness and, hence, changing the turbulence. At night, convection can become an energy supplier if the local surfaces cool below the regional macro-scale air mass temperature.

In following chapters of this book you will see that creating energy budgets, modifying radiant energy streams, and manipulating energy uses among several potential consumers are recurring problem-solving techniques. These techniques will be applied to human comfort, energy conservation in buildings, and a variety of other landscape design situations. Real-life design problems are necessarily more involved than the basic examples we have used in this chapter, but the energy budget principles stand firm. These concepts provide a robust framework for rationally creating site microclimates that meet specified design targets.

Things to think about . . .

1. **Think back to the tennis court you were asked to design in Chapter 1, question 3. Describe the energy budget of the asphalt surface of the court. On a sunny day, would the surface of the tennis court be warmer or cooler than the grassy areas in the park? Why? What is the difference in energy budgets between these two areas? Consider the air temperature at the chest height of people playing tennis. Would the air in the tennis court be warmer or cooler than the air at the same height over the grass? What if it was a very windy day? A very calm day?**

2. **Recall the hot parking lot described early in Chapter 1? Why was it so hot, and why did it feel so much cooler under the trees in the park? Describe the differences in the energy budgets of these two places.**

3. **Could you design a parking lot that would be cool even on a hot day? What components of the energy budget could you manipulate? Which would have the greatest effect for the least effort?**

4. **Could you design an outdoor area that would remain comfortable for evening use, despite the usual trend of cooling at night?**

5. **On which components of a microclimate do you think you can have the greatest effect through landscape design? Which components do you think you cannot affect very much through design?**

6. **What do you think about applying the concept of energy budgeting to a person? Could it work? What would it provide for you? What if you evaluated the energy budget of a person and found that there was a large surplus of energy? What would this say about the person's thermal comfort? How could you improve this person's comfort at a particular site?**

4

Human Thermal Comfort

■ **ONE OF THE MAIN** reasons for considering microclimate in landscape design is to create thermally comfortable habitats for people.

Introduction

We now understand how many visits of large, traveling pressure systems combine to produce regional-scale macroclimates. The of microclimates that are thermally comfortable for the people who will inhabit and use the sites. Sometimes it is important to design areas that are "generally" comfortable, so that no matter what the season or atmospheric conditions they will be reasonably comfortable. There are other times when it is more appropriate to design very specific conditions for particular activities, time of day, and season of the year. It is also important to be able to estimate ahead of time what effect a design will have on the thermal comfort of people using the particular landscape.

One approach to design for human thermal comfort is to take three steps: (1) understand the mechanisms by which landscape affects microclimate, (2) gain an understanding of microclimate conditions that can be considered thermally comfortable, and (3) connect these two ideas to create an understanding of how landscape design affects thermal comfort. Chapter 3 outlined the first step; this chapter provides you with details of the second step, as well as an overview of the third. Future chapters will provide further details.

As we discussed in the opening section of this book, some microclimates are inherently comfortable, while others are inherently uncomfortable. The important points in this chapter are:

■ 1. The "energy Some components of the microclimate can be modified through landscape design.

2. Microclimate affects human thermal comfort. Therefore, landscape design can significantly affect the thermal comfort of people in the landscape.

Thermally comfortable habitats can be created through an understanding of (1) which microclimatic elements (e.g., wind, air temperature) affect human thermal comfort, and (2) how landscape elements (e.g., trees, water) affect microclimate.

Measures of Thermal Comfort

Everyone has a lifetime of personal experience with thermal comfort and can estimate comfort levels of an existing landscape by simply visiting the location and making a subjective judgment based on how he or she feels *at that time in that place.*

The human body is the only true "instrument" for measuring the thermal comfort of microclimates. People instantly, often without thinking, assimilate a great deal of information and make judgments about whether a place is too warm, too cool, or thermally comfortable. There is some variability among people in making these judgments, but enough similarity that the differences can be ignored when considering the comfort level of various sites. This means that conditions that are thermally comfortable for one person are likely to be thermally comfortable for most other people.

If designers are going to use themselves as "instruments" to make judgments on the thermal comfort of a landscape, that landscape must be in existence. They then need to experience it under all atmospheric conditions, yet still would not necessarily know how to modify the landscape to improve the thermal comfort at times when it is uncomfortable. This personal judgment is much more difficult when a landscape is still on the drawing board or is not yet built. A more rational, objective approach is more useful in design; one that allows a landscape to be evaluated for inherent comfort levels, modifications to be proposed and tested, and an optimal solution determined.

Designing for thermal comfort requires tools that can provide for objective assessment of the landscape and an understanding of the conditions of comfort.

Thermal Comfort Models

One rational approach to determining thermal comfort is to build or create a "model" of thermal comfort. A model is an abstract representation of reality, providing a vehicle by which phenomena may be organized and understood.

■One simple model or estimator of thermal comfort is air temperature.

It is quite predictable that as air temperature rises, people become warmer, and as it falls, people become cooler. We know from experience that this can work quite well indoors, where a temperature of 20°C is predictably quite comfortable, 15°C uncomfortably cool, and 25°C uncomfortably warm.

■Air temperature is a less reliable estimator of thermal comfort in the landscape, owing to the variability of the other atmospheric elements outdoors.

An outside air temperature of 20°C could be perceived as anything from uncomfortably warm (when there is no wind and a person is standing in full sunshine on a humid day) to uncomfortably cool (on a windy, cloudy day). An air temperature of 15°C in full sunshine could feel quite comfortable or even uncomfortably warm, whereas an air temperature of 25°C with no sunshine, low humidity, and a strong wind could feel quite cool. So air temperature alone is not a reliable measure of thermal comfort for landscape design.

The reason for this difference is that the conditions indoors do not normally include the range of microclimatic characteristics found outdoors. For example:

■ The humidity, radiation, wind, and precipitation are often strictly controlled or very stable indoors, whereas outdoors these elements are highly variable.

Because, in considering an outdoor space, air temperature is not a complete indicator of human thermal comfort, attempts have been made to include other elements within somewhat more complex models. For example, "wind chill" is a combination of air temperature and wind speed that can be used to yield an "equivalent temperature." That is, the conditions of air temperature of 0°C and wind speed of 7 m/s might "feel" like an air temperature of –13°C. On winter days this can yield a better estimate of thermal comfort than air temperature alone. Another measure, "humidex," is a combination of air temperature and humidity, two measures that strongly affect thermal comfort on summer days. Again, an equivalent temperature can be determined.

These two models are more useful than air temperature alone and can be very effective in weather forecasts, but they are limited to conditions of **discomfort** (whereas we would like to achieve **comfortable** conditions) and still do not give the complete picture.

■ **For a complete assessment of comfort there are many other elements, both microclimatic and personal, that affect thermal comfort.**

Many researchers now model human thermal comfort through energy budgets, similar to those discussed in Chapter 3. We can determine the energy deficit or surplus of any surface in a landscape, including that of a person.

■ **Human thermal comfort levels can be estimated through a consideration of all flows of energy to and from a person's body (an energy budget).**

If a person has a considerable **deficit** of energy, we might guess that he or she would be too cool, whereas a **surplus** would suggest that the person would be too warm. To make this measure comprehensive, all flows of energy to and from a person must be considered.

Energy Budget Models of People

A person in the landscape can be considered to be thermally comfortable when the energy received nearly equals the energy lost.

■ **The main sources of energy available to heat a person are metabolic energy (generated within the body) and radiation (from the sun and lost from all objects on earth). The main ways in which energy can be from a person's body are through evaporation (due to perspiration), convection (due to the wind), and radiation (see Figure 4.1).**

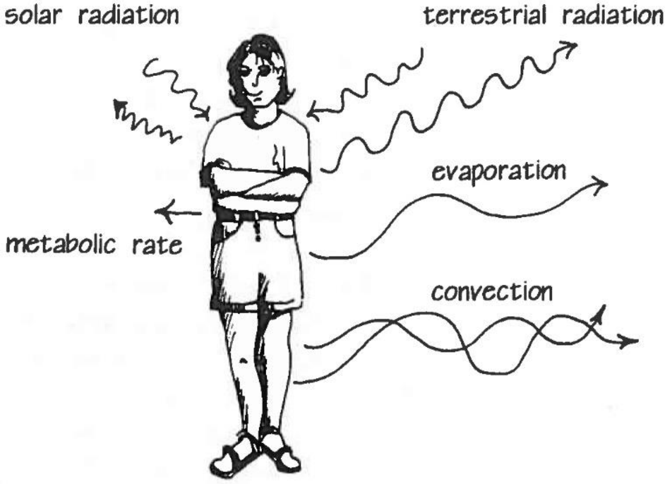


FIGURE 4.1. An energy budget of a person considers all streams of energy to the person and all losses of energy from the person. If the energy balance is positive the person will become overheated; if the energy budget is negative the person will become underheated. If there is a balance of energy, the person will be thermally comfortable.

When all of these "streams" of energy are considered, they form an **energy budget,** similar to the energy budgets discussed in Chapter 3, and can be written as:

■ **Budget = metabolic energy + solar radiation gained**
+ terrestrial radiation gained - evaporative heat loss
- convective heat loss — terrestrial radiation emitted.

The **metabolic energy** created by a person depends on activity level. For example, if you are sitting in a comfortable chair while reading this book you will be generating about 90 watts of energy per square meter of surface area of your body (we normally represent this as 90 W/m^2). We use the notation "per square meter" because there is considerable variability in the surface areas of people.

If you are walking around reading this book (a potentially dangerous activity), you might be generating about 120 W/m^2. Someone playing tennis could be generating somewhere around 400 W/m^2. The heat that is generated becomes an essential part of the energy balance.

Your activity level can substantially affect your comfort level. Think of microclimate conditions that are quite comfortable for strolling. If you stopped for a game of tennis, you would soon find that these conditions provide a surplus of energy for your energy budget and you would feel too warm. You have the option, possibly, to remove some clothing to reduce your insulating layer, but you might think that the tennis court should have a different microclimate than the walking paths.

Energy gained through metabolism is an important consideration in design for human thermal comfort. We know from expected activities how much heat people will be generating, and we can design the microclimate appropriately.

The energy received as **radiation,** whether from the sun or from objects on earth, is either absorbed or reflected by your body and your clothing. Terrestrial radiation is very efficiently absorbed, so most terrestrial radiation received by your body is absorbed. Solar radiation is much less efficiently absorbed, and the color of your clothing can significantly affect the amount of radiation absorbed and thus available for your energy budget. The lighter the color of the clothing, the more radiation is reflected; and the darker the color, the more is absorbed.

Landscape design cannot influence the color of clothing worn by people, so this variable simply must be considered as input for our consideration. What we can do through landscape design is influence the amount of solar and terrestrial radiation in a landscape. On a clear, sunny day a person could receive as much as 1,000 W/m^2 of radiation from the sun!

Energy lost through **evaporation** can occur through normal breathing as the moisture in the lungs evaporates, and evaporation of perspiration on the skin. Water requires a large amount of energy to turn from liquid to vapor phases (evaporate), so it has the potential to create significant cooling. In practice, however, this tends to happen only in conditions of low humidity and high temperatures.

The air can hold only a certain amount of water vapor, and this amount is dependent on its temperature. The higher the temperature, the more water vapor it can hold. Water will evaporate from a person's surface only if there is available "room" for it in the air. When the temperature is high and humidity is low, there is considerable room for water, and perspiration will evaporate readily. When the air temperature is low, or the humidity is high, there is much less room for vapor and perspiration may not evaporate, or may evaporate very slowly. This would provide little cooling of a person's skin.

When wind carries heat away from a person, the process is called **convection.** The amount of heat carried away depends on the temperature difference between the person and the air, and on the speed at which the air is moving. A simple equation can help to explain this relationship:

Convection is a function of wind speed (W) and temperature (T) difference between a person (T_{skin}) and the air (T_{air}):

$$C = f(W) \times (T_{skin} - T_{air})$$

You might notice the similarity between this equation and the representation of convection from a surface that was introduced in Chapter 3 (see page 56).

If the wind speed increases, the convection also increases. If the temperature difference between the surface of a person and the air increases, the convection also increases. An interesting result of this simple equation is that if the surface temperature of the person is the same as the air temperature, the convection becomes 0 and no cooling occurs.

■ There are other things that affect human thermal comfort, but these cannot be controlled or affected by design.

Some of the other factors that affect thermal comfort include the clothing worn by a person and the posture of the person (standing vertically or reclining on the ground, for example). Other potentially significant effects can be the result of what the person had been doing just before arriving at the landscape in question (e.g., swimming in cold water, or running in full sun), the amount and temperature of food recently consumed, and so on. These factors should be considered but cannot be controlled through design.

Effects of Landscape on Thermal Comfort

The five main streams of energy identified in the energy budget are affected mainly by humidity, air temperature, wind, and radiation. Of these four elements, two cannot be modified by landscape elements enough to affect human thermal comfort (see Figure 4.2).

Humidity

■ The humidity in any part of a landscape is very likely to be nearly identical to the humidity anywhere else in the landscape.

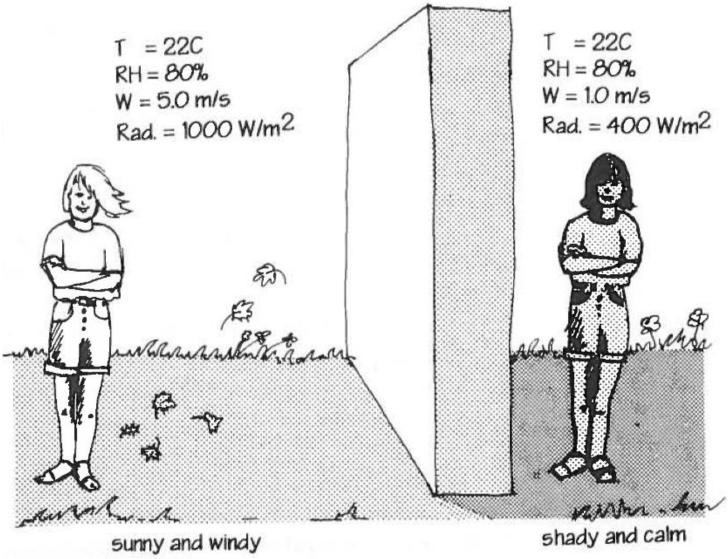


FIGURE 4.2. Of the four main microclimate elements that affect the 6trearno of enemy into and away from a person, only radiation and wind can be significantly modified by a landscape. These are the key elements in designing outdoor environments for human thermal comfort. Note that air temperature and relative humidity are not modified by the landscape.

This is due to the very efficient mixing of air as the result of turbulence. If we cannot affect humidity through design, then we can concentrate our efforts elsewhere. There are some special cases, however:

■ **When humidity is high, evaporation accounts for only a very small part of the energy loss from a person. It Is only when humidity is low and air temperature is high that evaporation can cause significant cooling in a person.**

In special cases, in which a landscape is isolated from the surrounding environment by solid walls, humidity can be artificially raised or lowered.

Air Temperature

■ **The temperature of the air, measured at any given height above the ground anywhere in a landscape, will be nearly Identical to the temperature at that same height anywhere else in the Immediate landscape at the same time.**

This is also due to the efficient mixing of air. There are temperature differences **with height** above the ground, or vertical temperature differences, but there are virtually no horizontal temperature differences.

Recall the discussion in Chapter 1 of the strong difference in microclimate between the parking lot and the area under the tree on a hot sunny day. This variation was **not** due to a difference in temperature. The air temperature experienced by a person would be very nearly the same in both of those places (barring some unusual circumstances that we will discuss in Chapter 8). The difference in thermal comfort was largely due to differences in the amount of solar radiation received by the person, and partly due to the amount of terrestrial radiation received from the ground surface.

■ Air temperature strongly affects thermal comfort, but cannot be affected very much through landscape design.

Wind

The speed and direction of wind in a landscape can be highly variable, both through space and over time. It can strongly affect the thermal comfort of people in the landscape, and can also be significantly affected by the elements of the landscape. It is one of the key elements in landscape design for thermal comfort.

The effects of landscape on wind are discussed in detail in Chapter 7.

Radiation

Radiation, both solar and terrestrial, can be highly variable, both through space and over time, and can also strongly affect the comfort of people in the landscape. Radiation is significantly affected by elements of the landscape and is one of the key landscape design elements in considering thermal comfort.

Radiation and how it can be affected by microclimate are discussed in detail in Chapter 6.

■ The microclimate components that can be modified through design and that strongly affect thermal comfort are wind and radiation.

This is certainly one of the key points in the whole area of creating microclimates through landscape design. There is no sense in spending time and energy attempting to alter air temperature or humidity in an area when this is both very difficult and of no particular value. It is much wiser to spend time altering the radiation and the wind, both of which are readily changed and can significantly affect human thermal comfort.

Applying Thermal Comfort to Design

When it comes to applying thermal comfort information to landscape design, there are several levels of application available. The first level can be achieved with the basic information in this chapter. There are two or three fundamental rules that can be used in everyday design. Start with the notion that:

■ **The purpose of design is the thermal comfort of the majority of people the majority of time.**

There is an overwhelming amount of detail that could be dealt with, and a great deal of slight variation among people, but look past all that detail and variation and think about the big picture and the majority of people. Once the big picture is resolved you can deal with specific cases.

Next, consider the **season of the year**. During the summertime, air temperature can be quite similar to the surface temperature of a person. The heat lost by a person to the wind through convection is strongly influenced by the difference in temperature between the person and the air. In fact, if the air temperature is higher than the surface temperature of a person, convection can actually heat a person. To prove this, go into a sauna where the air temperature is considerably higher than your skin temperature. Hold up your forearm to within about 10 centimeters of your mouth and blow on your skin. It will feel quite hot. It isn't that your breath has become hotter, only that you are moving very warm air past your skin and it is adding heat to the skin. This is an example of wind doing the opposite of cooling your surface. (If you check the equation for convection you will see that it predicts this result—the cooling becomes negative and turns into warming).

In winter, when air temperature can be **considerably** different from a person's surface temperature, the cooling available through the wind is maximized. If you have experienced very cold days outdoors, you know that even the slight breeze generated by your own movement can be uncomfortably cold.

If we abstract this concept to landscape design, we can say

■ **In overheated periods (e.g., summer) wind is not a major consideration in designing for thermal comfort.**

During these periods, when a person's body temperature is very nearly the same as the air temperature, wind is a very inefficient vehicle for cooling a person.

■ In underheated periods (e.g., winter) protection from the wind is the primary consideration in designing for thermal comfort.

The cooling power of wind depends on the temperature differential between a person and the air: the larger the temperature difference, the higher the cooling power of wind. In winter this differential is its highest, so controlling wind is the most important consideration in human thermal comfort.

The other main consideration in designing for thermal comfort is solar radiation. Unlike wind, the amount of solar radiation received in a landscape is not affected by air temperature; rather, it strongly influences the surface temperature (as you may recall from Chapters 2 and 3). The amount of solar radiation received is controlled by the angles between the sun and the earth. In summer the angle of the solar radiation received is much more nearly vertical to the ground surface, while in winter the angle is much less vertical.

Something to keep in mind, however, is that the sun does not "know" what season it is on earth (if you can allow this small anthropomorphization), so it is emitting radiation quite consistently whatever the season. This means that 400 W/m^2 of radiation received in winter delivers the same amount of energy to a person that 400 W/m^2 does in summer. So, relative to convection, radiation is quite consistent in its effect on thermal comfort throughout the seasons. What this means for the design of thermally comfortable places is:

■ In overheated periods, design primarily to control for solar radiation. Control of the wind is a secondary consideration.

In overheated periods, solar radiation can be quite intense and create a significant input to a person's energy budget. This effect can be very significant and you can have a major influence on thermal comfort by controlling solar radiation.

■ In underheated periods, design primarily for control of wind and convection. Control of solar radiation is a secondary consideration.

Solar radiation is generally a much less important factor in winter. Design primarily to lower wind speeds and don't worry much about solar radiation.

At other times of year this distinction between sun and wind is not as clear. Often they will be of nearly equal importance, so:

■ **When designing an area for spring and fall use, consider solar radiation and convection as nearly equal priorities. As general rule, however, control wind first, then provide solar access.**

To see whether these principles make any sense to your own personal comfort instrument (i.e., your body), recall the hot summer day discussed in Chapter 1 when you were trying to cool yourself in the parking lot. People often dream of cool breezes, but if the air temperature was very high, a wind might have been rather aggravating to you while you were standing in the blazing sunshine. Once you moved into the shade under the tree, a wind might have felt cool and been quite effective in helping you achieve thermal comfort. Now recall the cold winter day (again in Chapter 1). While you were walking down the street on that windy day, you would not have been concerned about whether you were in sunshine or not. However; once you stepped into the bus shelter and were out of the wind you might have begun to notice whether you were in sunshine. A bit of sunshine when you are out of the wind could warm you quite nicely.

Applications

Some examples of how these simple guidelines can be implemented may help to illustrate their effectiveness.

Summertime Use

Consider a restaurant in which the proprietor likes to have tables and chairs outdoors during the lunchtime period in summer. This is the period of most intense solar radiation and nearly the highest air temperature of the day (it normally peaks in midafternoon). The guidelines would suggest that the major concern is in reducing the amount of solar radiation received by the patrons. This allows a designer a tremendous amount of flexibility in design elements, from large umbrellas or overhead structures such as trellises covered in vines, to shade trees or siting the outdoor area on the north side of the building. As long as it is very clear what the problem is, a creative solution is quite possible.

Wintertime Use

Consider a restaurant at a ski resort in which the owner likes to have tables and chairs outdoors at lunchtime during the ski season. People can be quite thermally comfortable eating outdoors during the winter if the basic guidelines are followed. First consider the prevailing conditions. People are more likely to eat outdoors on days that are clear and sunny. A check of the weather records (using "conditional climatology" as described in Chapter 2) for the ski resort area might reveal that on clear, sunny winter days the wind is normally from the north and northwest. This would suggest that a designer should provide a shelter from those winds. Evergreen trees, shrubs, structures, or siting of the eating area may accomplish this objective. Once the shelter is in place, the location should also take advantage of solar radiation by orienting the lunch area to the south and ensuring that nothing obstructs the sunshine's entry into the place.

Again, a tremendous amount of flexibility is available to the designer as long as some very simple rules are followed.

Spring and Fall Use

Consider an outdoor cafe that caters to a college crowd and is concerned with spring (before everyone leaves) and fall (when everyone arrives back). If we address the lunchtime period, we have to consider wind and sun nearly equally. If we attempt to resolve the wind situation first, we need to look at the weather records to see what wind directions can be expected with sunny days. Whatever they are, provide shelter from them with vegetation or appropriate structures. Then consider providing unobstructed access for the sun. Spring and fall can be quite variable and some days may be underheated, while others are overheated. Therefore, it may be best to provide flexible solar control through the use of umbrellas or other structures such as trellises, that patrons can control themselves.

Detailed Analysis of Comfort Using a COMfort FormulA (COMFA)

For many applications, the general discussion provided in this chapter will be sufficient. However, there are situations in which a more detailed analysis of thermal comfort may be appropriate. For these applications we have developed a computer model that we affectionately call COMFA (from COMfort FormulA). It is based on heat budget equations that describe more completely the flows of energy to and from a person in any landscape. If you are not mathematically inclined you might prefer to skim this section without working through all the equations. However, the approach to the modeling and the discussion should be helpful in understanding how a person's thermal comfort is affected by a landscape.

A complete listing of the equations has been provided in Appendix A. It is presented in BASIC computer language so it can be typed directly into most computers or readily translated for use in most programmable calculators. We outline the main components of the model here and discuss a sample application.

The fundamental equation for COMFA is similar to the energy budget of any surface in the landscape (see Chapter 3). We simply have to add some components to describe the ability of people to generate their own internal heat, and to wear clothes that will buffer the gains and losses of energy by their bodies. Our main COMFA equation, then, is:

$$\text{Budget} = R\text{abs} + M - Conv - Evap - TR\text{emitted}$$

The components of the equation are as follows:

$R\text{abs}$ = the total amount of solar and terrestrial radiation absorbed by the person.
M = the amount of heat generated within the person, the metabolic energy.
$Conv$ = the heat lost (or gained) through convection by the wind.
Evap = heat lost through evaporation of water from a person, either from the lungs through respiration or by perspiration through the skin.
$TR\text{emitted}$ = the terrestrial radiation emitted by a person.

Consider the design of a sitting/eating area in a theme park. Our clients want the tables to be in the most comfortable microclimate le possible. We begin by determining how much metabolic energy people would be expected to be generating while sitting and eating. From Table A.1 we can see that we could use M = 90 W/m^2.

The second request from COMFA is for information on the values of people's clothing. Table A.2 lists the insulation value ($r$co) and permeability (P) for typical ensembles of clothing. Considering a summertime situation we might expect that people will be wearing ensemble B, so we input values of $r$co = 75 and P = 150.

Next we input typical meteorological values for the time of day and day of the year that we are interested in testing. We know that we can use air temperature (*T*) and relative humidity (*RH*) values as recorded at a nearby weather station, so we will use T = 28°C and RH = 75%.

Radiation can be dealt with very simply or in a more complete manner. Typically, we would have to consider the solar radiation arriving at the landscape and calculate how much is reflected, absorbed, and transmitted by landscape elements, ultimately determining how much solar and terrestrial radiation would be absorbed by a person in that landscape. We have included in Appendix B four approaches to the determination of radiation received by a person in the landscape. In this case we will use the approach described in Appendix B.1.

In our example we will consider clear sky conditions with a solar radiation measurement of 900 W/m^2 and a solar elevation of 45°. We will first consider a situation with no trees or structures intercepting solar radiation. From Appendix B.1 we calculate that the radiation absorbed by a person, Rabs, under those conditions would be approximately 514 W/m^2. For later considerations let's also calculate Rabs under the shade of (1) a tree casting a "light" shade, allowing 50% of solar radiation to reach the person under the tree, and (2) a "heavy" shade, where only approximately 20% of the solar radiation is able to reach a person. Rabs for the light shade tree would be approximately 441 W/m^2, and for the heavy-shade tree about 412 W/m^2.

Wind is very difficult to calculate accurately in complex landscapes, but there are some fairly effective means to estimate wind speeds. The first simply recognizes that the wind at a weather station is measured at 10 m above the ground, whereas we are interested in wind speeds at about 1.5 m above the ground. Because we know that wind speed increases with height, we can write an equation that describes the wind at 1.5 m based on a measured wind at 10 m (see Appendix C).

Given a measured wind of 5 m/s at 10 m above the ground, we calculate that the wind at 1.5 m above the ground would be approximately 3.6 m/s.

When we input the values for *R*abs (for full sun) and W (for full wind), COMFA calculates that the energy budget would be approximately 150 W/m^2. We can see from Table A.3 that the area would be considered very uncomfortably warm. This provides us an opportunity to see how effective shading is in improving the situation.

Let's try putting the person under the light shade of a tree with high permeability, thus modifying the *R*abs so that the person's energy budget is now 78 W/m^2. This represents a significant improvement, as the person is much more nearly comfortable. If we instead use the heavier shade calculated earlier, the resultant budget becomes 49 W/m^2 and we could now expect that people would be either comfortable or just slightly too warm under these conditions.

You can begin to see how powerful a quantitative model can be. COMFA can be built into an interactive computer system that allows you to move landscape elements at will and then test how comfortable people would be in those new environments. You can design with all your creativity, and then see whether there are small modifications that can be made to improve the comfort level.

Summary

Human thermal comfort is one of the most important considerations in designing landscape microclimates. If an area is to be used primarily in the summer, design to control the solar radiation first, then consider the wind. If an area is to be used primarily in fall, winter, and/or spring, design to control the wind first, then consider the solar radiation.

Things to think about . . .

1. **It is midsummer and you hear the humidex reading on the weather forecast. Do you think this gives you a complete picture of the comfort conditions everywhere outdoors? Can you suggest something that could be added to make it more complete?**

2. **Now consider a midwinter situation. You hear the wind chill index on the weather forecast. Do you think it gives the complete picture? Can you suggest something to make it more complete?**

3. **Consider once again the design of the courtyard in question 1, Chapter 1. How would your process of design include human thermal comfort? What are some solutions that you would suggest? Are they different from those you suggested in Chapter 1? Why?**

4. **In designing the deck in question 5, Chapter 1, did you consider human thermal comfort? Would you change your suggestion now?**

5. **You have the job of siting a volleyball court somewhere near a beach. What are the differences in the comfort needs of sunbathers and the volleyball players? Would the differences be significant enough to warrant different locations for the two activities? Are there any other facilities or microclimates that you might want to provide nearby the beach or the volleyball courts?**

6. **You have been asked to suggest the best location for an outdoor skating rink. There is a neighborhood group that wants to build and maintain one in the local city park. What site characteristics would you look for in deciding on the best spot? Would the microclimatic needs for maintaining ice be the same as those for keeping people comfortable?**

7. **The city has decided to construct a multipurpose hard surface trail through a city park. You would like to accommodate as many different types of users as possible. What site characteristics would best suit people who are strolling? Jogging? Running? Cycling? What about these characteristics in different seasons? Can everyone be accommodated equally?**

5

Energy Conservation in Buildings

■ **AN IMPORTANT** reason for considering microclimate in landscape design is to minimize the amount of energy required to heat and cool buildings in the landscape.

Introduction

Design with microclimate can save significant amounts of energy used to heat and cool buildings. When energy sources are inexpensive and readily available, people tend to develop homes that are neither well insulated nor energy efficient. As nonrenewable energy sources such as petroleum and natural gas become depleted, availability will fall and costs will rise. Energy-efficient homes will become increasingly essential over time. This issue was extremely important in the 1970s during the so-called energy crisis and will likely become very important again in the future.

Houses can be built to be highly energy efficient. Large amounts of insulation in walls and ceilings and airtight construction can reduce heat loss to very low levels. Strategically placed windows can provide solar heating during sunny, cool weather. However, the majority of houses in northern latitudes have relatively low levels of insulation, leaky joints between walls and windows and around doors, and poor solar access. These buildings can benefit greatly from the modification of the surrounding microclimate.

■ **Landscape design can significantly affect the amount of energy used to heat and cool buildings.**

The amount of energy reduction due to landscape-modified microclimates is dependent on the construction of the building: Well-insulated, airtight buildings will benefit the least, while poorly insulated, drafty buildings will benefit the most.

As mentioned in the discussion on human thermal comfort, there are many approaches to designing landscapes for energy conservation; however one approach appears to be the best:

■ **Energy efficient environments for buildings can be created through an understanding of (1) which microclimate elements affect energy use, and (2) how the landscape affects microclimate.**

The most efficient way to approach design for energy conservation is to first gain an understanding of the microclimate elements that most significantly affect energy use. This allows you to ignore elements that do not have much effect on the building energy budget. Second, you should gain an understanding of the elements of the microclimate that can be affected by landscape. We are already familiar with these elements as they influence human thermal comfort, and the effect for buildings is essentially the same (but not exactly).

Energy Budget Models of Buildings

As we have seen in Chapters 3 and 4, energy budgets can be modeled for any surface or element in a landscape. This is an efficient and rational approach to understanding flows of energy to and from a surface.

■ **Building energy use can be estimated through consideration of all flows of energy to and from a building (an energy budget).**

We can write an equation that describes the different flows into and away from a building (see Figure 5.1).

$$\text{Budget} = \text{Net Radiation} + \text{Internal Heat} - \text{Convective Heat Loss} - \text{Conduction} - \text{Air Exchanges}$$

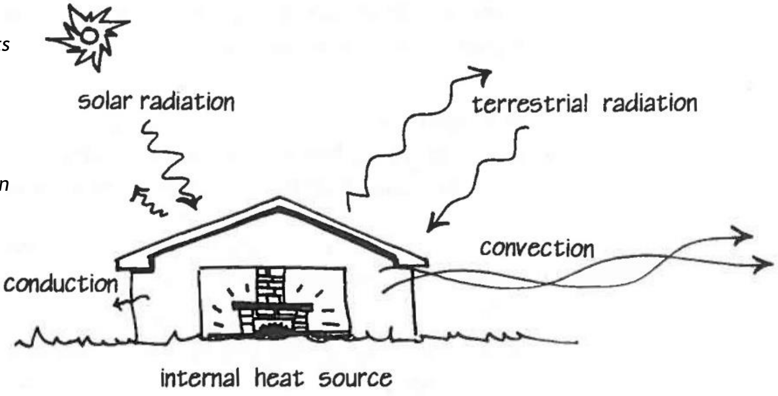


FIGURE 5.1. An energy budget for a building includes inputs and outputs of energy, similar to a human energy budget. However, some of the components are different.

Budget= net solar radiation
+ net terrestrial radiation
+ internal heat source
- convection
- conduction
- air exchanges.

■ **Whereas the result of a human energy budget is comfort level, the result of a building energy budget is the amount of energy required to maintain a set interior air temperature.**

Most buildings in northern latitudes have interior sources of heat—furnace, a fireplace, electrical heaters, or other sources. Many buildings also have means of cooling air in overheated conditions. Whatever the vehicle, the intent is normally to maintain a constant interior temperature in the building through the use of a thermostat. This instrument guarantees that the air temperature within the building will be constantly at a set value, often 18°C to 20°C.

When the microclimate around a building is very similar to the desired interior conditions, little or no extra energy is required. However, when the microclimate is significantly different from the desired interior conditions, large amounts of energy may be required. A modification of the microclimate through landscape design can reduce the amounts of energy required.

■ **Whether energy flows Into or out of a building depends on the relative temperatures of the inside and the outside. Energy will flow from areas of higher temperature to areas of lower temperature.**

■ **The streams of energy flow into and out of a building can be in either direction. That is, radiation can be received and given off. Internal energy sources can either add heat to, or remove it**

from, the building. Conduction and convection can either add heat to, or remove heat from, a building. It depends on whether the interior temperature is higher or lower than the outside air temperature.

- **Evaporation Is not normally a significant component in building energy budgets, as buildings are normally dry and do not perspire. However, in special cases it can be used to cool a building significantly.**

An example is a flat-roofed building that allows rainwater to pond on it. This can provide a source of water for evaporation and may result in reduced cooling costs for the building. Another example is a house covered in vines. As the vines grow and transpire, water evaporates and cooling occurs.

As in any energy budget model, the heat balance of a building considers the flows of energy to and from the building. The main source of heat for many personal dwellings in northern latitudes is internal, such as a furnace or a heater. The other main source of energy is radiation. When sunlight is allowed to enter a building through a window, it heats the interior of the building directly. If it falls on the walls and roof, it heats these surfaces and reduces the amount of energy lost by conduction through the sides of the building. The amount of solar radiation absorbed by the building depends on the albedo of the surfaces. Lighter colored surfaces generally reflect more solar radiation and absorb less than darker surfaces. Windows allow most of the solar radiation to enter the building and the albedo (reflectivity) of interior surfaces determines how much is absorbed and turned into heat.

Heat can be lost from a building through convection. The amount of convective heat loss is a function of the temperature difference between the building and the air, and a function of wind speed. The heat is available for convective loss by either (1) traveling by conduction through the walls, windows and roof from inside to outside, or (2) air exchange through cracks and openings around or through windows and doors. Either way, an important issue is the speed of the wind at the building. The higher the wind, the greater the heat loss. Generally, if the wind reaching the building can be reduced, the energy used by the building will be reduced.

Another means of energy loss from a building is through emission of terrestrial radiation. The real issue, however, is the terrestrial radiation balance (i.e., the difference between the amount of radiation emitted by the building and the amount received from the landscape). This amount is dependent on the relative temperature of surfaces. Generally, there is not very much radiation lost or gained by a building through the terrestrial radiation balance.

Some of the other factors that affect energy use of buildings are insulation levels, windows, and infiltration rates.

Effects of Landscape on the Energy Use of Buildings

Of the four main streams of energy affecting a building, only two are strongly affected by landscape and significantly influence the amount of heat used. As you will recall, humidity and air temperature cannot normally be significantly affected by landscape, but wind and radiation can be (see Figure 5.2).

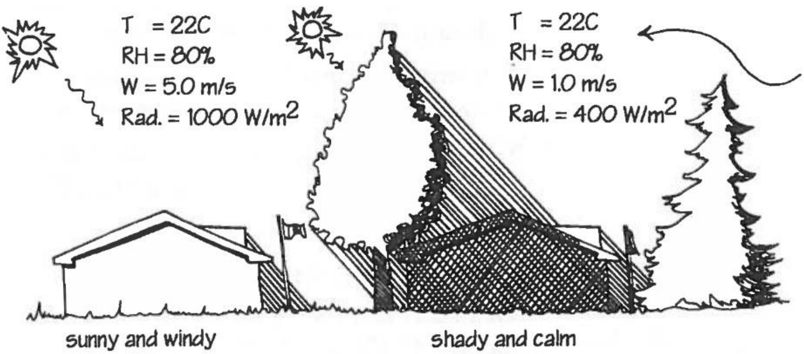
■ **As with human thermal comfort, wind and radiation can be significantly modified by landscape design and can also significantly affect the energy use of buildings.**

Applying Building Energy Use to Design

There are several general principles that can be followed in designing the landscape around buildings. As we know from other applications, these do not hold in all situations and may require modification in specific situations.

■ **The relative importance of the sun and the wind in different seasons Is not as clear for buildings as it is for people.**

FIGURE 5.2. Wind and radiation received by a building in the open can be significantly different from those received in different microclimates.



■ In considering the microclimate around people, the temperature of a person is nearly always higher than the temperature of the surrounding air. This means that flows of energy travel primarily in one direction only, which makes calculations quite straightforward and generalizations relatively simply. However, the interior air temperature of a building is often higher, and often lower, than the exterior air temperature, so energy can flow in either direction and generalizations are not so readily made.

There is also a great variety in building construction methods, materials, and workmanship. Different kinds of buildings react differently with a microclimate.

■ If a building is extremely well insulated and airtight, wind is never much of an Issue. Even under very cold conditions, wind will have little effect on the energy used. Therefore, when considering this type of housing, solar radiation becomes the key element all year round.

Some buildings are constructed to be airtight, meaning that air exchanges are tightly controlled and very little energy is lost. Whether or not the wind blows against an airtight house is of little consequence, as the amount of energy exchanged is so low. This means that during periods when the exterior air temperature is lower than the desired interior temperature (late fall, winter, and early spring) there is an advantage to allowing solar radiation to penetrate into the building through windows. During periods when the exterior temperature is higher than the desired interior temperature (late spring, summer, and early fall) there is an advantage to blocking solar radiation from entering the buildings. This can be done through a number of methods that will be described in later chapters. Among these methods are the following:

1. Planting deciduous trees strategically so that they cast shadows on windows in summer yet allow solar access when the leaves fall.
2. Using overhangs above windows so that sun can penetrate when the angle is low (winter) but is blocked when the sun angle is high (summer).
3. Installing of mobile shading devices.

There are many other possibilities that are only limited by your imagination.

■ If a building is less than extremely well insulated and airtight, wind Is probably the key element in wintertime. The landscape should be designed to reduce the speed of wind arriving at the building.

The majority of buildings in northern latitudes are not particularly well insulated, nor airtight and consequently can benefit from modification of wind near the building. A cool wind moving past a warmer building will carry heat away from the surface through the process of convection, and will cool the exterior of the building until it reaches the same temperature as the air. Much of the heat that is carried away is transported from the interior of the building through the process of conduction through the walls. The greater the temperature difference between inside and out, and the lower the insulation level, the more heat is transferred.

The other main avenue for energy loss caused by the wind is via the leakiness of the building. If cold exterior air replaces warm interior air through leaks in and around windows and doors, it requires additional input of energy to heat the new air.

The faster the wind is moving, the more efficiently it carries heat away. If we reduce the wind speed near the building, it will carry relatively less heat, and this means that less energy will be expended to heat the building. As with a person, wind becomes the key consideration in these situations, and radiation should be a secondary consideration.

■ In summer, solar radiation control is the key consideration. Design to reduce solar radiation received by a building during overheated periods.

In summer, air temperature is likely to be relatively close to the desired interior temperature of buildings, so convection is fairly inefficient. (There is an exception, however, in extremely hot conditions, where convection will actually heat a building.) Generally, radiation is a much more important consideration in summer, and solar radiation should be shaded from a building.

■ Radiation striking a building heats the exterior surface. In winter this lowers the temperature gradient between inside and outside and reduces the amount of heat passing through walls

or roofs. Therefore, design landscapes that will have full sun striking a building during winter months.

All heat sources are welcome in winter, so allow solar access to exterior walls, roofs, and, most important, to windows so that radiation can penetrate into the interior of the building and heat the living spaces directly.

■ **In summer, solar radiation striking exterior walls and the roof can cause a significant temperature difference between inside and outside and result in a large amount of heat moving through the walls into a building. Design landscapes that will provide shade on buildings during the summer months.**

As it is for people, shade is an important consideration for buildings in summertime. Recall that when the air temperature is nearly the same as the desired interior temperature, convection is a very inefficient mechanism, and solar radiation is the most important, modifiable element.

■ **In summer, the air temperature is more nearly the interior building temperature, so wind will have little effect on energy use in a building. When the air temperature is higher than interior building temperature, the wind will warm the building. The bigger the temperature difference and the higher the wind, the more heating will take place.**

There is a commonly held belief that there are "cooling winds" in summertime. As long as the wind is warmer than a building, it will heat the building. The only way a wind can be a cooling breeze is if the temperature of the wind is lower than the temperature of the building. In general, then:

■ **When designing for energy conservation of a building, provide shade on as much of the building as possible during the summer and allow the sun to shine as much as possible on the building during fall, winter, and spring. Also provide wind protection from any prevailing winter winds.**

These general rules will hold in most cases. Special cases are described in the following chapters, but in most instances these principles will serve you well.

Example Applications

■ **When designing for energy conservation, plan to have the building in full sun and out of the wind in fall, winter, and spring, and in full shade in summer (see Figure 5.3a and b).**

Year Round Efficiency

One way to achieve this is to plant deciduous trees that leaf late in the spring and drop their leaves early in fall. These trees should be on the south and west sides of buildings, but also can be on the east. Rows of coniferous trees can be planted on the sides of buildings most likely to receive cold winds in fall, winter, and spring (north, northeast, and northwest primarily).

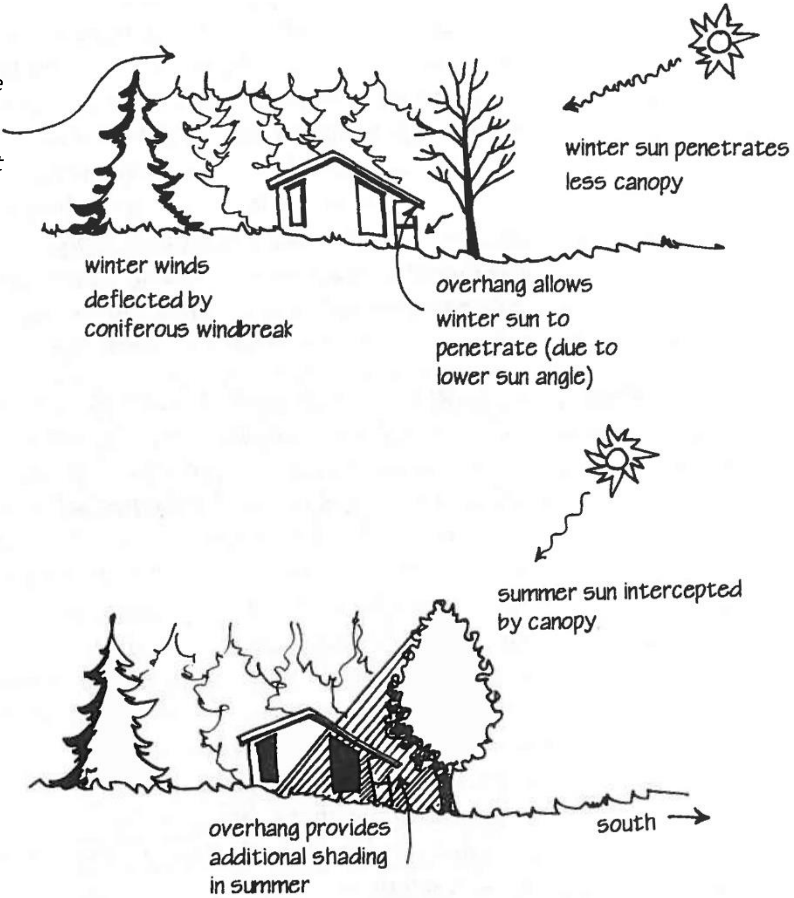


FIGURE 5.3. When designing a landscape for minimizing the energy use of a building, provide for it to be (a) in full sun but out of the wind in winter. During the summer (b) the building should be in full shade. These modifications can both be achieved through Use of deciduous trees and strategic plantings.

Summertime

Consider a house in a location where the winters are quite mild and the main energy cost is for cooling during the long, hot summers. Our main concern is for control of solar radiation reaching the house, and we have a secondary concern for wind, as hot winds could increase the heat load on the house.

The first step is to shade as much of the house as possible for the whole of the hot season. This can be done in a variety of ways, whatever would be most appropriate. Shade could be provided by the use of tall deciduous trees. Vines growing on walls could also provide shade, as well as evapotranspiration, which would create additional cooling. Shade-control devices over windows could be used to keep solar radiation out of the interior of the house.

If the exterior of the house can be kept in shade, then wind should be reduced to low levels. If the exterior of the house is in full sunshine, then wind can play a different role. Solar radiation can heat the exterior to very high temperatures, much higher than air temperature. In this case, the wind would tend to cool the surfaces to air temperature.

The albedo of the house could be changed to reduce the energy absorbed. A white exterior is much more efficient at reflecting solar radiation than is a black one, although both will absorb the near-infrared and the terrestrial radiation equally well.

WIntertime

Consider a house in a northern latitude where winters are very long and cold, and summers are short. The most important consideration in this case, besides creating a very well-insulated, airtight house, is to reduce the speed of the wind reaching the house. This may be done by first checking the climate records to see whether there are wind directions that are much more frequent than other directions. If, for example, you found that 60% of all winds in winter were from the northwest, and another 25% were from the north and west, you could control 85% of the winter winds by providing shelter from these three directions. That control could be in the form of coniferous windbreaks, solid structures, or even an alteration of the facade on the sides of the house facing these directions—perhaps coniferous shrubs next to the house, or vines growing on the exterior walls.

Once you have identified the problem, there are a wide variety of possible solutions.

Results of Quantitative Studies

Studies have shown that for a typical house in a temperate climate, energy consumed in heating the house during cool seasons can be reduced by more than 15% simply by reducing the wind speed near the house through the use of windbreaks. Substantial gains in energy input can also be realized through solar access. In some areas solar input can completely eliminate the need for additional heating sources, but in most areas it can be considered only as an inexpensive way to reduce the energy required to heat a building.

Summary

In considering the energy efficiency of buildings, many of the principles are similar to those for the thermal comfort of people. However, there are some differences, because our concern in buildings is the amount of energy required to maintain a set interior temperature, a temperature that is sometimes higher than exterior air temperatures, and sometimes lower.

■ Buildings designed for high energy efficiency will benefit least from landscape design. Older buildings, and those with low levels of insulation and high air leakage, will benefit most from landscape design for energy efficiency. Create landscapes that shade buildings in overheated periods, and allow solar radiation to reach and penetrate buildings during underheated periods. During cold periods reduction in wind is very important, while during hot periods it is often worthwhile to reduce the wind as well. Only in the special case that there is no shade on a building should wind be encouraged during hot periods.

Things to think about . . .

1. A neighbor asks you to help him reduce the energy use in his house. He wants some immediate results, but is also interested in long-term savings. What would you look for when you evaluate his house and yard? What would be the first thing you would suggest for him to do? What next? How much of an impact do you think your suggestion could have?
2. Local school board members would like to reduce energy use in their schools, but they don't want to do expensive renovations to the buildings. They ask you to assist them through landscape design. Do you think you can help? What would you suggest? Would you be prepared to offer some general guidelines that could be applied to all

the schools in the city? If so, what would they be?

3. **A developer would like to build a subdivision that she can honestly advertise as energy efficient, not only in construction but in the siting and landscape as well. What general suggestions would you make about the layout of the houses and roads to best accommodate this wish? How would individual houses be located on lots, and what landscape elements would you suggest for every house?**

4. **Members of your city council have heard that you can design subdivisions that are energy conserving through their layout. They would like to implement a by-law that requires all developers to achieve the same standards. What would you suggest to them in terms of a by-law or standards?**

5. **You have been asked to site some attached townhouses and associated parking. What are some of the considerations in deciding on which direction to orient the buildings, and what are some of the characteristics you would suggest that the buildings possess?**

6

Radiation Modification

■ **RADIATION IS** an element of every microclimate that can be significantly modified by the landscape and that also strongly affects human thermal comfort, energy use of buildings, and many other elements in a landscape. It is a very important consideration in landscape design for a microclimate.

Introduction

Radiation from the sun "drives" the weather on earth and is the fuel for virtually every microclimate. Solar radiation is one of the most important elements affecting human thermal comfort and in the energy use of buildings. It strongly affects microclimates, and it can be modified by the landscape and thus manipulated through design. Radiation (along with wind) is one of the two most important components of microclimate in the landscape.

Despite its importance, radiation often is an elusive element of the landscape. It is one of the most difficult concepts to understand and to visualize. It is important that you have a mental image of where radiation comes from, what happens to it when it reaches surfaces, and where it goes. You have been introduced to radiation in Chapter 2; now we augment that learning with a more detailed discussion as it relates to modification of radiation by landscape elements.

We begin with the basics.

■ **Everything emits radiation.**

There is a constant stream of radiation from the sun, from artificial lights, even from you and from this book. Some radiation is perceived by the eye as light, but much of it is not detected by the eye and is essentially invisible to us. This invisible radiation is very important, however, and cannot be ignored. It contains tremendous energy and can heat surfaces. For the most part, we can understand it in much the same way as we understand visible light.

It is important, first of all, to have a clear image of what visible radiation looks and acts like:

■ Radiation travels in a straight line (see Figure 6.1).

Radiation travels from its source in straight, parallel lines and doe. s not waver from this path until it is intecepted or deflected by an object. Solar radiation comes straight from the sun, and we can count on the rays being exactly parallel, so that shadows cast in one part of the landscape will be parallel to shadows cast everywhere else in the landscape.

This is a very important characteristic to be aware of. If you want to intercept radiation from the sun before it reaches a certain surface, you simply need to know the location of the sun (which we will show you how to calculate in a later section) and then put something between it and the surface. A direct beam of the sun cannot go around an object.

FIGURE 6.1. Direct solar radiation travels in straight parallel lines, casting predictable shadows.

■ **When radiation arrives at any surface, some of it may be reflected, some may be absorbed, and some may transmit through the object. Nothing else can happen to it (see Figure 6.2).**

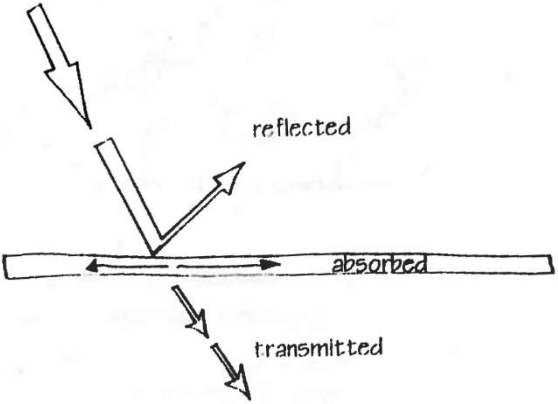
This is another very important concept. Some of the radiation that reaches a surface is normally reflected, and this is a function of the surface's reflectivity. When we discuss visible light, this is called the. **albedo** of a material. The albedos of several natural materials are listed in Table 3.1. You will notice that there is a range of values for most materials. This is due to the variability of natural elements.

The radiation that is reflected is then available to strike another surface and be similarly reflected, absorbed, or transmitted.

Normally some portion of the radiation reaching a surface is absorbed into the material. The energy from the radiation is transferred to the molecules of the material. This excites the molecules and consequently increases the temperature of the material. In opaque materials all radiation received must be accounted for through either reflection or absorption. Everything that is not reflected must be absorbed into the material.

For transparent and translucent materials there is one more avenue for radiation, and that is transmittal through the material. This radiation is then available to be received by another surface in the landscape. Natural elements that transmit radiation through them include leaves and water.

FIGURE 6.2. Radiation arriving at a surface will be reflected, absorbed, or transmitted through the surface. Nothing else can happen to it.



Types of Radiation

As mentioned earlier,

■ Radiation is normally discussed in terms of two types: solar radiation (that emitted by the sun) and terrestrial (that emitted by objects on earth) (see Figure 6.3).

This is simply a convenience for separating the two kinds of radiation. They are emitted in the same manner, they tend to move through a landscape in the same way, and all radiation has energy that it carries with it. The reason for dividing radiation into two categories is that there are some small but significant differences between the two, and these differences become useful tools in landscape design for microclimate. We may think that when we see sunshine illuminating the landscape we are seeing all of the radiation arriving from the sun. This is not the case, however, as only about **half** the total amount of radiation from the sun is visible to the human eye. The other half is **invisible**,

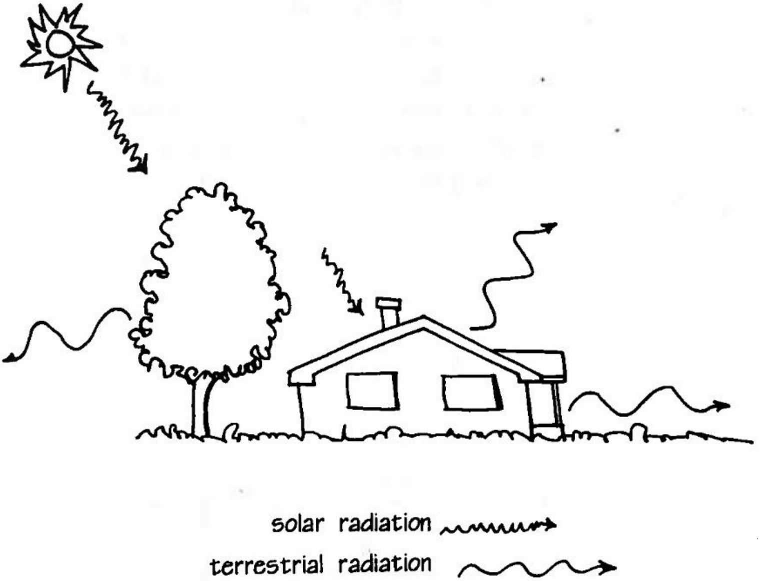


FIGURE 6.3. Solar radiation is emitted by the sun. Terrestrial radiation is emitted by everything on earth. It provides a considerable amount of energy to the landscape, but is normally nearly in balance with other objects in the landscape, so is not as noticeable as solar radiation.

yet carries tremendous amounts of energy with it. This energy can be transformed into heat, in the same way as visible light, when it is absorbed by a surface.

■ Some of the solar radiation received on earth Is visible (about half of solar radiation can be seen by the human eye as "light"), and some is invisible (about half of the solar radiation cannot be sensed by human eyes). All radiation, however, can be "visualized" or thought of in the same way as visible light.

The visible portion of radiation from the sun is relatively easy to imagine because we see it almost every day. The invisible, or **solar infrared**, portion of solar radiation behaves in much the same way as the visible portion, but there are some notable exceptions that can significantly affect microclimates. For example, most of the visible solar radiation received by a leaf is absorbed, with only about 10% reflected and 10% transmitted through the leaf. Conversely, about 30% of the solar infrared solar radiation is transmitted through the leaf, a further 40% is reflected, and only about 20% is absorbed. Physiologically this makes sense, as leaves require visible light to grow, whereas solar-infrared radiation would simply serve to heat the leaf if it were absorbed, and leaves have developed the ability to allow this unwanted radiation to be reflected or to pass through. From a landscape-microclimate point of view this is important information. Although the shadow of a fully leafed tree might contain very little visible radiation, there is probably a relatively large amount of solar infrared radiation under the tree (see Figure 6.4). This radiation cannot be seen, but certainly can be experienced by people and houses under the tree, and will provide an input to their energy budgets.

The other type of radiation in the landscape is **terrestrial radiation**, and it too is invisible to the human eye. We can use instruments to "see" or measure this radiation, so we know it is there. The amount of radiation being emitted from a surface is a function of its temperature. The surface of the sun is at a very high temperature, and consequently emits a large amount of radiation. Objects on earth emit relatively much less radiation, but because the sun is so far away the differences are not as great as we might expect. The maximum amount of radiation the earth receives from the sun, as mentioned in Chapter 3, is about 1000 W/m^2, and the amount

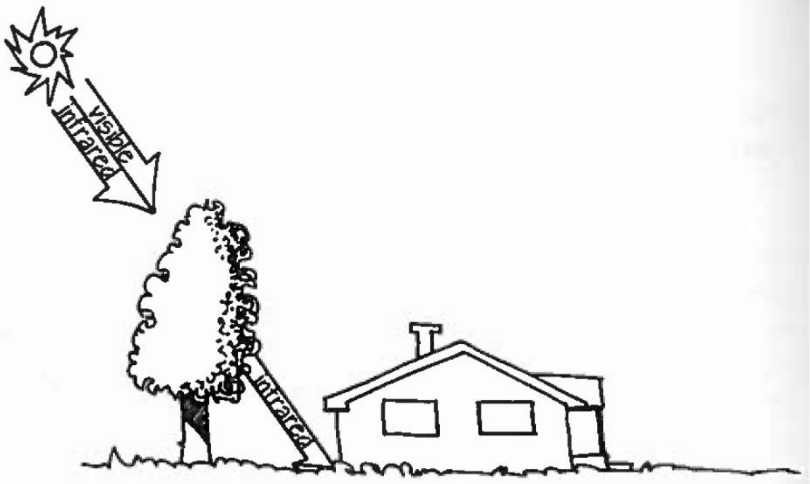


FIGURE 6.4. Very little of the visible solar radiation incident on a tree will be transmitted through, while up to 40Z of the solar-infrared will be transmitted. This means there is significantly more radiation in the shade of a tree than the eye would suggest.

that a person would receive from that, considering transmission through the atmosphere, reflection, and so on, would be about 600 W/m2. The amount of radiation you are receiving from this book is about 400 W/m2. A large difference, yes, but not as significant as one might expect. This terrestrial radiation, like the near infrared radiation, has many characteristics similar to solar radiation: it travels in straight lines, it can be reflected, absorbed, or transmitted, it carries energy that can be turned into heat, and so forth. However, it too has some characteristics that are a little different from solar radiation, which we can use to modify microclimates. The main differences are:

- **The amount of energy emitted as terrestrial radiation is a function of the temperature of the emitting object (see Figure 6.5).** The higher the temperature of the object, the more radiation is being emitted. A heated asphalt surface (one in full sunshine) emits more radiation than a cooler asphalt surface (one in the shade).

- **Most natural surfaces absorb almost all the terrestrial radiation they receive. Very little will be reflected or transmitted.**

Because all objects in a landscape are both emitting and receiving terrestrial radiation,

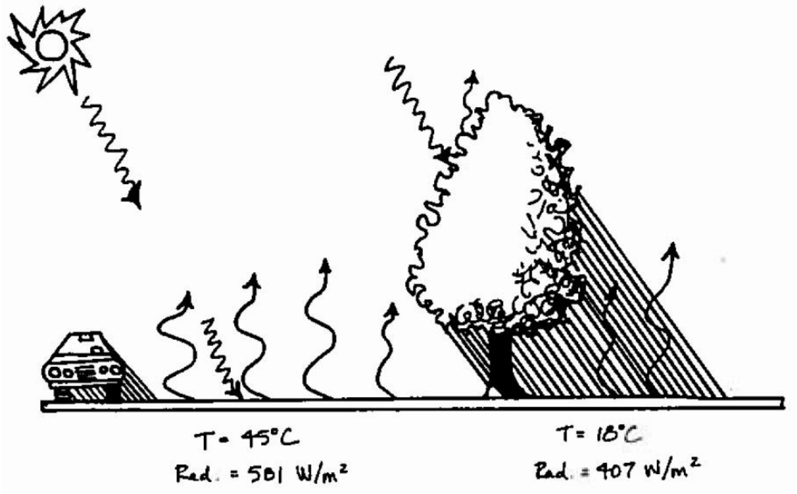


FIGURE 6.4. Surface emit radiation as a function of their temperatures. The higher the temperature, the more radiation is emitted.

■ The key is the radiation balance between the amount emitted by a person or building and the amount received from their immediate environment.

Try to visualize that this book is actually giving off radiation that is "shining" on you right now. You are also giving off radiation that is "warming" the book. Try to get an image in your mind of radiation streaming from everything. And all radiation carries energy with it that can heat objects.

One reason that most people are unaware of this pervasive radiation is that it normally is very nearly in balance. For example, the amount of radiation you are emitting toward this book is very nearly the same as the amount the book is emitting toward you. This balance of radiation results in your having no sensory perception of it. One way in which you might perceive a significant imbalance of radiation is to stand near a wood-burning stove in a cool room. Or stand near an outdoor bonfire on a cold winter day. You would feel significant heat on the one side of your body, and might be quite cold on the side away from the fire. The large imbalance of radiation is responsible for the differential heating. The side toward the fire would be receiving large amounts of radiation while giving off relatively much less. The side turned away from the fire would be emitting relatively much more than it would be receiving from the colder environment.

Another example of imbalance in terrestrial radiation may be felt by sitting near a window in a heated room when it is quite cold outside. The window surface, if not well insulated, may be considerably colder than the walls of the room. As you sit by the window, you would emit considerably more radiation to the window than you would receive from this relatively cold surface. The result might be that you feel quite chilly. People sometimes misinterpret this as a "leak" from the window, but you will perceive such coolness even when the window is tightly sealed (see Figure 6.6).

If a person is emitting more radiation than he or she is receiving from the environment, such as would be the case in an outdoor wintertime situation, then the deficit in terrestrial radiation would be a heat loss from the person. In terms of landscape design, places that are typically too cool can be made more comfortable by strategically locating sources of terrestrial radiation. An example is a transfer area

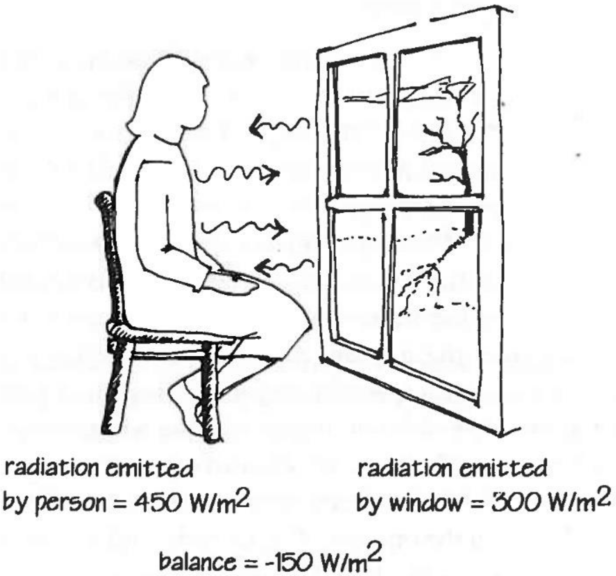


FIGURE 6.6. Normally, the terrestrial radiation balance is nearly zero, meaning that the amount of radiation received from an object is very nearly the amount emitted by another object. Sometimes there is a differential in radiation emitted, ouch as when a warm person emits radiation at a relatively high rate toward a cold window, which emits relatively much less radiation to the person. This differential in radiation can be sensed by the person and may make him or her thermally uncomfortable.

where travelers leave a train in the middle of the night and transfer to a ferryboat. I experienced this one time in traveling overnight from England to Ireland. We were half asleep and could have be England to Ireland. We were half asleep and could have become seriously chilled, as it was midwinter. The transfer area, however, had a series of radiation heaters that were turned on only when people were there. They did not significantly change the air temperature, but although we never went inside a building, we were actually quite comfortably warm because of absorption of the radiation. This is an extreme example, but it serves to illustrate that sources of heat in a landscape can affect the energy budget of people and buildings without affecting the air temperature.

You can imagine that a source of cool water, perhaps a fountain or a waterfall, can assist in cooling an overheated person through the radiation balance. In cold environments, warm surfaces emitting terrestrial radiation can add heat input to a person's energy budget. These can be effective design tools.

If we think of the energy budgets discussed in Chapter 3, we will recall that although we consider radiation as a single input, it can actually be received from many sources:

- **Solar radiation can be received as direct beam (directly from the sun, in parallel beams), as reflected radiation (after bouncing off another surface), or as diffuse radiation (reflected from the sky). Direct beam radiation travels in a straight line. Diffuse radiation comes approximately equally from all parts of the sky. Reflected radiation can be either directional or diffuse (see Figure 6.7).**
- **Almost all terrestrial radiation is received as direct beam (directly from other objects, but received from all quarters of the landscape, not in parallel beams).**
- **With both solar and terrestrial radiation, it is valuable to be able to determine how much radiation is being received and the exact location of the object emitting that radiation, be it the sun or some other element in the landscape.**

Radiation Geometry

Because radiation travels in straight, parallel lines, the geometry of radiation is fairly easily calculated and very reliable. Thus a knowledge of sun angles and some simple trigonometry can provide excellent

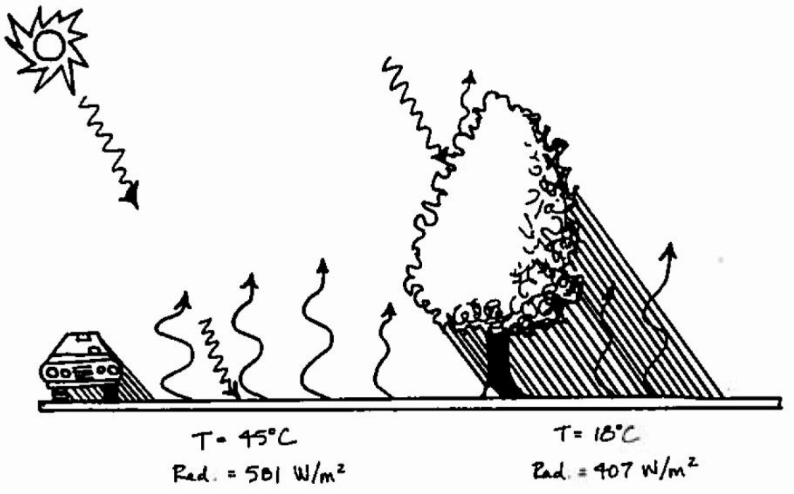


FIGURE 6.7. Solar radiation, once it reaches the earth, is split into several different components, each with distinct characteristics. Direct beam radiation is that which cameo directly from the sun. Diffuse radiation is that which has been bounced around in the atmosphere before reaching the earth. The visible portion of this is seen as blue sky by the human eye. Reflected radiation is that which has bounced off an object. ft normally travels in a straight line, unless the surface is rough and scattered the radiation. Then it behaves like diffuse radiation.

estimates of shadows cast by objects at various times of the year. Moreover, the amount of terrestrial radiation emitted is a direct function of an object's temperature, so amounts of radiation are also readily determined.

Calculating the Position of the Sun

The location of the sun in the sky at any place and at any time can be estimated either from equations or from tables and charts. We will provide you both methods. Equations are most accurate, but the charts work well for most situations.

Equations for Estimating the Location of the Sun

You can determine the altitude and azimuth of the sun in the sky at any time and at any location on earth using equations. The altitude of the sun is the vertical direction of the sun above the horizon, and the azimuth is the horizontal direction of the sun relative to some reference point. We will use the convention of South as 0°, East as -90° and West as +90° (see Figure 6.8).

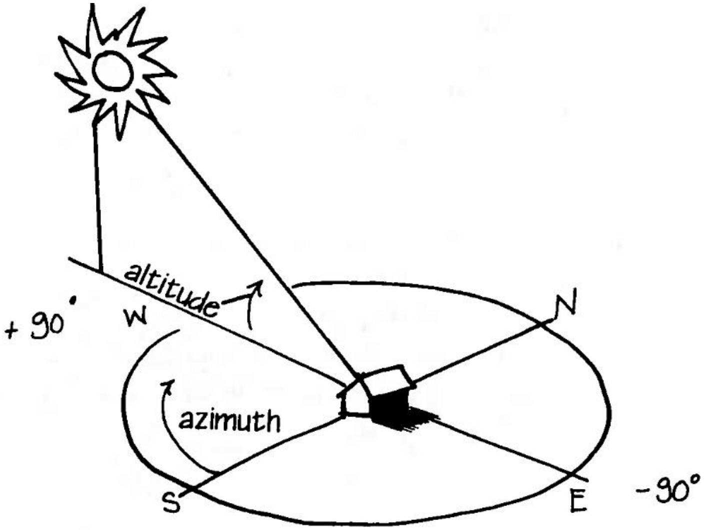


FIGURE 6.8. The angle between the sun and the earth is the altitude angle, and the bearing angle of the sun le the azimuth. These angles are constantly changing ac the earth moves around the sun and rotates on its axle, and you must know both angles in order to draw Shadow diagrams.

To determine the altitude (E) of the sun we can use trigonometric functions.

Sin (E) = sin L sin D + cos L cos D cos 15 (T - solar noon), where L = latitude of the test location (in degrees), D = the declination angle (in degrees) (see Figure 6.9), and T = the time of day in hours and decimals of hours (using a 24 hour clock). For example, if we were interested in the location of the sun at 9:30 A.M. on June 1 at latitude

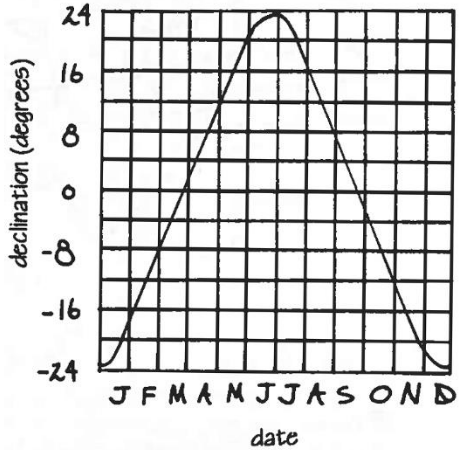


FIGURE 6.9. The declination of the sun can be read off this chart. Find the date you are testing on the bottom line and follow up vertically until you intersect the curved line. Follow horizontally from this point over to the left Side of the chart and read off the declination angle (after Marsh, 1991).

42°N, we would use the following inputs: L = 42°; D = 22 (from Figure 6.9); T = 9.5 (nine and one-half hours). Then sin(E) = 0.797 and therefore E = inverse sin(E) = 52.8° or approximately 53°.

The azimuth (A) of the sun can be calculated through:

$$\sin(A) = (\cos D)\,[\sin 15\,(T - \text{solar noon})] / \cos E$$

In our example the azimuth would be - 69.7° or approximately 70°.

Tables and Charts for Estimating the Location of the Sun

If you need to determine an approximate location of the sun at a given time at a given location, tables and charts are often accurate enough (Figure 6.10).

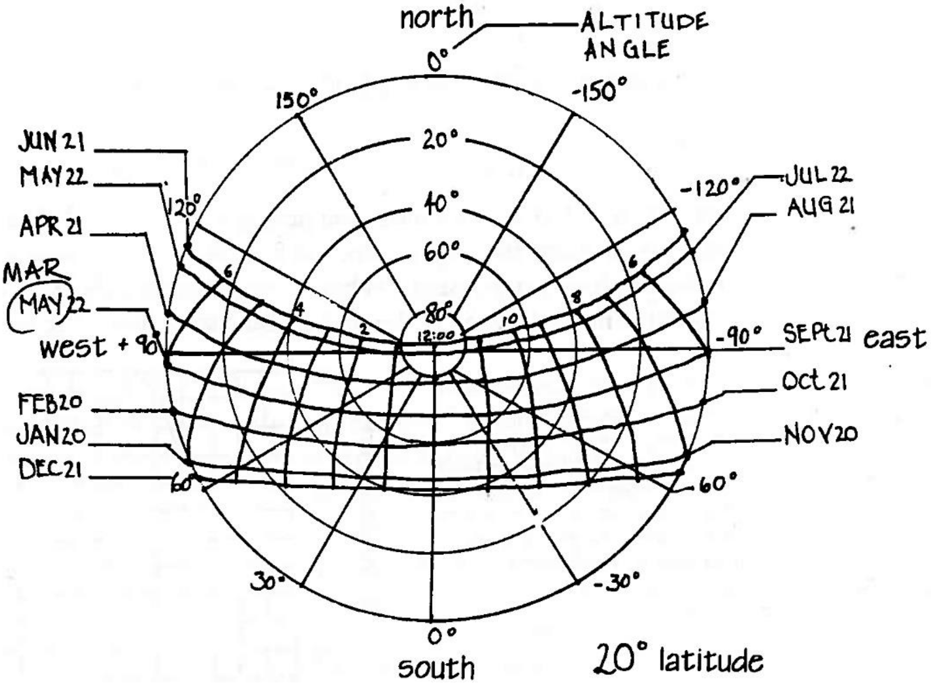
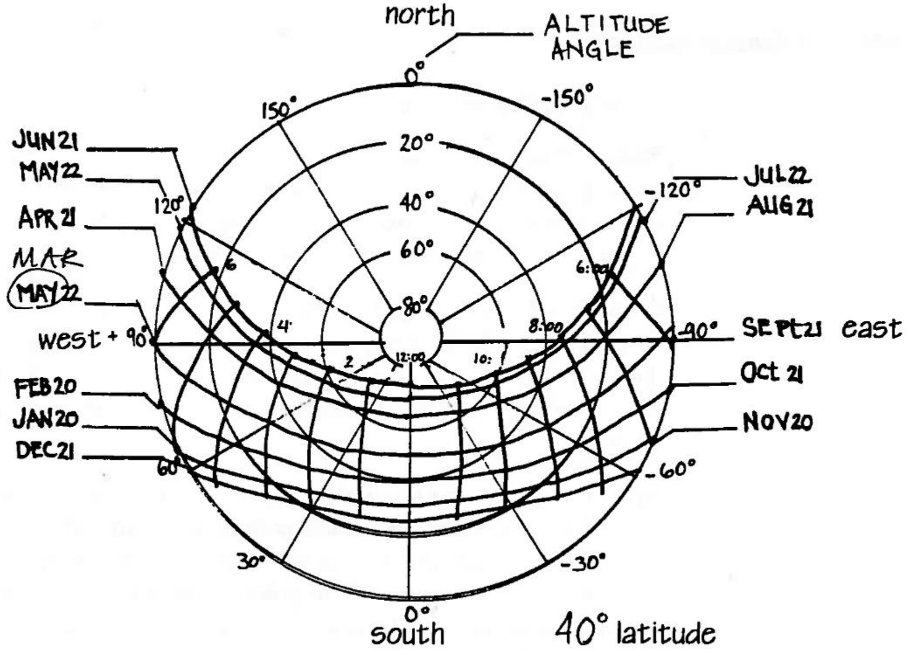
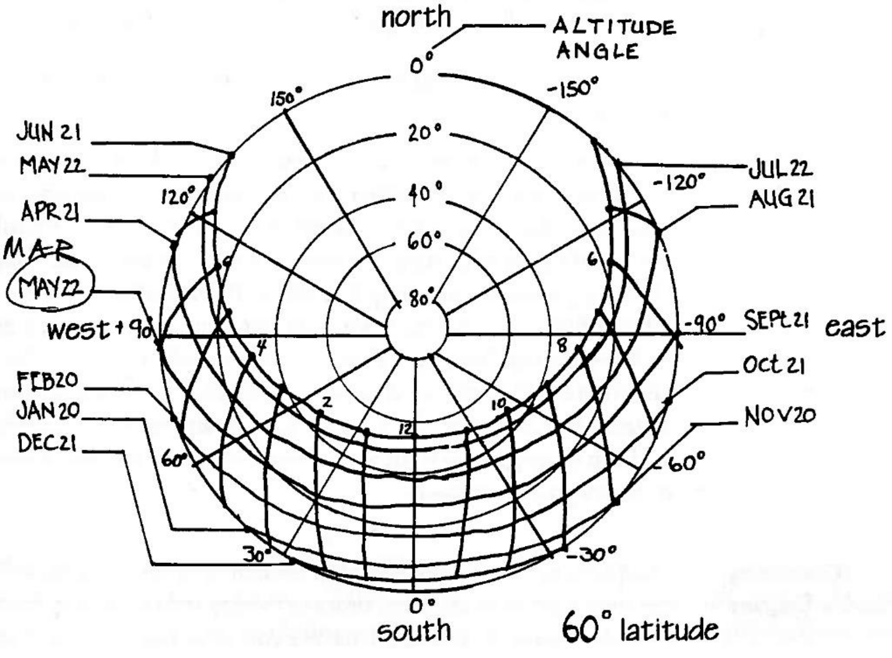


FIGURE 6.10. A skychart can be used to estimate the altitude and azimuth of the our,. Select the skychart representing the latitude nearest your site, then select the day, month, and time, and read off the altitude and azimuth angles. Although not as accurate as equations, such charts are normally accurate enough for most planning and design work (after Lowry, 1988).



40° latitude



60° latitude

The way to use the charts is as follows.

Step 1: Determine the latitude of your location, and decide on the day of the year and the time of day that you are interested in testing. For example, use the same values as above: Latitude = 42°N, day of the year = June 1, and time of day = 9:30 or 9.5 hours.

Step 2: Find the chart representing the latitude nearest to your location. In this case use the 40° latitude chart. Select the line that represents the date nearest the test date, in this case the line labeled May 22. Follow the line around until you reach the point midway between nine and ten o'clock.

Step 3: Read the altitude angle off the concentric circles, in this case the altitude is approximately midway between 50° and 60° so we might estimate it to be about 55 above the horizon. Then follow the radial line from the center, through our point on the chart, to the outside of the circle and read off a value of approximately -70°. This is the azimuth of the sun. These two values mean that the sun's location in the sky is 55° above the horizon, and is shining from 70° east of south.

Step 4: Use E = 55 and A = -70° as inputs to generate your shadow diagrams.

The differences between the equations and the charts is not normally significant. If you constructed two sets of shadow diagrams, one for each set of numbers, the results would be virtually indistinguishable. Charts are generally used for constructing the occasional diagram. However, if you are planning to generate diagrams for one site at many different times, or diagrams for many sites, it is worthwhile writing a simple computer program or using a calculator, to generate the numbers more efficiently. If you are not particularly adept at computer programming yourself, have someone program your calculator for you so that it simply requests the appropriate information and automatically provides you the answers.

Constructing Shadow Diagrams

Shadow diagrams can be useful in estimating whether areas will be in the sun or in the shade at key times of the day and of the year. It is worth considering ahead of time to what use you are going to put the diagrams.

For example, the location of a vegetable garden in a yard may require several diagrams, showing shadow patterns in morning and evening during spring and fall, as well as midday during the summer. By analyzing these diagrams you would be able to locate the sunniest locations for a garden.

Other uses may include determining the location of an outdoor cafe, or locations for sitting areas in a plaza. In each case it is worthwhile knowing the critical times when sunniness might make a difference in use. For example, in a plaza the sitting areas should receive full sun in winter and should be shaded as much as possible in midsummer. You might select a few key times, such as mid-July to represent summer, and mid-February to represent winter. The generation of two diagrams may provide you enough information to make decisions on locations. Later you may want to test the selected locations at more times and dates to ensure maximum sunniness in winter and minimum sunniness in summer.

To construct the diagrams, begin with a plan of your site. The plan should include contour information if there are significant elevational changes. If the area is relatively flat, then you require only the heights of buildings and trees.

Use the azimuth angle to determine the direction in which the shadows will be cast. All shadows will be cast in the same direction. In an earlier example we had an azimuth of -70°. In Figure 6.11 we can see that if the sun is at -70°, shadows will be cast **toward** +110° or toward 20° north of west. From each corner or each building, and from the base of each tree, draw a line **toward** +110°. This is the direction of every shadow.

To determine the length of each shadow requires the use of two pieces of information: the height of the object and the altitude angle of the sun. In our example the altitude is approximately 55°. Say we have a building 10 m tall. We would use the equation:

Length of shadow (S) = height of building (B)/tangent elevation (tan E)

or, in our case, S = 10/tan(55°) = 7.0 m. This means that the length of the shadow is 7.0 m, so we truncate our line at this length. We also truncate all the other lines from the corners of this building (assuming

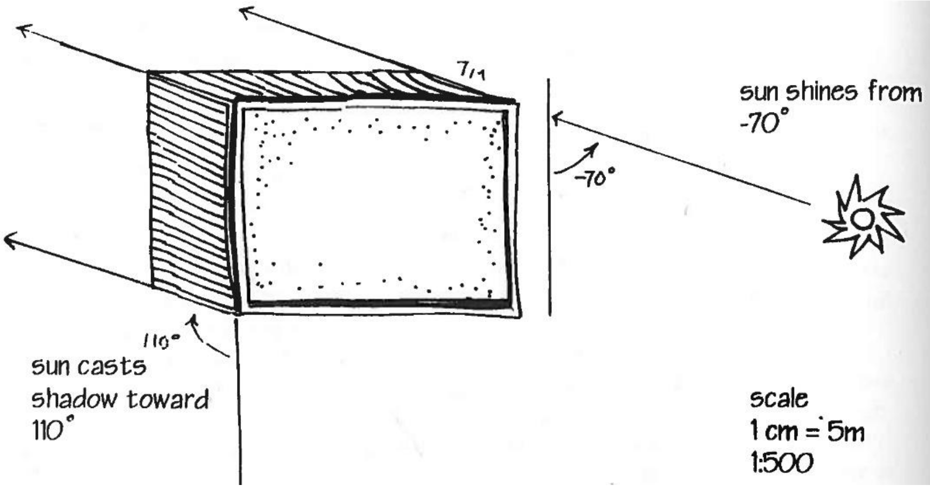


FIGURE 6.11. To construct a shadow diagram, first use the azimuth of the sun to determine the direction of the Shadows. Then use the altitude of the sun to estimate the length of shadows. In this example, the sun azimuth is -70°, which means the sun is shining from 70° east of south. The shadows will be cast in the opposite direction, 110° west of south. The length of the shadow is determined using the sun elevation and height of object in the equation on page 107.

it is a flat topped building) at 7.0 m, and then join the lines to determine the shadow cast by the building (see Figure 6.11)

Shadow diagrams can also be drawn in **section** or **perspective**, and can be quite revealing (Figure 6.12). For example, we might have a diagram that illustrates the shadow of a building, and you might be tempted to interpret that the whole of the shadow is cool and shady. This is only nominally true. If a person were to stand in the shadow, near the edge of the shadow, her ankles would be in shade, but the rest of her would be in sunshine. Certainly, for human thermal comfort, the radiation input would be nearly the same here as it is outside the shadow. It is important to analyze your diagrams and think about what is really going on.

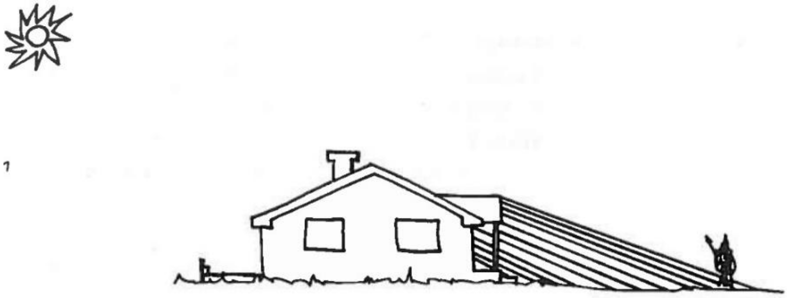


FIGURE 6.12. When shadow diagrams are completed, you should consider what they look like in section as well as in plan. This diagram illustrates that an area in shade might cast shade only on the ankles of a person!

Deciding on Times and Dates to Use in Testing

The time of day and date of the year are important considerations in constructing shadow diagrams. If you want to represent extreme conditions, such as the longest or the shortest shadow of the year, you would use the winter solstice (around December 21) and the summer solstice (near June 21). Other times you might want to illustrate shadow patterns at the equinoxes (near March 21 and September 23), times when there is equal day and night everywhere on earth. There may be other specific times of the year that you are interested in illustrating, for example during a local festival or holiday.

If you are interested in illustrating conditions that represent the most days of the year, you might select instead the days midway through the seasons. For example, February 6 is approximately halfway through winter and can be used to represent midwinter conditions, and May 6 is halfway through spring. Conveniently, the mean date for summer, August 6, provides the same sun angles as midspring. And, midfall provides the same sun angle as midwinter. Thus by casting two sets of shadows you can illustrate the sun angles in the middle of all four seasons.

Calculating the Terrestrial Radiation Emitted and Received

The amount of terrestrial radiation emitted by almost all natural materials can be estimated using the following equation:

$$R = 5.67 \times 10^{-8} \times (T + 273)^4$$

or in other words, the radiation emitted by an object is equal to the temperature of that object in Celsius plus 273 (to make the equivalent temperature in Kelvin), to the power 4 (you can use the button on virtually every calculator) times a constant with a value of 0.0000000567, or in shortened notation, 5.67 x 10^4 (again, you can use these keys on your calculator).

If we use these equations to calculate the amount of radiation being emitted by this book (assuming you are reading it in a comfortable location), we would have T = 20°C, so the first term would be $(293)^4$ or 7,370,050,801. We multiply this value by the constant and et 417.9 watts per square meter. So the book is emitting about 420 W/m toward you right now.

Let's check the radiation exchange between you and the book. If your surface temperature is approximately 25°C, the amount of radiation you are emitting toward the book is 447.1 watts per square meter. The difference is 447.1 — 417.9 = 29.2 W/m^2. This is not a large amount of radiation, and consequently you probably cannot sense this loss.

If we checked our earlier example of sitting near a cold window, we might find a larger difference. If the temperature of the window was 5°C, then the energy emitted by the window would be approximately 338.7 W/m^2, so our loss to the window would be approximately 447.1 — 295.5 = 154.6 W/m^2. If you recall our discussion of human thermal comfort, you will recognize that this amount of energy (approximately 110 W/m^2) is about the difference between the heat input from standing around doing nothing (90 W/m^2) and walking moderately quickly (250 W/m^2), which you know from experience is a large difference!

Radiation Data

Weather and climate information has been collected for a long time at selected locations. If you are interested in a location next to a weather station you can be confident that the data represent your site. However, an interesting characteristic of radiation allows you also to use data collected at some distance from your site. Radiation tends to be fairly similar in characteristics throughout a weather system. Within a high-pressure system the amount of solar radiation received tends to be quite consistent. Even within frontal systems the amount of solar radiation received is similar over a fairly large area, only the timing of it is different. The data recorded at a weather station within the region will provide enough detail for many landscape applications.

You can find the weather records in the library or request them from the weather service. The records are often recorded hourly, and you will find that summaries of months, years, and 30-year periods are also published. You can also request conditional climate information, as described in Chapter 2.

Solar Radiation Data

Weather records often consist of several different readings for every hour. The data of most interest to you will be the measurement of the amount of solar radiation received on a flat surface parallel to the ground surface. This might be found under a heading such as "Pyranometer" (the instrument often used for this measurement). There are often several other radiation measurements taken, many of which will be of limited use to you in landscape design.

Deciding on what radiation information you need (e.g., hourly, monthly) depends on the questions you are asking or the problems you are solving. We will discuss this further in Chapter 9. For now, be aware that there are many different forms in which you can accumulate data. You should be very selective in what you accumulate, as you will normally require a relatively small amount of the available data.

The most valuable general information that you might gain is an indication of the sunniness of an area or unique wind conditions (such as a Chinook, a warm wind that periodically blows down off mountains in wintertime). The general character of the climate of a region can be gained from climate data.

Terrestrial Radiation Data

When you check the climate normals for terrestrial radiation data, it may seem a little confusing at first. A measurement is sometimes taken of the amount of longwave radiation received from the sky, and not of objects in the landscape. This reading is normally of limited value to you in landscape design. We are much more concerned with terrestrial radiation emitted from objects in the landscape (which can be readily calculated).

There are specific cases in which information on terrestrial radiation from the sky might be of value to you. For example, if you were designing to eliminate frost pockets (areas that freeze first on cool evenings), the amount of radiation from the sky could assist in determining how much additional radiation you might provide by locating trees with canopies to replace the open sky.

Solar Radiation Modification

Conceptual

The tools that are available to you to modify radiation in a landscape are virtually limitless. Almost everything in the landscape will modify solar radiation in some way. All objects **reflect** some of the radiation received, **absorb** a portion, and possibly **transmit** some radiation. We know from Chapter 3 that some of the radiation that is absorbed will go toward raising the temperature of the object, some may go into evaporation of any water on the surface, some into convection, and some may be reradiated.

Although all objects affect solar radiation, some have much more impact on radiation than others. The most important landscape elements (those that can have the largest influence on solar radiation in a landscape) are woody plants and solid structures.

■ The landscape elements that have the greatest influence on solar radiation in a landscape are generally woody plants and solid structures.

The other important issue is the **location and orientation** of these elements relative to the area or surface in question.

■ There are two important Issues relative to the effect of landscape elements on solar radiation: (1) the characteristics (size, transmissivity, capacity to store heat, etc.) of landscape elements, and (2) their location and orientation.

There are a limited number of ways in which you can use the tools available to you: (1) You can plan to **intercept** radiation before it reaches a surface by placing something in its path. (2) You can cause more or less radiation to be **reflected** by altering the color and material of an object. (3) You can change the amount that is **absorbed** by an object by changing the material. Subsequently, you can modify the partitioning of energy in the energy budget by providing more or less water for evaporation, by modifying the capacity of the surface to hold heat, and so on, as discussed in Chapter 3. We focus our attention here on the modification of radiation in a landscape.

Hard Landscape Elements

Hard landscape elements (everything in a landscape except living plants) have some characteristics that allow them to be valuable radiation modification tools.

■ **Solar radiation can be intercepted by any object between the surface in which you are interested in and the sun.**

Provided you know the location of the surface or area under study, and the location of the sun at the time of interest, you can position an object accordingly.

■ **Buildings and solid structures create shade that has very little solar radiation in it. This radiation consists of only diffuse and reflected radiation, but there must be some solar radiation in a shadow or it would appear completely black to the human eye. The amount is typically about 10% of that in the open on a sunny day.**

Landscape objects often have identifiable albedos (ability to reflect solar radiation) that can be quite consistent between individual elements. For example, the albedo of a deciduous forest ranges from only about 5% to 15%. This means that of the solar radiation reaching a forest, about 5% to 15% of it is reflected back to the sky. Other landscape elements are not so consistent. For example, snow can have an albedo ranging from 40% for old snow to 95% for fresh snow. Table 3.1 includes typical albedos for landscape elements. The higher the albedo, the less radiation is available to be partitioned into the energy budget.

Some landscape elements have inherent characteristics that modify microclimates in quite predictable ways. For example, we can compare black asphalt and white concrete as two possible surface materials for a plaza. First of all:

■ **Black asphalt absorbs more solar radiation than will white concrete because of the difference in albedo.**

Given a warm, sunny day with no precipitation or water on either surface, the asphalt would become considerably hotter than the concrete.

Early in the day people in an asphalt plaza would receive much less reflected solar radiation than would people in a concrete plaza. The surfaces would not be of significantly different temperatures yet, so the terrestrial radiation would be quite similar and the overall radiation load on a person during the morning would be higher in the concrete area. Later in the day, when the asphalt is hot owing to the large input of solar radiation, the combination of solar and terrestrial radiation received by a person from the asphalt may be similar to the amount of radiation received by a person from the concrete. The solar radiation received from the concrete would be higher than from the asphalt, but the terrestrial radiation received from the concrete would be lower because of its lower temperature. After the sun has set, the radiation received by a person in the asphalt area would continue to be higher, possibly considerably higher, than that received in the concrete area.

By analyzing these results, we can see that there are times during a day when the asphalt surface might provide the most comfortable microclimate, and other times during the day when the concrete Would provide the best microclimate. You can see that it is very important to decide what time of day, what seasons of the year, and what activities you are designing to accommodate. When you make these decisions, the microclimate design decisions become much simpler and more straightforward. This subject will be discussed in more detail in Chapter 9.

Soft Landscape Elements

Soft landscape elements (living plants) have characteristics uniquely different from hard elements that make them valuable radiation modifying tools. When considering the effects of vegetation on radiation in a landscape, we have to first analyze the situation, then put it all back together again. First we must consider that there are normally two kinds of trees available in mid-latitudes: deciduous, which drop their leaves in winter, and coniferous, which keep most of their leaves in winter. There are some exceptions to this rule, but generally we can count on these categories.

In considering a deciduous tree, we must remember that even when it has leaves, it has branches and twigs as well. This might not seem very important at first. However, although leaves allow almost all of the near infrared radiation from the sun to pass through, twigs and branches do not. If the tree were made up only of leaves, then fully one-quarter available to heat surfaces below.

Think also about the tree with no leaves. The fact that it will still cast a shadow, because of its branches, twigs, and trunk indicates that it is intercepting solar radiation. The amount intercepted depends on the density of twigs and branches, and varies with species.

However, some reliable generalizations can be made:

- **Deciduous trees intercept more radiation when leaves are on the trees, and less radiation when they are leafless.**
- **All trees allow some solar radiation to pass through their canopies.**
- **Different species of trees Intercept radiation at different rates at different times of the year.**

Some species of trees provide a large amount of radiation interception, and consequently heavy shade, during the summer. Some species provide a small amount of radiation interception during the winter when they are leafless (see Table 6.1).

Solar radiation is strongly affected by virtually any object in the landscape. Deciduous trees can provide a reduction in radiation during overheated summer periods through interception by their leaves. These trees normally drop their leaves in winter thus allowing significantly more radiation to pass through during underheated times. They are therefore extremely valuable landscape elements. However, the difference in the effect on radiation between leafed and leafless periods is not the same as between 0% and 100%. Leaves allow substantial amounts of solar radiation (near infrared, invisible to the human eye) to pass through, and in winter twigs and branches can obstruct substantial amounts of radiation. Trees vary in their characteristics, but some vary between allowing one-quarter of the radiation through in summer to only three-quarters through in winter. This is still a significant difference, yet not as much as intuition might suggest.

- **Some of these characteristics cannot be modified, but can be used as valuable knowledge in design. For example, the transmissivity of trees varies by species. You cannot easily change the transmissivity of any given tree (except possibly by regular pruning), but knowing transmissivity values allows you**

TABLE 6.1

Characteristics of Selected Trees Commonly Used in the Landscape

A range of values is listed for most trees, as there is considerable variation within species owing to growing conditions, climate zone, etc. The range in transmissivity values may also be affected by the instruments used by various researchers in measuring the transmissivity of trees. Ideally, we use only values that represent the transmissivity of solar radiation. Use a value at about the middle of the listed range. Foliation and defoliation dates and maximum heights will vary by region.

Botanical Name	Common Name	Transmissivity Range % (reported in the literature)		Foliation[a]	Defoliation[b]	Maximum expected height (m)
		Summer	Winter			
Acer platanoides	Norway Maple	5-14	60-75			15-25
Acer rubrum	Red Maple	8-22	63-82	M		20-35
Acer saccharinum	Silver Maple	10-28	60-87	M		20-35
Acer saccharum	Sugar Maple	16-27	60-80	M		20-35
Aesculus hippocastanum	Horse Chestnut	8-27	73			22-30
Amelanchier canadensis	Servicebeny	20-25	57			
Betula pendula	European Birch	14-24	48-88	M	M-L	15-30
Carya ovate	Shagbark Hickory	15-28	66			24-30
Catalpa speciosa	Western Catalpa	24-30	52-83			18-30
Fagus sylvatica	European Beech	7-15	83			18-30
Fraxinus pennsylvanica	Green Ash	10-29	70-71	M.L	M	18-25
Gleditsia tricanthos inermis	Honey Locust	25-50	50-85	M	E	20-30
Juglans nigra	Black Walnut	9	55-72	L	E-M	23-45
Liriodendron tulipifera	Tulip Tree	10	69-78	M-L	M	27-45
Picea pungens	Colorado Spruce	13-28	13-28			27-41
Pinus strobus	Whilte Pine	25-30	25-30			24-45
Platanus acerifolla	London Plane Tree	11-17	46-64	L	M-L	30-35
Populus deltoides	Cottonwood	10-20	68			23-30
Populus tremuloides	Trembling Aspen	20-33				12-15
Quercus alba	White Oak	13-38				24-30
Quercus rubra	Red Oak	12-23	70-81			23-30
Tilia cordata	Littleleaf Linden	7-22	46-70	L		18-21
Ulmus americana	American Elm	13	63-89	M		18-24

[a]Foliation: E = Early = Before April 30
M=Middle = May 1-15
L =Late = After May 15
bDefoliation: E =Early = Before November 1
M=Middle = November 1-30
L =Late = After November 30

the opportunity to use a tree with a heavy or a light shade in given situations.

■ **Landscape plants have characteristics that affect solar radiation:**

1. **Individual leaves that allow some radiation to be transmitted through them (normally about 20%), absorb some radiation (normally about 50%), and reflect some radiation (normally about 30%),**
2. **The dates when individual species leaf in spring and the dates when they drop their leaves in fall,**
3. **The maximum height of the plant, and**
4. **The transmissivity of the canopy in different seasons (a combination of the characteristics of the leaves, twigs, branches, dates, and size).**

These characteristics are summarized in Table 6.1. Depending on the microclimatic conditions you want to achieve, you can determine the most appropriate species (include trees, shrubs, vines, ground covers, etc.).

■ **The dates on which trees grow their leaves and drop their leaves are critical to the value of trees in radiation control in a landscape.**

Terrestrial Radiation Modification

Conceptual Approach

There are situations in which terrestrial radiation can have a significant effect on a microclimate. Consider again the example of a black asphalt surface as compared with a white concrete surface. The black asphalt would absorb solar radiation very efficiently, while white concrete would reflect a considerable amount and absorb relatively less. At the end of the day the asphalt, which may have become very hot, has the ability to hold the heat. The concrete might be quite cool. During evening hours the asphalt will emit terrestrial radiation as a function of its temperature and thus will emit considerably more radiation than will the cooler concrete. For a person sitting outside on a cool evening, this added terrestrial radiation might make the difference between being too cool and being comfortable.

■ **Landscape elements can affect terrestrial radiation in a microclimate as a function of their ability to absorb and hold solar radiation and their ability to emit terrestrial radiation.**

All natural elements in a landscape emit terrestrial radiation at approximately the same rate, as a function of their temperature. This means that if two elements of different materials have the same temperature, they will emit the same amount of terrestrial radiation. There are some notable exceptions that are rarely a major component of a landscape: aluminum and gold. Both emit radiation at a much lower rate and can be used quite effectively in specific situations. For example, windows covered on the outside with a very thin layer of gold will emit radiation from a building at a very low rate. This effectively reduces the amount of energy required to heat the building, allows people to see through the windows, and enhances the image of the building's owner at the same time.

■ **Longwave radiation cannot be seen by the human eye but can be a significant component of a microclimate. This is especially true on clear nights in spring and fall. The earth emits large amounts of Longwave radiation, while the clear sky emits very much less. The negative balance can result in considerable cooling of surfaces, and possibly frost. However, if there is the canopy of a tree between the ground and the clear sky, the tree emits considerably more radiation toward the ground than would the sky, so frost can often be eliminated.**

Examples of Radiation Modification

New information often doesn't make much sense until you apply it to a realistic situation and see how it can be used. Here we will give some examples of different situations in different seasons to show you how radiation can be effectively modified.

Summertime Patio

Consider a very specific requirement: a patio cafe in a midlatitude city that will be used primarily during lunchtime in midsummer. Recall that we should make radiation control the first priority. Secondary consideration is control of the wind if the opportunity arises.

There are virtually a limitless number of ways that radiation can be controlled in a patio. The first opportunity would be to intercept the radiation before it reaches the patio. This can be done by using anything from a solid structure, such as a roof, that would intercept 100% of direct solar radiation, to a very porous tree that would cast very light shade, such as a honey locust. Once solar radiation reaches the patio, it can be reflected or absorbed by different materials. Because we are most interested in the thermal comfort of people at high noon, we may decide on dark-colored surfaces to absorb and hold the solar radiation, thus minimizing the amount reflected onto people. We may also consider the area immediately adjacent to the patio, and control any reflection of solar radiation into the patio.

Control of terrestrial radiation received by patrons can be achieved by keeping surfaces near the people as cool as possible. Surfaces that are shaded tend to be very near air temperature, while wet surfaces are even lower than air temperature because of evaporation. These surfaces will emit less terrestrial radiation than would dry sunny surfaces. You can achieve this effect by providing water to run down a wall, and you might moisten brick-covered ground surfaces.

There are many other ways to maintain a cool noontime environment in the patio, and through using the principles of microclimate and energy budgets, you can invent effective ways that do not interfere with creative design.

College Plaza

Another outdoor situation that can benefit from radiation control is a plaza on a college campus. The college population is typically largest during the fall and winter semesters, from about September until May. To facilitate outdoor human thermal comfort in a plaza for as much of this period as possible requires wind control. But setting aside wind for the moment, how can we maximize the radiation in this plaza?

First, start with orienting the plaza toward the south and blocking as little of the solar radiation as possible. This can be achieved in any number of ways, for instance: (1) having no trees or buildings casting shadows into the area (check with sun angles and shadow diagrams) or (2) allowing only deciduous vegetation that drops its leaves in early fall and grows new leaves in late spring.

Second, whatever solar radiation is received in the plaza, maximize its intensity by sloping surfaces toward the south and reflect the solar radiation onto people to maximize their radiation input. Light-colored surfaces in and around the plaza might be appropriate.

Third, whatever energy is absorbed by the landscape elements, provide for most of it to be translated into emitted terrestrial radiation by ensuring that surfaces remain dry. Thus, little energy will go into evaporation.

Finally, to enhance the microclimate in the evening, provide some dark walls or solid surfaces that will absorb solar radiation during the day and emit terrestrial radiation in the evening.

Quantitative Determination of Radiation Absorbed by a Person

In Chapter 4 we determined the thermal comfort levels for a sitting/eating area in a theme park. At that time we estimated the R_{abs}, the radiation absorbed by a person, by using a model in Appendix A. We will explore this model a bit further here to demonstrate quantitatively some of the effects of landscape elements on R_{abs} and the thermal comfort of people.

We begin by investigating the effect of different trees during warm sunny summer conditions. The air temperature is 25°C, relative humidity is 75%, wind speed measured at 10 m above the weather station is 5 m/s, solar radiation is 1,000 W/m^2 and the solar elevation is 35°. We will dress our test person in ensemble C and have him standing (M = 90). The COMFA budget (using programs in Appendix A) would be 137 W/m^2. This suggests that a person would be uncomfortably warm.

We will first reduce solar radiation by placing the person under a tree that casts a light shade, providing 50% of full solar radiation. This results in a budget of 49 W/m^2, a value that is at a point between being uncomfortably warm and being comfortable. If we instead place the person under a tree that casts a heavy shade, say, 20% of full solar radiation, the budget becomes 4 W/m^2, a very comfortable condition.

We can also investigate the effectiveness of terrestrial radiation losses in cooling people during hot conditions. Let's reduce the wind speed to 2 m/s to create a very uncomfortably hot condition, a budget of 235 W/m^2. First we will put the person in the shade of a building, a move that would result in a budget of 23 W/m^2—a very wise move! If we now locate the person near a wet wall, the terrestrial radiation loss to the wall results in a budget of 3 W/m2, and if we similarly allow the ground to become wet and to cool down, the budget becomes -19 W/m^2, clearly a much more comfortable microclimate on a hot day.

Now let us extend our discussion into nighttime situations to see how effective radiation control can be when the sun is not shining.

First, we will consider a person with the same characteristics as in the preceding example, but now the sun has set and the air temperature has fallen to 20°C. In a completely open landscape, the energy budget of the person would be -70 W/m^2, a condition that is uncomfortably cool.

We can test a variety of landscape treatments to see the effect on thermal comfort. We will first add a tree to the site, and have the person standing under the tree. This will increase the amount of terrestrial radiation received by the person, as the tree emits more radiation than does the clear night sky. The energy budget is now -45 W/m^2, a clear improvement and reasonably comfortable conditions.

Now, instead of a tree let's say that the ground surface is asphalt and we have allowed its temperature it to rise during the sunny period so that it will emit radiation during the evening. If we estimate that the temperature of this asphalt is 30°C (a conservative estimate), we can determine the budget to be -47 W/m^2, achieving nearly the same effectiveness as a tree.

If we combine these two elements, the budget becomes -22 W/m^2, a very comfortable condition.

Let's add some other elements that emit terrestrial radiation. The combination of warm asphalt (35°C) and a sun-warmed wall (45°C) will result in a budget of-12 W/m^2, while warm asphalt, wall, and tree will yield a budget of +17 W/m^2, clearly a much warmer environment than the original open landscape at -70 W/m2.

Summary

Virtually every part of a landscape modifies radiation, and consequently affects the thermal comfort of people and the energy use of buildings.

■ **There are many good solutions to any design problem. By understanding the principles of radiation, you can create unique design solutions that will maximize the benefits of radiation in a landscape.**

Things to think about . . .

1. **Let's revisit the courtyard considered in Chapter 1, question 1 yet again. With more tools now at your disposal, how might you make the eating area more comfortable during midsummer lunchtime periods? What would you do for immediate effect, and what for a longer-term effect?**

2. Mr. and Mrs. A went ahead and built their deck as you suggested in answer to question 5, Chapter 1 and now they tell you that it is too hot to sit there in the summer, but is just fine in all other seasons. What would you suggest they do to retrofit the landscape?

3. The school board (Chapter 5, question 2) has implemented your siting suggestions and now would like to make all the school buildings even more energy conserving. How would you suggest it be done, using radiation modification? Can you suggest a general guideline for school officials that would apply to all schools? Would this be a different from the suggestion you made in Chapter 5?

4. The developer (Chapter 5, question 3) laid out her subdivision according to your suggestions. Now she wants to provide radiation control for each individual house. What would you suggest she do?

5. The city council (Chapter 5, question 4) adopted your suggestion for a by-law. What details can you now provide to the homeowners of the city as to how to achieve the radiation controls suggested in the by-law? How effective do you think this might be?

7

Wind Modification

■ **WIND IS** an element of microclimate that can be significantly modified by landscape components and also strongly affects human thermal comfort, energy use in buildings, and many other things in the landscape. It is a very important consideration in landscape design for microclimate.

Introduction

Wind is one of the most important components of microclimate in the landscape. Wind efficiently mixes differences in temperature or humidity that occur in the landscape. It carries heat away from people and buildings and strongly influences their energy budgets, and can be modified through landscape and manipulated through design.

Despite its importance, wind is an elusive element, extremely difficult to visualize and even more difficult to control. We begin our journey toward the understanding of wind by trying to visualize it, to "see" how it moves through a landscape. Later we will discuss tools for modifying the speed, direction, and turbulence of wind.

Wind Characteristics

Let's start at the beginning:

■ **Wind is movement of the air. Air moves because of differences in pressure. It simply moves from areas of higher pressure to areas of lower pressure.**

As discussed in Chapter 2, wind is simply air molecules moving in response to pressure differences in the atmosphere. To demonstrate, force air molecules into an area of high pressure by inflating a balloon. Release your hold on the end of the balloon, and the air rushes out, moving from an area of high pressure to an area of lower pressure. This wind is created by the same mechanism that is causing wind in the landscape.

While the air is moving toward the area of lower pressure, however, the differential heating of the atmosphere at virtually all scales is creating more pressure differences. This is a never-ending challenge for the wind, and as evidenced by the fact that there is almost always at least some wind, it is never able to smooth out the pressure differences. We have to accept the fact that wind will blow and that we cannot affect the mechanism that causes wind. We must focus our energies instead on *modifying* the prevailing wind.

Who Has Seen the Wind?

We cannot normally see wind, because it consists almost entirely of gases. There are times, however, when wind transports visible particles, such as snow or dust. During these times we can "see" the movements of the wind. Whenever you have the opportunity, watch as the wind blows particles around a landscape. It will help you to understand the movements of wind.

■ Watch and learn when snow or dust h being carried by the wind.

It is helpful to develop a mental image of what the wind is doing and how it is flowing. Some people use the analogy of water flowing in a stream. Obstructions in the landscape are like rocks in a stream—water flows around them and creates turbulence behind them. The air is fluid and behaves like water flowing through a stream. The difference is that water has much greater mass and is held next to the ground quite firmly by gravity. Water moves mainly in two dimensions (back and forth and downstream, with only limited vertical movement), whereas air is much less dense and can swirl around equally in all three dimensions. Despite this difference, air flows around objects and through the landscape in much the same way as water does.

Another way in which you might also begin to "see" the wind is by absorbing diagrams (see Figure 7.1a), graphs, and charts, or by "seeing

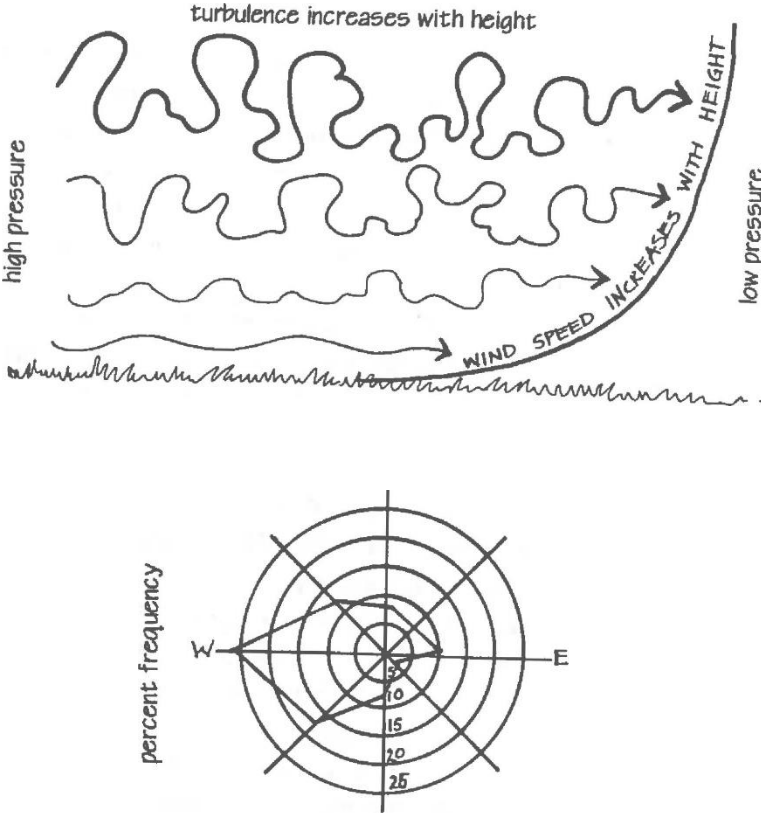


FIGURE 7.1. (a) Air moving through a landscape will tend to move more slowly near the ground, and will increase in speed with height. This is not a linear relationship, but tends to be somewhat logarithmic, which means that wind speed increases very quickly near the surface, then doesn't increase as much with height after it is a short distance from the surface. The amount of turbulence in the air also tends to increase with height above the ground (after Lowery 1988). (b) This wind rose illustrates the portion of time that the wind blows from each direction. In this case, the prevailing winds are clearly from the west.

with your mind" rather than with your eyes. Whatever your method, try to develop mental images of how wind moves, and whenever you receive new information, update that image.

As wind blows, it is not a steady flow of air. There is virtually always turbulence in the air. This is typical of fluids; they do not flow in straight lines. For example, look at a stream channel. It wanders back and forth as it has been created by the flowing water. Even when channels are artificially straightened, they quite quickly return to their wandering form. This is due to turbulence. Turbulence increases the cooling power of wind. The more turbulence, the higher its ability to carry heat away from a body.

Turbulence is a function of the speed of a wind (the faster it is moving, the higher the turbulence) and the roughness of the underlying surface (the rougher the surface, the more turbulent is the wind).

The direction of wind flow changes quite quickly and almost continually, so we cannot count on a specific direction of flow. But there are patterns that become evident, as mentioned in Chapters 2 and 3. Wind is extremely variable, both in the direction from which it flows and in its speed. When we hear weather reports that the wind is from a certain direction at a certain speed, we may think that the wind is consistent. Although a weather report might state a 10 km/hr wind from the northwest, the wind may vary from calm to 25 km/hr from the west to the north over a short period of time. It is important to keep this characteristic of wind in mind when analyzing and designing landscapes.

Wind direction and speed often change with the time of day and with the seasons. Wind is generally strongest during the afternoon and weakest in the very early morning. The prevailing direction of the wind can be illustrated by a wind rose, a diagram that graphically displays the percentage of time the wind is from each direction (see Figure 7.1b), or through other graphic techniques. These often show a trend across seasons. For example, some northerly locations have a tendency for winds to be generally from the north in winter and more evenly distributed throughout the rest of the year. This type of information is valuable in locating winter windbreaks. You cannot generally design for all wind in all conditions, but you can design for the majority of the time.

You "feel" the wind because air molecules moving past you come in contact with your skin, albeit for a very brief period of time. During this contact they exchange some energy and moisture with your skin. If the air is drier than your skin, some water will evaporate from your skin and enter the air. Some of the heat used to evaporate the water will be taken from your skin, and you will sense this as a cooling effect. If the air is cooler than your skin temperature (normally the case out-doors), heat will be transferred to the air and your skin will feel cooler.

Obviously, wind can strongly affect human thermal comfort. The magnitude of the effect depends on several things: the speed of the wind, the temperature (T) difference between a person (T_{person}) and the wind (T_{air}), and the insulating characteristics of clothing worn by the

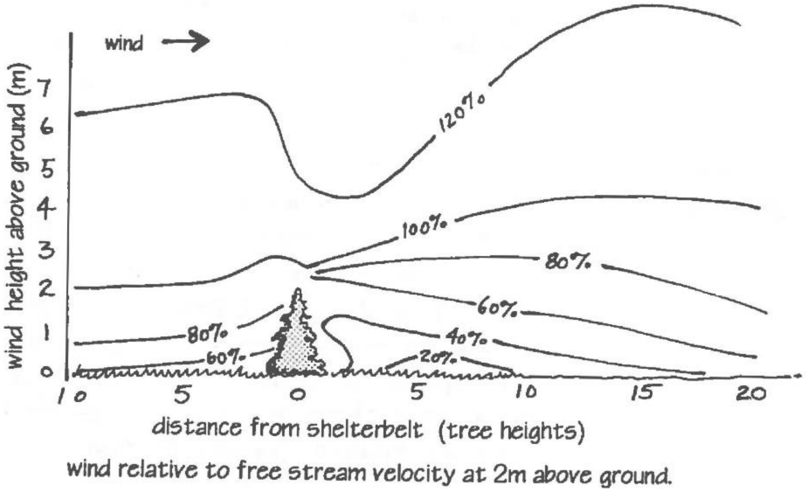


FIGURE 7.2. This diagram illustrates a row of cedar trees planted close together so as to form a continuous, permeable barrier against the wind. When wind encounters the windbreak, a reasonably predictable pattern of wind speeds is established. The wind increases in velocity over the top and around the ends of the windbreak, and zones of decreased wind speed are established in the lee of the trees (after Geiger 1965).

We can write this as a simple equation to illustrate the situation:

Convection = (Tperson — Tair) X wind speed/insulation factor of the clothing

This equation is not really accurate, as we would need constants and powers attached to some of the components, but it illustrates that amount of convective cooling increases as wind speed increases, and as the temperature difference between the person and the air increases. It also tells us that as the insulating power of the clothing increases, convective cooling decreases.

■ Interestingly, both of the microclimate elements that are most important to us are virtually invisible to us. 01 all the radiation and wind in the landscape we can see only the visible portion of the sunlight. However, it is essential to consider these "Invisible" elements in microclimate design.

To visualize wind for use in design, we cannot map wind per se. We can map the wind at one time over a landscape, or we can map the wind over time at one given point in a landscape. But we cannot map the wind over time for the whole landscape. Therefore, it what is often best to (1) determine the generalized characteristics of the wind over time and (2) map the landscape elements that affect wind speed and direction. The result can be analyzed for different situations and goals.

Wind Data

Every country is dotted with weather stations measuring wind speed and direction at all times. You can likely find wind records in your local library, which usually include hourly speed and direction at 10 meters above the ground. There are also summaries of yearly records and 30-year "normals." There are two kinds of data that are valuable in landscape design: the general characteristics of an area and data on wind that typically occurs at the times of day and year for which you are designing. This subject is discussed further in Chapter 9.

Wind-Modifying Characteristics of Landscape Elements

Most objects in a landscape affect the wind, some by reducing its velocity and redirecting it, others by increasing its speed. Wind is also influenced by the relative locations and orientations of objects. Whereas radiation can be described quite neatly through equations, wind still cannot be adequately described this way.

Visualize the movement of air through a landscape. Imagine a very simple landscape first, one with a flat land form and one row of cedar trees that happen to be perpendicular to the flow of air (Figure 7.2). The air makes its way across the landscape and when it reaches the row of trees it is forced to go somewhere because there is more air coming along behind. Some of the molecules are forced to go up and over the windbreak, some through the trees between twigs and leaves, and others around the ends of the windbreak. This image provides enough information for us to see that the area on the upwind side (that first reached by the wind) will have a piling-up of molecules as they are repelled by the windbreak. This back pressure creates a little bubble of air next to the trees that has a lower wind speed than that in the free stream. At the places where the air is forced to go around the edges of the wind break, molecules speed up. This is experienced as an increase in wind speed. Downwind of the windbreak there are fewer molecules moving past at any given time. This is experienced as a relatively lower wind speed—lower than the free stream and much lower than the flow around the ends and over the top (Figure 7.2).

Now imagine the same landscape, but instead of a row of trees imagine that there is an impermeable wall perpendicular to the direction of wind flow (Figure 7.3). The patterns of wind flow are similar for the wall and the trees, but the sizes of the zones and amounts of turbulence are different.

All this information can be accumulated into one diagram (Figure 7.4). This graph illustrates the differences in wind reduction and the area of reduced winds for windbreaks with a variety of permeabilities.

■ **Wind can be significantly modified by landscape elements. Unlike their effect on radiation, however, the effect of landscape elements on wind cannot be determined with certainty. We can make educated guesses, based on theory and observation, to suggest how wind can be modified in a landscape.**

■ **Elements in the landscape affect wind in a variety of ways. Some of the characteristics of objects that affect the wind are size, location, orientation, porosity, and proximity. Some of these cannot be altered, and the elements become objects for our pallette. We can simply place objects with the appropriate characteristics in the appropriate places.**

A windbreak is anything upwind that will affect the wind. The size, location, and porosity of a windbreak are its most important characteristics. Diagrams can be helpful in understanding the effect, but

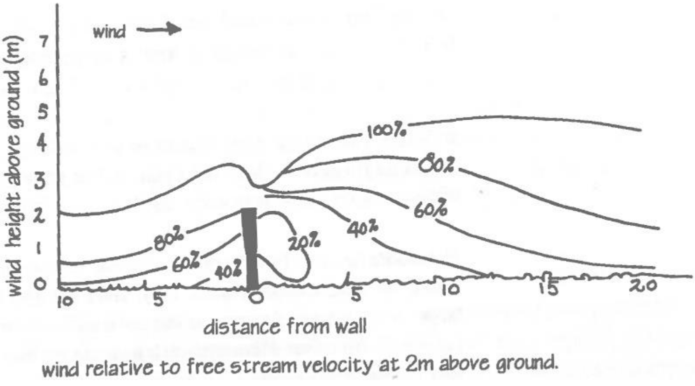


FIGURE 7.3. When a barrier is impermeable, such as a solid wall, the typical pattern of wind speeds established has a relatively small area of wind reduction, but the magnitude of the reduction is quite large (after Geiger, 1965)

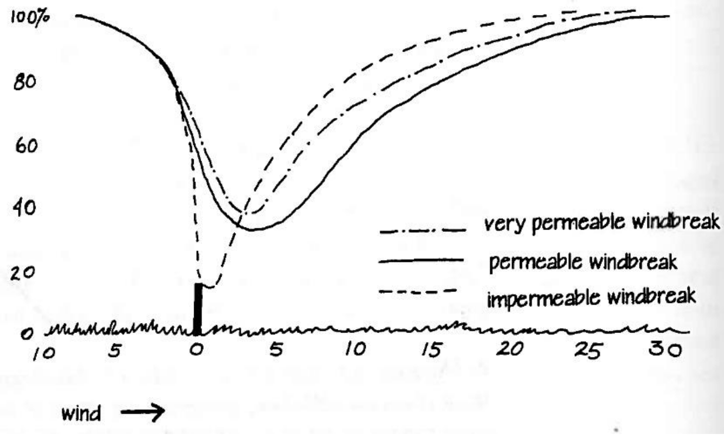


FIGURE 7.4. This diagram illustrates the wind reduction behind windbreaks of varying permeability. Solid, impermeable barriers produce the lowest wind speeds, but these are confined to the smallest areal extent. The more permeable the windbreak, the less the magnitude of the reduction, but the larger the areal extent of the wind reduction (after Geiger, 1965).

generally there is a relationship between the wind and the windbreak that can be useful in design.

- **The denser (less porous) a windbreak, the greater the effect on wind speed, but the smaller the area of affected air. Conversely, the looser (more porous) a windbreak the lower the effect on wind speed, but the larger the area affected.**

The goal is often optimization of the area affected by a windbreak and the actual reduction in wind speed (i.e., to design a windbreak that creates a fairly low wind speed over a fairly large area). In specific cases, however, you may need to create a very small, very calm area, or a very large area of slightly lower wind speed. There are tools available to do so.

- **When you create a small area of very calm air, you may be introducing extra turbulence into the area, so the effect may be lost. It Is quite difficult to create a very calm outdoor area when It is windy.**

- **Landforms can force wind to change direction and can increase or decrease All of the elements discussed so far have been isolated components in an idealized landscape. When these are applied to a typical, diverse landscape, many of the ideals break down. There are two ways to apply wind speed (Figure 7.5). They do not, however, have a very large effect on wind speed when used on their own. Landforms in conjunction with other elements such as trees or shrubs can enhance the effect of the vegetation.**

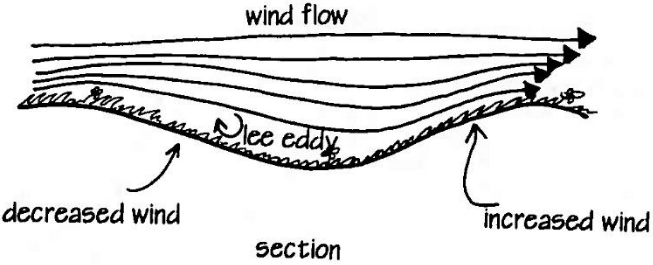


FIGURE 7.5. Landforms tend to have a relatively minor effect on wind speed and direction unless the landform is quite large. There will be an increase in wind speed on the windward side of the hill, especially near the top of the hill. There will be a decrease in wind speed on the lee of the hill.

■ **Woody plants can have a significant effect on wind flow in a landscape. They can affect both direction and speed. Generally, the larger the plant and the denser It is, the greater the effect. Deciduous plants can have a great effect in summer but virtually no effect in winter. Evergreen plants are most useful in winter wind modification, but can also affect wind flow In the other seasons. This is generally acceptable, as wind modification is much more important in winter than in other seasons.**

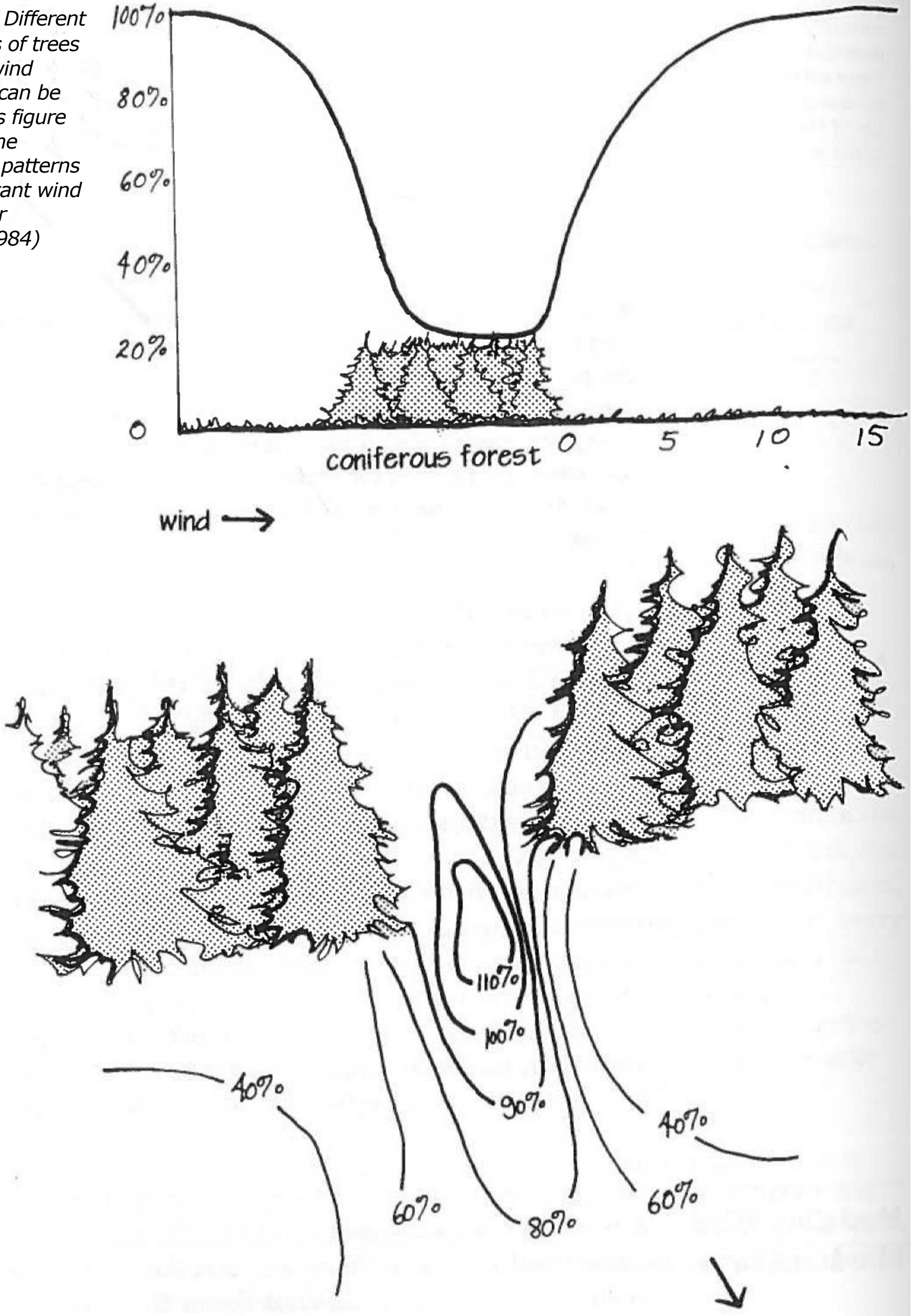
Trees are probably the most effective landscape elements in modifying wind speed and direction. The effect is not entirely predictable, but some generalized situations can be described. Figure 7.6 illustrates some of the effects of trees as individuals and as groups. It is important to remember that the diagrams are only two-dimensional and that the third dimension must be considered as well. Figures 7.3 and 7.4 illustrate how the wind pattern behind a windbreak can suggest that there is a zone of very low wind speed, but if a person were to stand in that location, only the ankles would be in the area of low wind. The rest of the person might experience relatively higher wind speeds (Figure 7.7).

Shrubs have essentially the same effect on wind as trees, it is only the scale that is different. Shrubs can be very effective in protecting small areas where people will sit and can effectively reduce wind near a house and, consequently, reduce energy consumption in winter.

Modeling Wind in a Landscape

All of the elements discussed so far have been isolated components in an idealized landscape. When these are applied to a typical, diverse landscape, many of the ideals break down. There are two ways to apply

FIGURE 7.6. Different configurations of trees have typical wind patterns that can be expected. This figure illustrates some common tree patterns and the resultant wind patterns (after McPherson, 1984)



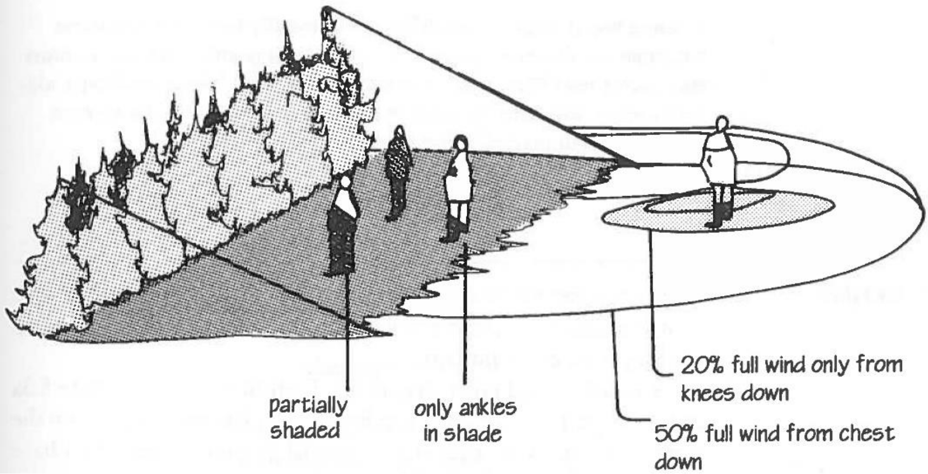


FIGURE 7.7. Three-dimensional drawings of wind zones can reveal unexpected situations. In this case, the calm wind zone is very shallow and would not affect thermal comfort.

the principles to a real site: (1) map the characteristics of the site that modify wind, then overlay a map with the prevailing winds to analyze expected wind zones on the site, or (2) build a scale model of the site and simulate wind through a wind tunnel or water flume. These two methods are further described in Chapter 9.

There are basically two methods for understanding wind in a landscape. First, through the use of scale models in wind tunnels or water flumes, you can recreate the natural conditions, as nearly as possible, then measure the wind speeds across the landscape. This provides the opportunity to modify the landscape and "see" the resulting effect on the wind. The second method, which is more common and easier to use, but not as accurate or precise, is through empirical means, that is, by using measurements of generalized situations and extending of these data to other landscapes. For example, different researchers have taken careful measurements of winds around a single-row windbreak of cedar trees. This information can be of considerable value in other landscapes where conditions are similar. The limitation of this type of work is in that the conditions are seldom exactly the same, and some assumptions must be made.

■ Some useful questions in designing to modify wind in a landscape are, What are the prevailing winds? How do they affect thermal comfort and energy use? What would I like the winds to be? What landscape elements could influence the wind in this way? How can they be located and oriented to maximize the effect?

Examples

It is instructive to discuss examples of landscape design that have created positive wind environments, as well as those that have created negative wind environments.

A positive wind environment has been illustrated in Figure 5.3a and b, where a windbreak of coniferous trees has been planted on the north, east, and west sides of a residential property. These trees have been planted far enough away from the house so as not to obstruct solar access in winter and, because of the midlatitude location, will affect most of the winds received in fall, winter, and spring. The effect of the trees increases as they grow, ultimately creating a pocket of relatively calm air in which the house sits. This will reduce the energy required to heat this house in winter, and will increase the thermal comfort of the outdoor environment in fall, winter, and spring.

If we were to couple this wind modification with radiation control of the house, we could locate deciduous trees on its south and west sides of the house where they will cast shadows during hot afternoons in summer but allow considerable solar access when the trees have no leaves in winter. This simple approach to residential property layout can create significantly improved microclimates for much of the year.

There are many examples of wind being modified in negative ways. These are particularly prevalent in urban areas. One of the main problems is that tall buildings intercept faster-moving air from aloft (recall that wind increases in speed above the ground) and transport it to the surface (see Figure 7.8a). These fast-moving winds travel down the faces of buildings and then seem to blow "out of the building." This can create a very uncomfortable and inconvenient situation, especially when people are attempting to enter the building. One simple approach to solving this problem is illustrated in Figure 7.8b. The wind is deflected before reaching the ground.

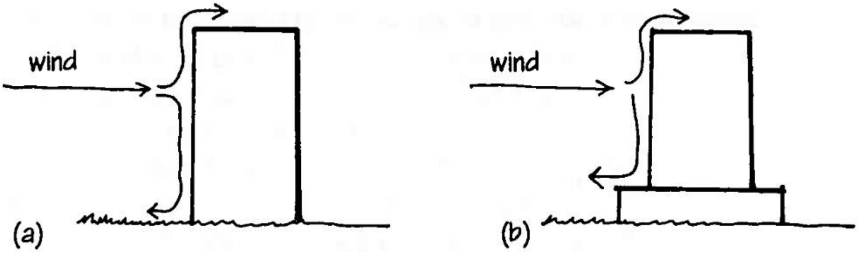


FIGURE 7.8. (a) In urban areas, tall buildings can intercept the faster-moving air at high levels and transport it to the ground surface. This can be a very inconvenient wind near entrances to buildings, and can cause tremendous cooling of pedestrians in winter. (b) One possible solution to the wind problem is to deflect the wind before it reaches the ground (after Oke, 1987).

Other negative effects can result when building orientations funnel wind through pedestrian spaces. Buildings that have great deal of traffic between them are sometimes located close together. If the opening is oriented on an approximate north—south axis it can channel winds from the northerly direction between buildings. In winter this can create a very uncomfortable and inconvenient situation for pedestrians.

The problem could be resolved by one of several approaches: (1) modify the wind upwind of the location, so that it is reduced in speed and its direction has been altered before it reaches the walkway, (2) reorient the buildings so that the walkway is oriented in a more appropriate direction (possible only if the problem is discovered before construction), (3) provide a wind-modifying element in the landscape at the upwind end of the walkway, one that will deflect or diffuse the wind, or (4) provide a sheltered walkway that is disconnected from the outside environment. There are, of course, many other options. The solution requires a creative mind to apply to real situations the principles learned in this book.

Quantitative Determination of Wind Speeds in a Landscape and Effect on Thermal Comfort

There are several equations that can be used to estimate wind speed in different parts of a landscape. We consider a couple of situations that can be applicable in many design problems.

We first investigate the relative value of wind modification in summer and in winter situations. First a winter scenario: Consider a very cold day; the air temperature is at —10°C, relative humidity = 50%, wind speed at the weather station is 5 m/s, and it is a cloudy day, so we will use a constant Rabs value of 217 W/m^2. If we dress our test person in ensemble F (Table A.2) and have her walking quite quickly *(M* = 250 W/m^2) the COMFA budget (Appendix A) would yield a value of —151 W/m^2. We can see from Table A.3 that under these conditions a person would prefer to be much warmer.

Now consider a reduction in wind to 25% of full wind speed, a value that might be found in the lee of a cedar windbreak. The COMFA budget would be —70 W/m^2. This is much better, but a person would still prefer to be warmer. If we now put this person in a very calm air situation, such as might be found in a bus shelter, the budget becomes —49 W/m^2, a value that would suggest reasonably comfortable conditions.

Hot, windy summer conditions could be represented by inputs of *M* = 180 (walking quite quickly), *7'3* = 50, *P* = 175 (clothing ensemble A), air temperature = 30°C, wind speed = 5 m/s, and relative humidity = 75%. The solar radiation is 1,000 W/m^2 and the solar elevation is 35. If we consider first a situation in which a person is walking in an area with only 25% of full wind speed (for example behind a windbreak), then the COMFA budget would be 290 W/m^2, a very uncomfortably hot situation. If we then allow the person to walk out from behind the windbreak into full wind, the budget would be 268 W/m^2, still very uncomfortably hot. If we leave the person behind the windbreak but have him walking in the shade, allowing 15% of full sun, the budget becomes 97 W/m , still too warm but a large improvement. If we keep the person in the shade but now allow him to be in full wind, the budget becomes —74, nearly comfortable. We can see from this example that under conditions of high air temperature, solar radiation control is most important, but once this has been modified, wind can enhance the comfort of the microclimate.

Summary

Every part of a landscape modifies wind. Wind can be affected by most parts of the landscape, and significantly affects the thermal comfort of people and the energy use of buildings.

■ **There are many possible solutions to every wind-related problem in a landscape. There are also many tools available to the designer. Use them to enhance your design, but don't allow them to control your creativity.**

Things to think about . . .

1. **Question 6 in Chapter 4 asks you to decide on a location of a skating rink. Once the rink has been built, is there anything else you can do to make it even more comfortable for the skaters and to make it hold the ice longer?**

2. **Consider the suggestions you have made to the school board, the developer, and the city council (see questions at the end of Chapter 5). What detailed suggestions might you now give to each in terms of wind control?**

3. **You live in a snow-belt area and you hate shoveling snow. How can you determine the best location for your driveway so that it will stay free of snow? Once you have the location determined, what landscape elements would you locate near it to enhance the effect on the microclimate?**

4. **Mr. and Mrs. A (Chapter 6, question 2) are so happy with their deck that they would like to use it even in midwinter for barbecuing. They say the winter wind can be a bit cold on some days. What can you suggest for them? If you could relocate the deck, where would you put it?**

8

Temperature, Humidity, and Precipitation Modification

■ **AIR TEMPERATURE** and atmospheric humidity cannot normally be significantly modified by landscape elements, and so can often be ignored in design. Precipitation in the form of rain can be readily modified through use of overhead structures. Snow can be manipulated through wind modification. In general, temperature, humidity, and precipitation are not very important elements in design for microclimate modification.

Introduction

can be modified through landscape design, but must be dealt with differently than radiation and wind, in that it seldom is considered part of the energy budget of a person or a building. Instead, it is often dealt with as an inconvenience to people in a landscape, and designed for in a very straight forward manner (i.e., with the use of overhead structures).

Temperature and humidity both strongly affect the thermal comfort of people and the energy use in buildings. However, they normally cannot be modified significantly through landscape design. The atmosphere IS such an efficient mixer that any temperature or humidity differences that may occur arc normally dissipated very quickly.

There are some notable exceptions, however, that are worth exploring. If a microclimate can be disconnected or isolated from the prevailing atmospheric .systems, then significant effects can he achieved. An example is the “vest-pocket” park in heavily urbanized areas such as Manhattan. These can be completely isolated from the prevailing conditions by tall buildings on all sides and a canopy of trees above. Similarly, walled gardens can be isolated to achieve significant differences in temperature and humidity.

Characteristic

Air Temperature

■ Any localized changes you can make in air temperature will be quickly dissipated by air movement. However, if you isolate an area completely (such as by construction of a wall around the whole area), you can achieve some differences in air temperature, but even these are fairly small.

An example of a situation in which the air temperature of an area is lower than the surrounding landscape is a walled garden with high-canopied deciduous trees (Figure 8.1). Cool air may "pool" or collect inside the wall during the night. When the sun shines on the landscape the next day, the walled garden may be relieved of this input of energy by the canopy of the trees. Moreover, any wind that begins to blow will have difficulty mixing with the air inside the wall, and the heavier cold

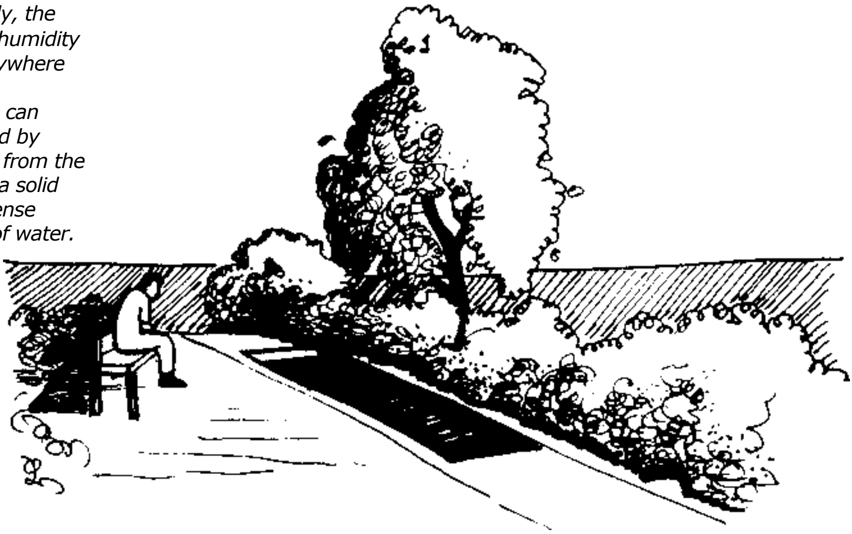


FIGURE 8.1 *Normally, the air temperature and humidity are very similar everywhere In a landscape. However, differences can sometimes be created by isolating a landscape from the surrounding area by a solid wall and providing dense shade and a source of water.*

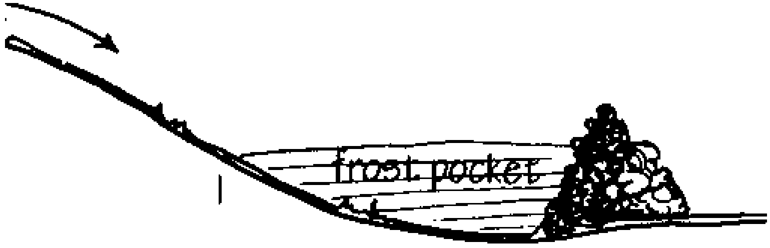
air inside will not have any opportunity to flow out. Consequently, the air temperature inside the wall may remain significantly lower than the prevailing air temperature.

This is a relatively difficult and expensive method of microclimate modification, and less efficient than most others. It is recommended only for unusual circumstances.

Frost pockets are another example of situations in which air temperature IS significantly different from prevailing conditions. Frost pockets occur on clear, calm nights in spring or fall when the temperatures are near freezing. Air on unobstructed hilltops will become cooler and denser than the surrounding air and will flow downhill until it encounters an obstruction (Figure 8.2). The pooling of cold air will create a very cold pocket in the landscape that can cause damage to plants.

Air Humidity

■ In general, any modification you can make in terms of humidity will be very quickly dissipated by air movement (wind). However, if you can completely isolate an area to reduce or eliminate air movement, you can achieve some humidity differences. For example, a walled garden can have a different humidity than the surrounding air. This sort of design might be beneficial for growing humidity-loving plants in dry climates.



Cool air flows down slope and pools against any obstruction

FIGURE 8.2 *On clear, calm nights air can cool rapidly. Cold air* is *denser and heavier than warm air and will flow slowly down slopes. It will pool in depressions or against: obstructions, creating frost pockets. These areas will he the coldest location in the landscape and can cause damage to plants. Frost pockets caused by obstructions can be eliminated by providing an outlet for the cold air.*

If the walled garden previously described (Figure <8.l) is completely isolated from the surrounding environment, and the wind is not able to stir the air, there is an opportunity to modify the humidity. This would require a relatively low prevailing humidity, such as might typically be found on the prairies or great plains iii summer. In an area of already high humidity it would be difficult and inadvisable to increase the humidity. However, in drier climates, an increase in humidity requires a source of water, such as a pond, or through transpiration from plants. As the water evaporates, it utilizes heat from the air and therefore cools the air.

Like modifying air temperature, modifying humidity is a relatively expensive and difficult effect to achieve, but there are clearly cases where it is worthwhile and beneficial. For example, m midwestern cities, where it is hot and dry in summer, parks with a cool, moist environment would be most welcome.

■ **Adding water to an otherwise dry landscape can provide another avenue for energy loss and, consequently, reduce the amount of energy that goes into heating surfaces and the air.**

■ **Snow and the subsequent transport of that snow by the wind are important considerations in landscape design.**

■ **Moving air carries amounts of snow relative to its velocity. The faster the wind, the more snow it can carry. If the air slows (or is forced to slow by a snow fence or windbreak), the snow will drop out and be deposited (Figure 8.3). If the air speeds up (such as through an opening in a windbreak or an opening between buildings), snow will be removed and carried away.**

Modification of snow deposition can be achieved through modification of wind patterns and an understanding of what you want to achieve. For example, if you want a driveway to remain clear of snow, you must achieve a general increase in wind speed as it passes over the driveway.

In areas where snow is deposited as it falls (for example, areas where the snow tends to be very wet and sticky) you must design the landscape based on the prevailing wind directions during snowfalls. These can be determined from weather records; typically, snow is

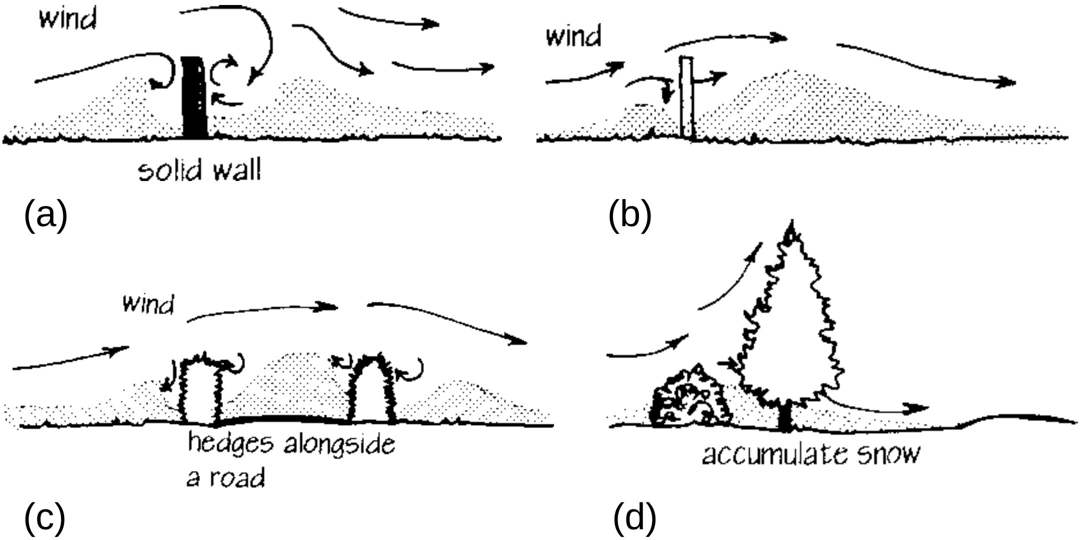


FIGURE 8.3 *The amount of snow that can be carried by a wind is a function or its speed. The faster it moves, the more snow it can carry. When a wind is strong and carrying a large amount of snow. You can make it drop that snow by reducing its speed. This can be done by installing a windbreak, such as a snow fence or evergreen hedge. Generally, solid barriers demonstrate some snow-catching ability, but porous barriers accumulate more snow over a larger area. Conversely, if you desire to remove snow from an area, you can do so by increasing the velocity of the wind (after Oke, 1987).*

accompanied by winds from the easterly directions.

In areas where snow is blown around after it fills (or more snow is added after the main storm by regional-scale effects such as those occurring near the Great Lakes) and is typically deposited in drifts (for example, areas where the snow is very dry and light), you must design the landscape based on the prevailing direction of **strong winds after a snowfall.** Again, these can he determined through analysis of weather records; typically, snow is blown around by winds from the northerly directions.

As we know, wind can also he locally increased in speed through channeling of air. This can be quite effective in removing snow from selected areas.

It is apparent, as we discuss snow removal, that this is going to create a dilemma. One way to resolve it is to ask whether you would prefer a thermally comfortable environment in which to shovel snow, or a thermally uncomfortable environment that does not require the shoveling of snow?

The converse to the removal of snow is the enhanced accumulation of snow. There might be situations in which you would like to have increased snow accumulation, such as on a cross-country ski trail, or in a garden area in a drier climate where added moisture would be welcomed. This can be achieved through the same means: modification of wind speed at critical times. In such cases you will attempt to reduce the wind speed as much as possible to have the snow deposit in the desired locations.

■ **Check local weather records to see which direction the snow-laden winds are most likely to come from. In many midlatitude regions northerly winds are associated with clear, cold weather, and the southerly or easterly winds are more likely associated with snow and other precipitation.**

■ **If you have the opportunity, make the snow drop out of the air before it reaches an area that you want to keep clear of snow (e.g., a road). This can be done by reducing the wind speed substantially for a short time upwind of the area. You can achieve such a reduction with permanent windbreaks of evergreen shrubs, or with temporary windbreaks such as snow fences.**

Summary

Every part of a landscape affects the air temperature, humidity, and precipitation. However, the effect is usually so small that there is often little observable effect on the thermal comfort of people or the energy use of buildings. Landscape elements can significantly modify the deposition of snow in an area. You can have snow deposit where you want It by reducing the speed of a snow-carrying wind.

Things to think about . . .

1. **You are working on a project on the North American Prairies where summers are very hot and dry. What can you do to make the landscape more thermally comfortable? How can you use water? How can you reduce the air temperature?**

2. **You have another project in New York State where it can be quite hot and humid in summer. How can you reduce the humidity and make it more comfortable? How about reducing the air temperature?**

3. **How can you design a country estate property so that trees planted to reduce winter energy use in the house do not create a snow accumulation problem?**

9

Integrating Microclimate information in Design

Introduction

The preceding chapters have provided tools for integrating microclimate information into design. Now we discuss **processes** for doing so in a more rational manner.

You have gained a basic understanding of microclimate and how it can be affected by the landscape. You now know;

1. **the components of microclimate that are important** (those that can affect the use of a space **and** can be modified through design).
2. **the effects that objects in a landscape can have on important microclimate components** (how different landscape elements affect microclimate).
3. **the effects of microclimate on people and buildings in the landscape.** You are now ready to use this information in designing new landscapes or modifying existing landscapes.

The approach to the use of this information in specific projects depends on a number of variables, including the amount of time and money you have to consider microclimate, the client's goals, your goals, the inherent characteristics of the site, whether people or buildings are involved m the design, and so on. There is no one "right" or "best" approach, nor is there ever a unique, "best" solution to any microclimate problem. Rather, approaches and answers are myriad; this is the nature of design. We provide you with a framework for evaluating microclimate in design. Feel free to use all or part of it as it works for you and your problems. It can be treated as anything from a checklist to a mandate.

Consideration of Microclimate in Design

One way to apply microclimate to design is described in Figure 9.1. It illustrates how microclimate considerations can be integrated into any design or planning process. Key steps m thinking about microclimate in landscape design include the following:

1. Decide on the microclimatic **goals**.
2. Set clear, achievable **objectives**.
3. Determine the amount of **time and money available**.
4. Determine the **activities, times of day, and seasons** of the year that you will he designing for.
5. **Reevaluate** your goal and objectives based on the information gleaned through steps 3 and 4.
6. Decide on an **approach** to microclimatic design (intuitive or rational).
7. Conduct an **inventory** of the microclimate, including both appropriate climate data and relevant site information.
8. **Analyze** the data through **mapping and determination of inherent characteristics** of the microclimate. (Because microclimate has tremendous variability through space and over time, there is no way to map it per se. Instead, map the **site characteristics that modify the climate** to create microclimates.)
9. **Superimpose proposed interventions** onto the site (design, plan, etc.) and determine whether they will affect the inherent characteristics.
10. Utilize the **microclimate modification tools** described in this book to enhance positive microclimates and improve negative ones.
11. **Test** the proposed interventions in a water flume and/or wind tunnel and through other tests.

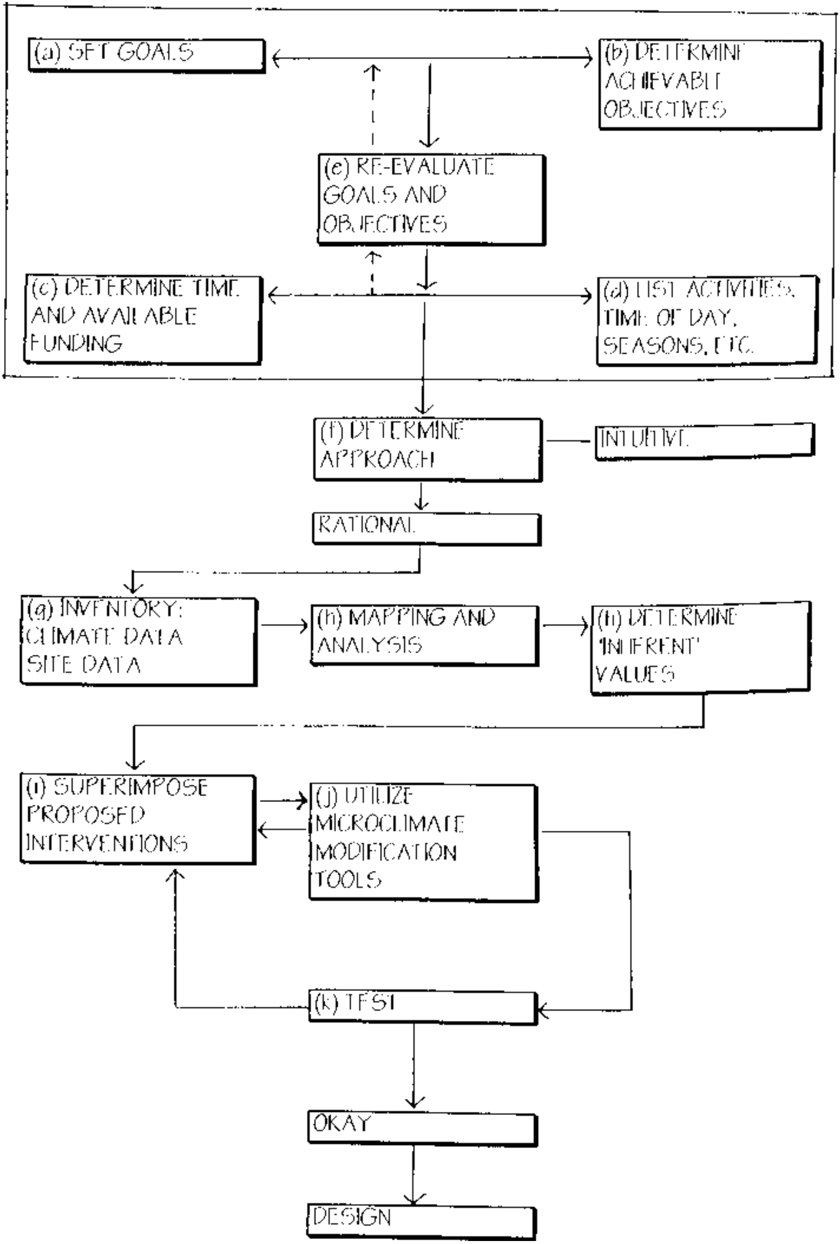


FIGURE 9.1 *This flowchart, outlines one way to apply microclimate information in designing or planning landscapes. It shows each step of the process to ensure that you do not miss essential information or bypass important steps. Use it as a reference in conjunction with the text.*

The following sections discuss these steps in greater detail.

Goals When setting microclimate goals for your design, first consider this definition of a goal.

- **A goal can be something that you want to achieve yet may never be able to measure directly whether or not it has been met.**

For example, a microclimatic goal might be “to provide a thermally comfortable environment.” You may be able to measure this tor discrete times and for specific people, but you will never be able to demonstrate that you have completely achieved the goal. The goal must be coupled with objectives that are measurable and must completely describe the goal. That is,

- **If all objectives can be determined to have been met, then the goal can be said to have been achieved.**

For example, a microclimate goal for a design might be “achieving thermally comfortable environments for people eating lunch in a park” or “minimizing the energy required to heat a house.” There could be more than one goal for a project. For instance, you might want to “provide thermally comfortable seating for spectators as well as a thermally comfortable playing area for athletes,” also want to “minimize the amount of energy required to heat and cool the fieldhouse.” This may require the prioritizing of goals, as maximizing one goal might adversely affect another.

It is important to write down your goals and continue to keep them in mind throughout a design process. If you change direction for some reason (e.g., is clients change their minds), evaluate how this affects your goals statement. If need be, rewrite your goals to meet the new situation. But,

- **Whatever you do, always have a clear goals statement to work from.**

Objectives Objectives go hand in hand with goals. Whereas a goal can be a lofty, unmeasurable statement, objectives must be clear and achievable. You must be able to measure or determine whether the objectives have been achieved. The objectives should be written so that:

- **Once all the objectives have been achieved the goal will be realized.**

An example may clarify the relationship between a goal and its objectives. Let’s say we set a goal to: **“provide a thermally comfortable outdoor eating area for a cafe.”** The objectives might he as follows:

1. Determine the times of day and seasons of the year when the client wishes the cafe to be used.
2. Conduct an inventory and analysis of the site and of the climate data to identify any inherently comfortable microclimates that occur during the desired time periods.
3. Propose a design that enhances positive microclimates and ameliorates negative microclimates.
4. Test the design tor comfort levels using a water flume and typical radiation data
5. Modify the design as required to achieve the maximum comfort levels.

- **Stated objectives can be expanded to provide more detailed instruction or tasks.**

For example, the tasks for objective 2 could be as follows:

a. Conduct an inventory of the site elements that might affect the radiation and the wind on the site.

b. Build a scale model of the site and test it in a water flume.

c. Acquire climate data from the weather station nearest the study site.

d. Request that the meteorological service provide data for typical summer days, typical fall days, and typical spring days, as well as wind directions and speeds that occur during the time periods the cafe is planning to be open.

e. Determine the microclimate of the site by interfacing the climate data and the site characteristics.

f. Map the microclimates as they would influence human thermal comfort for a person eating in the cafe.

g. Identify those microclimates that are inherently very comfortable for much of the desired time period, and note the characteristics that must be maintained (e.g., solar access).
h. Identify the key elements of the uncomfortable microclimates that make them uncomfortable and suggest how these might be ameliorated.

These tasks will lead to the achievement of the objective and ultimately to the realization of the goal.

■ State very clear objectives that will lead to the achievement of your goals. Write precise tasks that will operationalize the objectives.

Time and Money Available

Given unlimited resources of money and time, you could do a complete microclimate analysis and consider it in every aspect of design. However, this IS rarely the case, and most often you will be forced to make tradeoffs in your design work. The amount of time you have available to work on a project and the amount of money available to construct it should be clearly identified and factored into a reevaluation of the goals and objectives of the project. This may take the form of a simple prioritizing of objectives, or cutting back on each one so that all objectives can be achieved to a given extent.

■ State clearly the limitations in time and money, and use this to assist in determining priorities among your goals and objectives.

Activities and Times

It can be difficult to decide what information is needed for microclimatic design. Sometimes you may require detailed information on the winds during specific times of the year; other projects may need data on solar radiation during the winter as a primary input. People often gather much more climate data than they can use, and, frequently, much or most of it is inappropriate to the problem at hand.

■ In order to best utilize your resources and times, you should carefully consider time of use and the projected activities for the site or project.

This will allow you to decide specifically what microclimate is appropriate, and how to best use resources.

■ **The best way to determine what microclimate information is required is to start with your goal and work backward to see what information is needed to achieve it.**

Reevaluation of Goals and Objectives

Once you have completed the preceding two steps it is tune to revisit your goals and objectives to determine whether they need to be revised in any way. Perhaps you were too ambitious, or perhaps you now see the need to prioritize your objectives and tasks. This is an activity that should be ongoing throughout any project.

■ **Take time to revisit your goals and objectives and determine if they are still appropriate, given the information you have accumulated.**

Determining Approach

Once you are clear on your goals, objectives, tasks, and priorities, it is time to determine die most appropriate approach to the project. There are essentially two approaches that can be taken, but an infinite number of hybrids are possible. You will decide what works for you and your specific project. We discuss the intuitive approach anti the rational approach, but mix and match as you like.

intuitive Approach

Through reading this hook you now have considerable knowledge of the mechanisms that affect microclimate and of the ways that microclimate affects people and buildings. When you design you can keep these concepts in the "back of your mind," and your decisions will be altered based on this knowledge. Using this *intuitive* approach, you do not need to use the rest of the steps in the framework, just design keeping microclimate in mind.

Many of your design decisions will now begin to reflect microclimate concepts and will often be the appropriate decisions. If you use this approach you must often visit projects that have been constructed and observe and measure how they are working. That is, are people using the spaces the way that you had envisioned they would? Is the microclimate what you thought it would be? Then feed all this new information into your intuition, and future designs will be even better.

■ If you have little time, a small budget, and no real obvious microclimate problems, use the intuitive approach to design for microclimate.

Rational Approach

The rational approach suggests microclimate influence in every step of the design process or design framework. You can use microclimate information in the inventory and analysis of a site, in developing design concepts, in determining basic layout, at the detail design stage, in developing construction drawings and documents, during supervision of construction, and in postconstruction evaluation. Most of the tools for doing this have been provided in earlier chapters. The **process** for applying them involves all of the other steps in Figure 9.1, namely the inventory, analysis, mapping, superimposition of interventions, use of tools, and evaluation of proposals.

■ If you can afford the time and budget, or if you have a major microclimate problem, you should use a rational approach to design for microclimate first, and use the intuitive approach as you fine-tune your design.

Inventory of Climate and Site Information

■ Inventory, analysis, and design for microclimate must be more goal-oriented than for any other resource.

■ To develop an inventory of a site requires two activities: (1) measurement and mapping of appropriate site characteristics, and (2) accumulation of appropriate climate information.

This makes sense to us now, as we have spent time developing and learning techniques for estimating **microclimate** from **climate and site information.** We now need to apply these techniques.

Inventory of Climate Data

Some **general** climate information is valuable to collect, especially if you are unfamiliar with the climate in the region of the site. You may want to know generally what the seasons arc like. For example, are winters generally sunny and cold; cloudy, rainy and cool; or sunny and warm? You may also want to have information on frost-free periods, wind speeds and directions in different seasons, sunniness in summer, minimum temperatures in winter, and so on. However, much of what you gather will depend on your goals and objectives,

■ Some general climate information can be very helpful

When you begin to accumulate **specific** climate information, there are really two issues to consider: (1) determination of critical times of the year and of the day that are most likely to be uncomfortably hot or cold, and the conditions during these times, and (2) general or typical daily conditions that are likely to occur quite often in different seasons (a “typical day”). It can be useful to find actual hourly recorded values for typical days m each season where you might expect that people would want to be outdoors. People tend to prefer to be out of doors on sunny days, and these are most likely to provide the extremes of climate, so you would do well to find typical clear days in each season and record the hourly air temperatures, amounts of radiation, wind speed and direction, relative humidity, and how often you might expect each type of day to occur in any given year.

You will gain some insight into specific conditions, but in general the characteristics discussed earlier still hold: in summer design primarily to control sun, and in winter design primarily to control wind. In spring and fall design first tor wind, then for sun in northern locations, and first for sun and then for wind in more southern locations. When you couple these general principles with specific data, you acquire insight into specific conditions that need attention.

The most valuable information you can gain through hourly weather information will be about wind speed and direction in tall, winter, and spring, and about solar radiation levels in spring, summer, and fall. You can also gain information about these factors through climate summaries. It is worthwhile gathering information on the amount of time the wind blows from each direction and the speed of the wind from early direction in each month of the year or each season. Such data can be represented graphically through a simple wind rose (Figure 7.1b). This will give you general information, but even more valuable would be to determine the prevailing speed and direction of the wind during particularly cold events, for instance, when the air temperature does not rise above 0°C during the day. Ibis is “conditional” climate data as described in Chapter 2, which provides you with information on which winds to be most concerned about when considering human thermal comfort and energy conservation in buildings.

■ **Always keep your goal in mind. There is an incredible amount of climate and microclimate information available, much more than you can ever deal with. Only some of it will be of interest to you. Disregard all other information.**

Inventory of Site Data

There are some site data that are very valuable for microclimatic analysis. It is information that you will likely collect for other reasons, and you can reinterpret it for microclimate.

■ **The landform information that will most influence microclimate is the "slope and aspect."**

The slope (angle relative to horizontal) and aspect (the compass direction that a slope faces) together will strongly influence tire amount of solar radiation received and therefore available to drive the microclimate. The slope will also influence the local air flow, particularly on clear nights when there is radiation cooling.

Other land-based information that may be of interest in specific cases includes soil moisture levels (which influence the energy budget of a surface), and standing water (which may cool the air near it during the day and keep the air relatively warmer at night).

■ **Vegetation information that most influences microclimate concerns type and density.**

Deciduous trees, as we know, provide solar access during leafless periods, and obstruct much solar radiation during leafed periods. Coniferous trees obstruct solar radiation in all seasons. Shrubs, herbaceous plants, and ground covers do not normally provide shade for people, but do influence the energy budget of the ground surface, and thus the local ambient conditions. A surface with little or no vegetation (such as a paved parking lot or a sandy desert or beach) indicates the likelihood of extreme microclimates.

Mapping and Analysis

The mapping and analysis of microclimate of a site is necessarily different from analysis of most other resources. Most resources are reasonably static. For example, soils tend to change very little over time, so they can be mapped spatially. Moreover, once you have identified the soil characteristics you can interpret that information tor many different applications: potential for growing different crops, water holding capacity, and so on. Microclimate, however, cannot really be mapped because of its tremendous variability in both space and time. It you mapped the microclimate of an area at one moment, your effort may be wasted, as it might be completely different a moment later.

One way to resolve this dilemma is to map the microclimate as it relates to some issue of importance in specific design (e.g., your goals). For instance, if we wanted to design an area to maximize human thermal comfort, we know that our map would need to include wind and radiation but could probably ignore humidity, air temperature, and precipitation, as these will remain largely constant across the site. We also know that it is unrealistic to map wind spatially and radiation directly, except perhaps at one point in time. But,

■ **What we are most interested in is how the landscape modifies the prevailing wind and radiation on our site. Remember, we cannot do anything to change the prevailing atmospheric conditions, we can only modify them with landscape elements.**

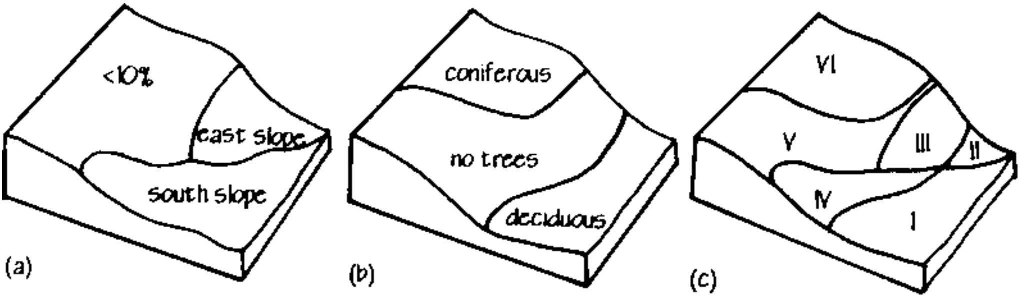
So,

■ **Map the slopes and their aspects and derive from this the first "layer" of a radiation map.**

The slope of the land will affect the intensity of the solar radiation received (see Figure 9.2a). As we learned in Chapter 3, the closer the slope comes to being perpendicular to the rays of the sun, the higher the intensity of radiation received. The orientation of the slope is also important, as south-facing slopes have higher intensity of solar radiation than north-facing slopes because of the movement of the sun in the sky. There are specific times of day when east- and west-facing slopes have high and low intensity of radiation, so projected time of use must be taken into consideration.

■ **Map the vegetation types to derive the second "layer" of a radiation map.**

A vegetation map can range from very simple categories, for example: three categories of (1) no trees, (2) deciduous trees, and (3) coniferous trees (see Figure 9.2b) to much more complexity where required. We are again trying to determine the effect the landscape will have on radiation. *No trees* will intercept no solar radiation before it reaches the ground surface; *coniferous trees* will intercept solar radiation m all seasons; and *deciduous trees* will intercept more solar radiation in summer than in winter. If we combine the slope and aspect layer with the vegetation layer we end up with a basic solar radiation map (Figure 9.2c). We can apply this to determining human thermal comfort across our site, or to evaluating the amount of energy required to heat buildings in different locations.



Legend

I = south slope, deciduous trees
II = east slope, deciduous trees
V = <10% south slope, no trees

III = east slope, no trees
IV = south slope, no trees
VI = <10% south slope, coniferous trees

FIGURE 9.2a *When producing a map fora microclimate, map the areal extent of landscape characteristics that modify the climate to create a microclimate. For example, when considering solar radiation, map the slope and aspect of the land, as this will determine how solar radiation is captured and what energy is available to drive the microclimate.*

FIGURE 9.2b *While the slope and aspect will provide you with the first step in radiation analysis, the second* step *is to determine whether there are trees to modify solar radiation. Deciduous trees affect the solar radiation differently in different seasons, whereas coniferous trees and areas with no trees tend to be fairly consistent through the seasons.*

FIGURE 9.2c *By superimposing the maps from Figures 9.2a and 9.Zb we can create an overlay map that identifies both characteristics simultaneously. This map can be analyzed to determine the most appropriate location for activities. For example, a trail to be used as a cross-country ski trail in winter and a walking trail in summer might be best located among coniferous trees on north-facing slopes. This can allow snow to remain on the trail as long as possible and provide a cool environment for summer hiking.*

The way to interpret the map depends on the projected season and time of use and the projected activity. It we take the example of determining the best site for a interpretive trail tor school groups, we might be able to limit our search to tall, winter, and spring and not concern ourselves with summertime when schools are typically on break. We then are searching tor locations with minimum wind and maximum sunshine, in that order. In very cold conditions the coniferous forest might be the best location because of its effect on lowering wind speed. The deciduous forest with a slope toward the south would also be a very good site, especially during spring anti fall, as it will provide considerable solar radiation to penetrate to the level where people would be walking, and would also reduce wind speed somewhat. The least comfortable situations would be in the open and on all north-facing slopes.

Another example is the determination of the best location fora cafe with an outdoor eating area. We might know that the projected time of use will be primarily during noontimes in midsummer. We will be attempting to reduce the solar radiation load as much as possible, anti to provide winds if this does not significantly affect the radiation modifiers. The north-facing slopes would be the coolest, and either deciduous or coniferous trees could provide substantial shade during midsummer. The cafe may he recommended for a very different environment than would the interpretive trail.

Superimposing Proposed Interventions

At this point, we know a lot about the study site and are very clear on what we are trying to achieve. It is time to propose our intervention, be it a landscape design, a plan, or the siting of a building. The siting of facilities can be done in the first instance through the use of microclimate maps and any maps you may have produced regarding capability for human thermal comfort or energy conservation in houses. A suitability map can now be produced. Whereas capability is the raw ability of a location to support certain functions or activities, suitability asks whether it is suitable to locate them there, based on other considerations. For example, although a site may be ideal microclimatically for an outdoor cafe, it may be much too far from the kitchen and the indoor cafe to make it feasible, and you might select instead a site of less microclimatic value, but located next to the building.

A suitability map can be produced for every goal you have set. You can have one for the outdoor cafe, one for the tennis courts, one for the driveway and parking lot, and so on. An area may have high capability for several activities, but suitability maps can help you decide among them.

Using Microclimate Modification Tools

Once the general locations have been identified, the actual detailed design and layout of facilities should be done using tools and procedures outlined in the chapters on radiation and wind modification, and, in special cases, m the chapters on modification of humidity, air temperature, and precipitation. These tools can be applied to every task to determine the most appropriate manner in which to design.

When layout has been determined by someone else: Sometimes the basic layout and siting of buildings and activities will be decided before you become involved in a project. At other times you will be asked to try to resolve problems in existing facilities. In either case you will not have the ability to move buildings and decide on locations of activities, only to fine-tune the existing situation. There is likely a considerable amount that you can do to improve it.

The first step is to evaluate the situation and identify the problem. As you are well aware, what the client tells you the problem is may be only a symptom of the real difficulty. But it is a good place to start. For example, a client may tell you that no one is using a courtyard set up as an outdoor eating area, which is restricting the number of people who eat at her restaurant.

When you evaluate a situation like this it might be worthwhile to options. If the existing eating area is on the north side of the building, it may be too cool to eat there during spring and fall, and people might be seeking a place in the sun. Possibly there is another location where the eating area could be situated that would provide for sunshine during spring and fall (on the south side of the building or, if the main time of business is late afternoon, for example, on the west side of the building).

■ A designer makes decisions while conscious of tradeoffs. If you make an area particularly comfortable for summer lunchtime use, you may be making it tremendously uncomfortable for evening use, or for fall and spring use. Always be conscious of the required tradeoffs.

Suppose the courtyard is on the south side of the building, and the problem is that it is too hot during the summer. You may try to intercept some of the solar radiation before it reaches the diners, by planting deciduous trees. The best trees might be those that leaf late in the spring, thus allowing maximum sunshine during cool spring days, and drop their leaves early in the fall, again allowing maximum sunshine during cool fall days. The trees would give maximum shade during the midsummer period, providing relief on hot, sunny days. It there is no opportunity for planting trees, or if the client wants immediate relief, you could provide other radiation filters. One approach might be to provide umbrellas with flexibility in location. Allow the diners to set up or take down umbrellas as the solar situation requires. This is not normally as good a solution, however, as umbrellas seldom shade all the people at one table. This limits the usefulness of umbrellas. An alternative might be to provide an overhead trellis that would provide a more general shade. This could be eventually covered with a vine that would act very much like a deciduous tree. Another approach would be to use your imagination and design abilities, rather than be constrained by what this book says or what others have done in the past. You now know the issues and what you are trying to achieve, and you can solve the problem in a creative manner.

■ Actually, one of the main intents of this book is to provide designers with a conceptual understanding of what they are trying to achieve and why, and let them be creative in how they solve it. There is no right answer, and not even any real prototypes. There are only creative solutions that resolve a problem and create the best situation possible.

Evaluation of Design Proposals

It is important to test your design before you construct it so that any potential microclimatic problems can be identified in the laboratory, rather than in the finished product.

Testing Designs Before Construction

Once a design has been determined “on paper” it can be tested in the laboratory to estimate what the microclimate might be like. This is a very important idea:

- **We can make our mistakes in the lab rather than in the real world.**

Several different tools and techniques are available for testing, each providing a different view of the resulting microclimate.

Wind tunnels and water flumes are scientific facilities that allow scale models of landscapes to be tested to estimate what the wind will be like once the project is built. Both require a physical model of the proposed landscape. Models must be fairly robust so that wind and water don't destroy them during testing. They should be constructed on a circular base, normally one meter or less in diameter. This configuration allows the model to be placed in a channel and rotated between tests so that the wind or water can flow over the landscape from all directions. File landscape will affect the wind differently with each wind direction, but will not change very much with different speeds. This allows the testing of each direction, but does not necessitate the testing of different wind speeds. The wind values that are yielded can be "relative" wind speeds, relative to the "free-stream" velocity (i.e., the velocity of the wind that is not affected in any way by the landscape).

A wind tunnel is literally a tunnel through which air is forced at regulated speeds. It is designed to model the way wind moves over and through a landscape. A model of the landscape to be tested is constructed and set in the middle of the tunnel. A large fan pushes or draws air over the model and mimics the way wind would move over and through the real landscape. A wind tunnel requires fairly sophisticated instrumentation and is not a particularly enlightening activity to watch, as you cannot see the wind in the tunnel any more than you can see the wind in any outdoor environment.

Sometimes the wind can be visualized through tiny flags or bits of cloth strategically placed throughout the model to indicate wind directions and speeds. As an alternative, smoke can be released upwind and you can see how it flows through a landscape. In general, however, wind tunnel activities don't yield particularly visual results.

A trained technician can measure the relative wind speeds and directions strategically throughout the model and map the wind flow. An isopleth map (a map with lines joining points of equal wind speed) can yield valuable information about wind speeds across a site when the wind is blowing from each different direction.

A water flume is similar in design to a wind tunnel, but instead of wind moving past the model, water flows over it. Water and air are both fluid, and water mimics air in moving over and through a landscape. Water has the advantage of allowing sand or other particles to he injected into the flow so an observer can visualize the flow. You can watch the water flow over and around your landscape, and also measure the relative speeds and directions around the landscape.

Both a wind tunnel and a water flume allow you to test a landscape both before and after construction, and you can move buildings and facilities around on the model site and retest if you get negative results. They are very powerful tools, but testing can be quite expensive.

Provide an "Ideal" Solution Using New Technologies

With the ever-increasing speed and capability of computers, many microclimate issues can now be modeled through computer programs. For example, we can input the equations that describe human thermal comfort and then, simply by inputting microclimate values for air temperature, humidity, sunniness, wind, and personal characteristic s such as activity level, and clothing, we can determine whether a people would be comfortable in a particular microclimate. It they would be too cool we can modify the microclimate to provide more sun, less wind, and so forth.

If you are also computer models available to estimate the microclimate of a site through inputs of site characteristics and climate data. These are primarily research tools at this time, but they are increasingly applied to real situations.

If you can envision coupling these scientific models with high-resolution computer animations, you might see what is on researchers' desks right now: a computer screen with a tour-dimensional image on It (the fourth dimension is time, meaning that the image moves and objects within the image move as well). At the request of the person sitting at the terminal, a microclimate analysis is conducted to estimate and map the radiation and wind across the site. Then a request can be made to estimate the thermal comfort levels across the site for any specific situation, say, for a tennis player on a typical summer day in midafternoon. Another four-dimensional image would be displayed on the screen indicating those areas predicted to be comfortable, as well as those predicted to be too warm or too cool. The operator might then request advice as to the reasons that an area might be too warm, and suggestions as to how that might be rectified. The computer might advise that the most effective modification would be to reduce the solar input, and suggest that this could be done most effectively through use of deciduous trees. An alternative suggestion might be to provide umbrellas at the sidelines so that players can cool off during a break in the game.

The computer may even begin to "learn" how you normally make your decisions, and may begin to provide you with better suggestions over time. If, for example, it noted that you seldom use umbrellas, but prefer to use native plant materials, it may begin to suggest these as preferred options. It might also indicate to you the potential advantages of using other plants or other materials that you often overlook.

This scenario may frighten some people and may excite others. It is still in the prototype stage at present and requires much development before it will be particularly valuable. In fact, as we know, wind is notoriously difficult to model on a computer, and until this problem has been resolved it is unlikely that the new technology will be of much value.

Conclusion

The framework presented in this chapter (Figure 9.1) can be applied to most microclimate design problems. Steps that don't apply to a given project can be skipped, and vital steps can be expanded as appropriate. It is important to follow some sort of rational process, though, to ensure that you have not forgotten something important.

Other Applications of Microclimate in Design

Throughout this book we have focused our attention on two main reasons for microclimate design: human thermal comfort and energy conservation in buildings. However, there are many other applications, several of which you are now capable of resolving by using the information in this book. The following sections will discuss a few other applications; we leave it to you to determine how to resolve others.

Survival of Plants in the Landscape

Most plants have been assigned a hardiness zone within which they can be expected to survive and thrive. These are often based on criteria such as minimum temperature in winter, length of the frost-free period, summer rainfall, maximum temperatures, snow cover, and wind. These are quite adequate for many applications, hut as we know, microclimate conditions can he significantly different from climate conditions. Hardiness zones arc based on climate, but you can determine your own micro-hardiness zones through some microclimate analysis.

In southern Ontario, peach tree orchards are restricted by hardiness zone charts to certain restricted areas: near lakes, in the extreme southern areas, and so on. However, individual trees can be grown quite adequately farther north, well outside their expected range. This is because northern microclimates can be created that have the same characteristics as the regional climate in the warmer hardiness zone.

By investigating the specific requirements and limitations of any particular plant species, you can often modify the climate by one hardiness zone or more. If, for example, the crucial characteristic of the peach tree is not survival, but the integrity of the blossoms in the spring, you can attempt to design for this. For instance, if the blossoms freeze solid they will not set fruit. If they are planted in a very open area, where there are no structures or other trees nearby, and are at the bottom of a long open slope, the microclimate would be ideal for a frost pocket to form, even on nights that might not frost elsewhere. However, if a peach tree is planted near a building that continued to emit longwave radiation at a rate higher than the clear sky, is located near other trees, and is on a slope that allows cold air to drain past it and create some convectional mixing of the air, you might very adequately grow peaches, The key is to determine the central characteristic and design the microclimate to reduce the negative effect.

More generally, there are many things that can be done in the siting of vegetable gardens, flower gardens, tender crops, and so on, that can increase the potential for survival and higher yields. For example, a vegetable growing season can be extended in the spring and the fall by designing an adequate microclimate, considering sunshine, wind, frost, and moisture. The combinations will change in different climatic regions, but normally the best conditions in midlatitude areas are (1) full sun in all seasons to provide warming in the spring and fall, (2) moderate wind (a reduction from full wind so that solar warming in spring and fall will not be quickly dissipated, but nor dead calm as this might enhance frost pocket creation on cool nights), (3) location on a slope with no barrier at the bottom, so that cool air can drain away during cool, clear nights, and (4) well-drained soil (drier soil will warm up earlier in spring than wetter soil), and, of course, many other things related to all parts of the microclimate.

Comfort and/or Survival of Animals

The comfort of animals can be considered and modeled in the same way as thermal comfort for humans. The main differences, of course, are that animals do not change their clothing regularly, and they cannot be asked whether they are comfortable (at least, if they are asked they normally will not answer). In other ways, the situation is the same.

This type of analysis can be valuable in agriculture, especially if livestock are kept outdoors at any time. There are many examples of appropriate pens and environments for livestock, and some of them seem odd at first analysis. For example, on the prairies cattle are often kept outdoors even during extremely cold winters. Board fences are often provided for the animals to shelter behind on windy days. These fences, however, are not solid, but have spaces between the boards, sometimes as much as several inches wide. It may seem that this would not provide much shelter, but we know from our discussion on windbreaks that a somewhat porous windbreak provides a larger area of reduced wind speed. So this porous fence actually provides a better shelter for the cattle than would a solid one.

Other Applications

There are many other applications to think about. One is the dispersion of dust or fumes across a site. These can be treated as point-source or line-source pollutants and their dispersion modeled with the use of wind tunnels or water flumes, as well as information on fallout rates and so forth. Proposed interventions can be tested to see whether they will reduce the pollutant levels at key points.

Another application is the dispersal of sound across a site. Sound can also be dealt with as a point-source or line-source, and computer models are available that can estimate sound levels at any point in a landscape. These can also, to a certain degree, predict the effect of interventions in the landscape. This field is being actively researched, as it has tremendous implications for urban dwellings near roads, rural dwellings near industrial plants such as gravel crushers, and so on.

Summary

There are many options for making microclimate an integral part of landscape design.

The information you have learned sometimes fits neatly and conveniently into the landscape design or planning process. In other instances it can be used most effectively through the enhancement of a design or to assist in determining management procedures.

■ Microclimate is still an inexact science, so when you have designed the best microclimate possible, always allow for people to modify the landscape as they desire (i.e., provide a range of opportunities, such as umbrellas, movable trellis pieces, etc.).

Things to think about . . .

1. **What climate information do you really need to decide on the location and the details of the deck for your Mr. and Mrs. A (question 2, Chapter 6)? For the courtyard (question 1, Chapter 1)? For the skating rink (question 6, Chapter 4)? For the trail through the park (question 7, Chapter 4)?**

2. **If you could ask the weather records people for a specific analysis of their data, what would you ask for? For the courtyard problem? For the skating rink?**

3. **If you could design an instrument that weather stations would begin to use regularly, what would it measure? Why?**

Appendix A

Quantitative Determination of Human Thermal Comfort Using a COMfort FormulA-COMFA

An energy budget can be used to determine quantitatively the thermal comfort level of a person in an outdoor environment. We begin with the basic COMFA equation:

$$\text{Budget} = M + \text{Rabs} - \mathit{Conv} - \mathit{Evap} - TR_{\text{emitted}}$$

where

M = metabolic energy used to heat up the person
R_{ab} = absorbed solar and terrestrial radiation
Conv = sensible heat lost or gained through convection
Evap = evaporative heat loss
TR_{emittcd} = emitted terrestrial radiation

When the budget is near zero, a person can he expected to he thermally comfortable. If the budget is a large **positive** value, then a person would he receiving more energy than would be lost, so overheating would occur and the person would be uncomfortably warm. Conversely, it the budget is a large **negative** value, a person would he too cool.

Each of the components of COMFA can he described through equations as outlined in the following sections. A complete listing of the equations as they would be written in the BASIC programming language is included in the last section of this appendix.

Metabolic Heat Production - *M*

The total metabolic heat generated by a person (M*) is utilized by the body in two ways: (1) a small part (f) is consumed during breathing through evaporation of water and sensible heat loss, and (2) the rest (M) is conducted to the outer body surfaces and ultimately is lost through convection, evaporation, and radiation. To describe these heat losses we use:

$$f = 0.150 - 0.0173e - 0.0014(Ta)$$

where e is the saturation vapor pressure at air temperature and is the air temperature (°C) and

$$M = (1 - f) \times M^*$$

Values for M* are a function of activity level. Values for some typical landscape activities can be found in Table A.l.

Absorbed Solar and Terrestrial Radiation - Rabs

The value of Rabs can be determined in a number of different ways, four of which are outlined in Appendix B: (1) **measure** solar and terrestrial radiation received at a site, or use data measured at a nearby weather station, and **calculate** how much would be absorbed by a person, (2) **estimate,** using equations, the radiation absorbed by a

TABLE A.1

Metabolic Rates (M*) for Selected Activities

	M* (W/m^2)
Sleeping	**50**
Awake, resting	**60**
Standing, sitting	**90**
Working at a desk or driving	**95**
Standing, light work	**120**
Walking slow (4 km/hr)	**180**
Moderate (5.5 km/hr)	**250**
Short spurts of intense activity	**600**

person at your site (often the most useful for landscape design), (3) use a simple-to-build “radiation thermometer” that can be used to estimate the Rabs value of any environment at any time, or (4) estimate radiation received under trees by considering the porosity of the canopy.

Convective Heat Gain or Loss-CONV

The flow of heat from a person’s core to the open air must pass through the body, through any clothing, and finally through the boundary layer of air around the person’s body. The equation that describes this heat flow is:

$$CONV = 1200 \text{ x } (\mathrm{Tc} - \mathrm{Ta})/(r_t + r_c + r_a)$$

Where Tc is the core temperature (°C) of a person, r_t is the resistance to heat flow of body tissue, r_c is the resistance of the clothing, and r_a is the resistance of the boundary layer around the body. These can be estimated through:

$$Tc = 36.5 + (0.0043) \text{ x } M$$

and

$$r_t = -0.1 \text{ x } (\mathrm{M}^*) + 65$$

$$r_c = 0.17 \text{ x } (\mathrm{A} \text{ x } \mathrm{Re}^n \text{ x } \mathrm{Pr}^{0.33} \text{ x } \mathrm{k})$$

$$r_a = r_{co} \text{ x } [1 - (0.05P^{\,0.4} \text{ x } W^{\,0.5})] \qquad \text{when } W > 0.7 \text{ m/s}$$

$$\text{when } W < 0.7 \text{ m/s}$$

where

r_{co} = insulation value of clothing in units of s/m
P = air permeability of clothing fabric
Re = Reynolds number = WD/v = 11,333 x W in this case
Pr = Prandtl number $\equiv$ 0.71
D = Diameter of the person
W = wind speed in open (m/s)
V = kinematic viscosity
k = thermal diffusivity of air = 0.0301

For values of r_{co} and P for typical ensembles of clothing refer to Table A.2.

TABLE A.2
Insulation and Permeability Values of Some Typical Clothing Ensembles, for Application in COMFA Calculations

	r_{co}	P
A: T-Shirt, short pants, socks, running shoes	**50**	**175**
B: T-Shirt, long pants, socks, shoes or boots	**75**	**1 50**
C: T-Shirt, long pants, socks, shoes, windbreaker	**100**	**100**
D: Shirt, long pants, socks, shoes, windbreaker	**125**	**65**
E: Shirt, long pants, socks, shoes, sweater	**175**	**125**
F: Shirt, long pants, socks, shoes, sweater, windbreaker	**250**	**50**

Rco = insulation value (s/m) and *P* = permeability of clothing ensemble

Emitted Terrestrial Radiation - *TR*emitted

The terrestrial radiation emitted by a person can be estimated by:

$$TR_{emitted} = 5.67 \text{ x } 10^{-8} \text{ x } (T_s + 273)^4$$

Where T_S is the surface temperature of a person and can be found from the equation

$$(Ts - Ta)/r_a = (Tc - Ta)/(r_t + r_c + r_a)$$

Evaporative Heat Loss - *EVAP*

Evaporative heat losses occur through respiration and perspiration. Respiration losses were dealt with through *M*. Perspiration can be divided into "insensible" losses (Ei) through the skin and "sensible" losses (Es) through perspiration. The following equations can be used:

$$Es = 0.42 \text{ x } (M - 58)$$

and

$$Ei = 5.24 \text{ x } 10^6 \text{ x } (q_s - q_a)/ (r_{cv} + r_{av} + r_{tv)}$$

Where the subscript "v" denotes resistance to water vapor, q_s and q_a are saturation-specific humidity at skin temperature (Ts) and air dew point temperature (Ts), respectively, and can be determined by using the appropriate temperature value in the following equation:

$$q = 0.6108 \times \{\exp [(17.269 \times T)/ (T + 237.3)]\}$$

Similar to the surface temperature determination discussed earlier, a series resistance analog allows skin temperature (T_k) to be found using:

$$(T_k - T_a)/(r_a + r_c) = (T_c - T_a)/(r_t + r_c + r_a)$$

We use values of 77 x 10^3 for r_{tv}, and 0.92 x r_a for r_{av}. We assume $r_{cv} = r_c$. Then total evaporation is simply:

$$Evap = E_i + E_s$$

There is a situation wherein humidity in the air can be so high that evaporation cannot occur rapidly enough to consume perspiration available at the skin surface at a rate that ensures a person's comfort. A maximum possible evaporation (E_m) is calculated as follows:

$$E_m = 5.24 \times 10^6 \times (q_s - q_a)/ (r_{cv} + r_{av})$$

For energy budget calculations, we use the lower of E or E_m.

To implement the model, we write it as a computer program and simply have the computer request the required information. All values are in metric units (degrees Celsius, meters, watts, etc.).

The value that is returned by the equations is in units of "watts per square meter" and these can be translate into comfort values approximately according to Table A.3.

TABLE A.3
Translation of Energy Budget Values into People's Comfort Levels

Budget (W/m^2)	Interpretation
Budget < - 150	**Would prefer to be much warmer**
- 150 < Budget < - 50	**Would prefer to be warmer**
- 50 < Budget < 50	**Would prefer no change**
50 < Budget < 150	**Would prefer to be cooler**
150 < Budget	**Would prefer to be much cooler**

BASIC Program of COMFA

Type the lines into a microcomputer and type “run.” The computer will request the information required and will calculate a “comfort budget” for any microclimate.

```
 10  INPUT “Metabolism (W/m²) =”; M
 20  INPUT “Air Temperature (C) =”; T
 30  INPUT “Wind speed (m/s) =”; W
 40  INPUT “Insulation value of clothing (s/m) =”; C
 50  INPUT “Permeability of clothing =”; P
 60  INPUT “Relative Humidity (%) =”; H
 70  INPUT “R(abs) in (W/m²) =”; R
 80  H = H/100
 90  B = (- . 1*M) +65
100  E= (0.6108* (EXP((17.269*T) / (T+237.3)))
110  F= (0.15 – (0.0173*E) – (0.0014*T)
120  J=36.4+((0.0043) *M)
130  G=J – (((1-F) *B*M)/ 1200)
140  X= 11333*W
150  IF X<4000 GOTO 180
160  IF X<40000 GOTO 190
170  Y=0.0226: Z=0.805: GOTO 200
180  Y=0.683: Z=0.466: GOTO 200
190  Y=0.193: Z=0.618
200  N=204/ (.0214*Y*(X^Z))
210  K=C*(1-(0.05*(W^.5)) *(P^.4))
220  Q=1200*((G -T) / (N+K))
230  X=T+ (N*((G – T) / (N + K)))
240  O=0.8*((.95*5.67E-08) *((X+273) ^4))
250  X=0.6108*(EXP((17.269*G) / (G+237.3)))
260  Y=5240000*(X – E) / ((7700+K+(.92*N)) *(G + 237.3))
270  U=Y*((7700+k+(.92*N)) / (K+(.92*N)))
280  V=0.42*(M – 58)
290  IF V>0 GOTO 310
300  V=0
310  Y=Y+V
320  IF Y<U GOTO 340
330  Y=U
340  S= (R+((1 – F) *M)) – (Y+Q+0)
350  PRINT “BUDGET =”; S
360  END
```

Appendix B

Estimating Radiation Received by a Person in the Landscape

B.1. Estimating Radiation Using Weather Station Measurements

We use models that describe separately both the solar and terrestrial radiation balance of a person. The total radiation received by a person in any environment consists of two components: (a) the total solar radiation absorbed, Kabs, plus (b) the terrestrial radiation absorbed, Labs, or

$$\text{Rabs} = \text{Kabs} + \text{Labs}$$

We typically model a person in a landscape as a vertical cylinder within a sphere of influence (see Figure B. 1). The upper hemisphere is generally dominated by the sky and objects above the ground plane, while the lower hemisphere is generally dominated by the ground surface and objects on the ground.

Solar Radiation Model

The amount of solar radiation absorbed by a person can be estimated by first summing all the sources of solar radiation received by the person, including (a) direct solar radiation transmitted through any canopy, T, (b) diffuse sky radiation received directly, D, (c) diffuse radiation reflected by trees or other objects in the sky hemisphere, S, and (d) radiation reflected by the ground, R (sec Figure B.2). The sum of the inputs is multiplied by (1 - albedo) to determine the amount absorbed by a person:

$$\text{Kabs} = (T + D + S + R) \text{ x } (1- A)$$

Typical values for the albedos of humans are 0.35 for Eurasians to 0.18 for Negroids. The amount of radiation absorbed by a person is more dependent, however, on the albedo of the clothing than the skin. In our modeling we use 0.37 for the albedo of a *clothed* person, as suggested by several authors in the literature.

Each component of this equation is estimated by other equations as follows;

a. Under a canopy of foliage with solar radiation transmissivity, t, the transmitted direct solar radiation received by a person, T, is estimated by several steps, as follows: (1) subtract the diffuse solar radiation, K_d, from the total solar radiation measured on a horizontal flat plate at a nearby weather station, under an unobstructed sky, K, to obtain the amount of direct solar radiation reaching the tree; (2) divide this value by the tangent of the solar elevation angle and divide by π to estimate the amount of radiation received by a vertical cylinder; and finally, (3) multiply by the proportion of incident radiation transmitted by the tree canopy or other objects(s) between the person and the sun, t. So;

$$T = \{[\ (K - K_d) \text{ x } \sin e)/\ \pi\} \text{ x } t$$

Diffuse radiation can be estimated as 10% of K under very clear sky conditions.

b. The diffuse component received by a person, D, is estimated (in clear sky conditions) by multiplying the amount of diffuse radiation available, K_d, by the proportion of the sky hemisphere unobstructed by trees or other objects, the sky view factor, SVF.

$$\mathrm{D} = K_d \text{ x } SVF = 0.1 \text{ x } K \text{ x } SVF$$

c. Some diffuse radiation, S, is reflected from objects in the sky hemisphere onto the person. This can be estimated by multiplying the proportion of the sky obstructed by objects, $(1 - SVF)$, by the diffuse radiation available, K_d. This value is then multiplied by the albedo of the object(s) in the sky hemisphere, A_o, or

$$S = [\ K_d \text{ x } \{1 - SVF)\ ] \text{ x } A_o$$

d. The solar radiation reflected from the ground surface onto a person, R, can be estimated by multiplying K by the transmissivity,

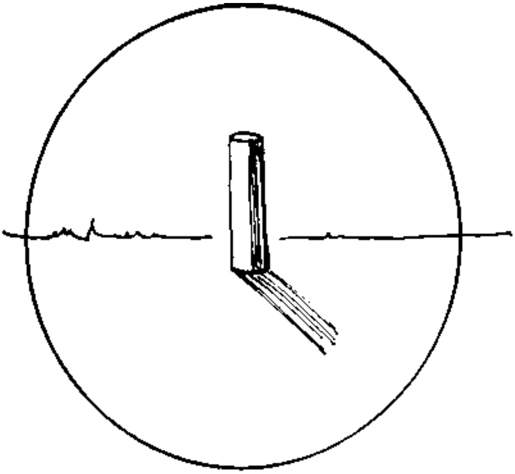


FIGURE B.1 *Sphere of influence for a person in the landscape*

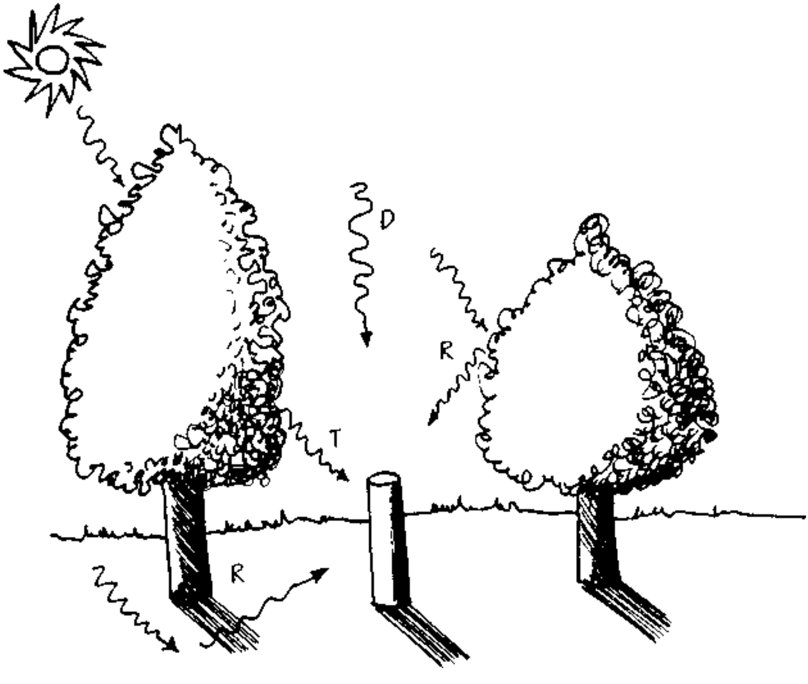


FIGURE B.2 *Modeled paths of solar radiation from the sun to a person* *t,* of the object(s) in the sky hemisphere between the sun and the point of ground that reflects solar radiation onto the person. This value is then multiplied by the albedo of the ground surface, *A*g, or

$$\mathrm{R} = K \times \mathrm{t} \times A\mathrm{g}.$$

Values for *t* range from 0.15 for spruce to 0.75 for willow. The albedo of the ground is often taken as 0.09.

The terrestrial radiation absorbed by a person can be modeled in a manner similar to that used for solar radiation; that is, as a cylinder in a sphere, with equal influence from every part of the sphere (see Figure B.3). The terrestrial radiation received from the sky hemisphere is a sum of the sky radiation, *V*, plus the radiation from objects in the sky hemisphere, *F*. The terrestrial radiation received from the ground hemisphere is simply the radiation from the ground surface, *G*. The resultant sum is multiplied by the emissivity of a person, *E*, which is approximately 0.98

$$\mathrm{Labs} = \{[0.5 \times (V+F)] + (0.5 \times G)\} \times E$$

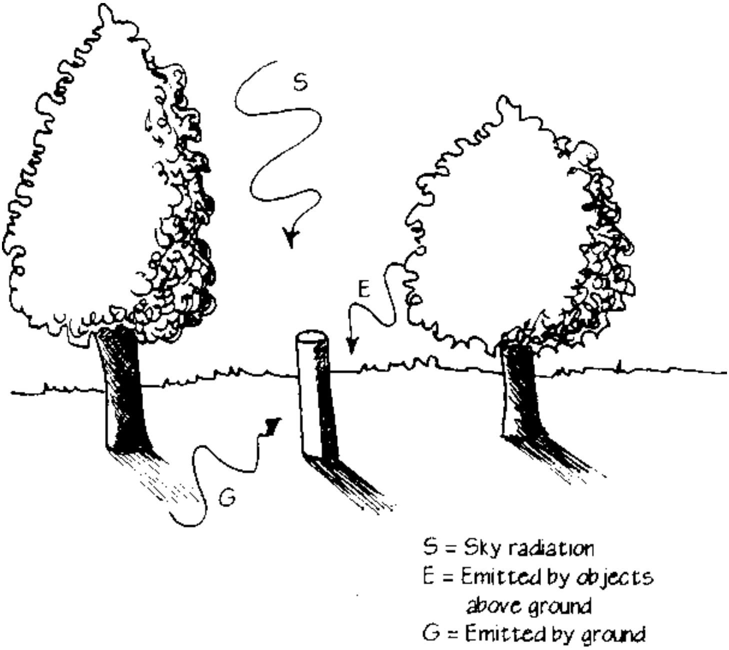


FIGURE B.3 *Modeled paths of terrestrial radiation from the environment to a person.*

The factor 0.5 allows for the sky and ground hemispheres.

The components of this equation can be estimated from the following equations;

a. The sky emits terrestrial radiation, *L*, that is received by a person, *V,* based on the proportion of the sky that is visible, the sky view factor (*SVF*), or

$$V = L \times SVF$$

The value of *L* can be estimated from an empirical equation based on the temperature of the air in kelvin (Celsius + 273), T_a

$$L = (1.2 \times E \times [5.67 \times 10^{-8}] \times Ta4) - 171$$

b. The radiation received from objects in the sky hemisphere can be estimated based on the temperature of each object, T_a

$$F = (E \times [5.67 \times 10^{-8}] \times To4) \times (1 - SVF)$$

It is often fine to estimate that the objects in the sky hemisphere are at air temperature.

c. The radiation from the ground surface received by the person, *G*, can be estimated by knowing the temperature of the ground, T_g, from

$$G = (E \times [5.67X 10^{-8}] \times Tg4)$$

We have included a complete listing of the computer program written in BASIC language. This program can be typed into a computer and used to calculate radiation received by a person in different microclimates.

```
10  INPUT "Air Temperature (C) ="; T: TK=T+273.15
20  INPUT "Measured Solar Radiation in the Open
    (W/m²) ="; SWO
30  INPUT "Solar Elevation =" ; EL
40 INPUT "Diffuse as % of Measured Solar
    Radiation ="; DIFFP
50 REM A safe estimate is 10% for very clear skies
60 INPUT "Transmissivity of object(s) between
    person and sun (%) ="; SR
```

```
 70  REM For no obstruction use SR = 100; for a building use SR = 0
 80  SR=SR/100
 90  INPUT “Albedo of object(s) in the sky hemisphere (%)”: ALBO
100  ALB0=ALB0/100
110  INPUT “Albedo of ground (%)”; ALBGRND
120  ALBGRND=ALBGRND/100
130  INPUT “Albedo of test person (%)”; ALBP
140  REM We typically use 37% for a clothed person
150  INPUT “Sky View Factor (%)”; SVF
160  SVF=SVF/100
170  DIFFS-DIFFP*SWO/100:DIFFD=DIFEP/100
180  RAD=0.017453293
190  EERAD=EL*RAD
200  EONGS=(1.2*(5.67E-08*(TK^4) ) ) - 171
210  SWPLT=((1-DIFFD)*SW0)/(TAN(ELRAD))
220  SWCYL=SWPLT/3.141592654
230  TOTAL=.98*( 5.67E-08*(TK^4) )*(1-SVF)
240  REFL=SW0*SR*AEBGRND
250  LGRD=.98*(5.67E-08*(TK^4) )
260  LABS=(((T0TAL+(SVF*LONGS))*.5)+(LGRD*.5))*.98
270   KABS=((SWCYF*SR) + (SVF*D1FFS)+DIFFS*(1-SVF)*ALB0) +(REFF))*(1-
ALBP)
280  RABS=(KABS+LABS)
290  PRINT “Solar radiation absorbed by a person (W/m2) =”: KABS
300  PRINT “Terrestrial radiation absorbed by a person (W/m2) =”; LABS
310  PRINT “Radiation absorbed by a person (R(abs)) {W/m2) =”; RABS
320  END
```

B.2. Estimating Radiation Using No Measured Radiation Data

Rabs can be estimated for a person at a site some distance from a weather station using an approach similar to that described in Appendix C.l, but using an estimate of the radiation based on some global modeling. Radiation values are often difficult and costly to obtain, whereas air temperature values are measured more easily and at far lower cost.

This approach requires the estimation of *K,* and then the input of this value into the model described in Appendix C. 1. K can be estimated as follows:

a. Start with the solar constant, C = 1360 W/m^2. This is the nearly constant amount of radiation received by the earth from the sun.

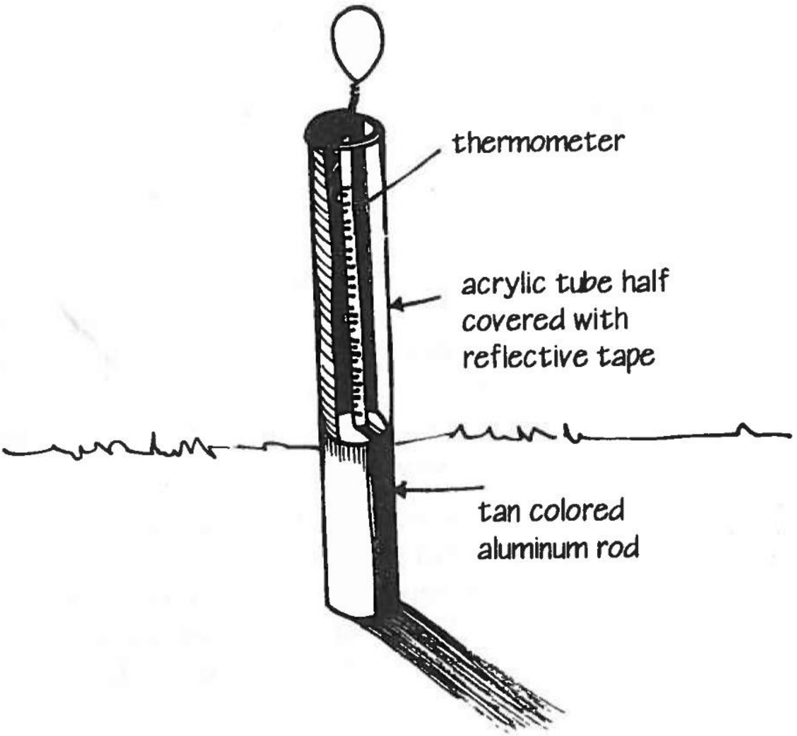
b. Solar radiation at the top of the atmosphere, K_t, can be determined by multiplying the solar constant by the sine of the elevation angle of the sun, *e,* then further by the square of the mean distance from earth to sun, *d,* over the instantaneous distance from earth to sun, d_i. If you make your estimates near equinox, it is reasonable to assume that $d/di = 1$, so that $K_t = C \text{ x } \sin e$. At other times actual values would be required.

c. K_t is reduced in value by the atmosphere before it reaches the surface of the earth. On a clear day some of the radiation is reflected. A_r, and some absorbed, A_a, by dry air molecules, dust, and water vapor in the air. These values are approximately $A_r = 6\%$, $A_a = 17\%$ on clear days. This means that a reduction of 23% by the time K_d reaches the surface, thus K = 0.77 x K_t. This estimation approach has yielded surprisingly good estimates of radiation without the need for measurements.

B.3. Estimating Radiation Using a Simple-to-Build “Radiation Thermometer

We have devised a simple-to-build instrument that allows anyone to monitor the amount of radiation that would be received by a person in any outdoor environment. This “radiation thermometer,” which we affectionately call “littleman,” (see Figure B.4) is a tan-colored 11.0-cm-long by 1.3-cm-diametcr aluminum cylinder with a thermometer inserted in the top. The cylindrical shape is similar to a standing person, and the color (Munsell 7.5 YR 7/3) has an albedo (37%) similar to that of the average clothed person, so the instrument acts to absorb solar and terrestrial radiation in much the same way as would a person standing in that environment.

We inserted a mercury-in-glass thermometer so that the bulb was about halfway down the aluminum cylinder and used a “thermal compound” to ensure fast response. We then used an acyclic tube, half



covered with reflective tape, to protect and shield the thermometer from radiation.

To use the cylinder, simply hang it near chest height in the environment to be tested, and wait until the thermometer temperature reaches equilibrium. You must measure two other things at the same time: air temperature and wind speed. You can then use the following equations to determine the amount of radiation absorbed by a person in any environment R_{abs}

$$R_{\mathrm{abs}} = [5.67 \times 10^{-8} (T_{\mathrm{e}} + 273)^{4}] + [(1200) \times (T_{\mathrm{e}} - T_{\mathrm{a}}) / r_{\mathrm{m}}]$$

where

$r_{\mathrm{m}} = D / \{A \times \mathrm{Re}^{n} \times \mathrm{P}^{33} \times \mathrm{k})$
Re = Reynolds number = $V \times \mathrm{D/v} = 833 \times W$ in this case
Pr = Prandtl number = 0.71

D = diameter of cylinder
V = tree stream air velocity (m/s)
v = kinematic viscosity
k = thermal diffusivity of air = 0,0301 and A and n are empirical constants derived through experiments on heat flow from cylinders.

When Re < 4,000, $A = 0.683$ and $n = 0.466$; if Re is between 4,000 and 40,000, $A = 0.193$ and $n = 0{,}618$; and if Re > 40,000, then $A = 0.0266$ and $n = 0.805$.

When you complete these equations you will have the value for Rabs, which can be inserted into the COMFA equations to determine thermal comfort of a person.

A listing of a computer program, written in BASIC, that uses these equations to estimate Rabs is as follows:

```
 10  INPUT “Air Temperature (C) =”; T
 20  INPUT “Wind Speed (m/s) =”; W
 30  INPUT “Temperature of Radiation Thermometer (C) =”; A
 40  L=(((273+A)^4)*.95)*5.67E-08
 50  X=833W
 60  IF X<4000 GOTO 90
 70  IF X<40000 GOTO 100
 80  Y=0.0266: Z=0.805: GOTO 110
 90  Y=0.683: Z=0.466: GOTO 110
100  Y=0.193: Z=0.618
101  I = 15/ ( 0.0214*Y*(X^Z) )
120  D=(1200*(A-T)) / I
130  RABS=(D+L)*0.8
```

B.4. Estimating Radiation Environment Under Trees in the Landscape

The amount of radiation received by a person under a tree in the landscape can be estimated by the process outlined in Section B.1, but there is an additional component that must be considered to provide a very accurate estimate. You may recall that leaves will allow a considerable amount of invisible, near infrared, solar radiation to pass through. We have not yet considered this component in our calculations, but it can be significant for a person under a deciduous tree in full leaf on a very sunny day.

This component can be calculated by simply following a few steps:

1. Subtract the winter density of the canopy from the summer density. For example, a photograph of a tree in winter may reveal a density of 45% in winter (owing to twigs and branches), while a photograph in summer may suggest a density of 75%. The difference (75% - 45% = 30%) is the amount of the canopy that is occupied by leaves only.
2. We multiply this value by the amount of solar radiation reaching tire canopy, and then by 50% to represent the proportion of the total solar radiation reaching the tree that would be near infrared radiation, then by a further 40% to represent the portion of the near infrared radiation that could be expected to pass through the leaves.
3. The total calculated in step 2 is added to the amount of solar radiation reaching a person, some of which would be absorbed and act to heat the person.

In some cases this additional near infrared radiation can raise the solar radiation received by a person from 23% to 38% - a significant increase on a sunny day.

Appendix C

Estimating Wind in the Landscape

C.1. In Open Areas Based on Measurements Taken at a Nearby Weather Station

Wind measurements taken at a weather station are recorded by instruments at 10 m above the ground. Given the wind at one height above a uniform surface, we can readily estimate the wind at any other near-surface height using the so-called logarithmic wind profile, The generic equation that can be used for all heights up to 10 m is:

$$W\ (z) = U_{10}\ \mathrm{X}\ \{[\ln(z/z_{OS})]/\ (\ln 10/z_{OW})\}$$

where

z = height above the ground of the wind in question,
U_{10}= wind speed at 10 m above the weather station (the normal height of measurement),
z_{OS} = a constant based on the height of the vegetation at the test site (z_{OS} = 0.13 x height of vegetation),
z_{OW} = 0.13 x height of vegetation at weather station =0.13 x 0.1m = 0.013.

We often need to know the wind at a height of 1.5 m above the ground, and we can calculate this using:

$$W(1.5) = U_{10}\ \{[\ln(1.5/\ z_{OS})]/6.65\}.$$

C.2. Behind Windbreaks of Known Porosity

Once the wind at 1.5 m above the ground has been calculated, you can consider this to be the free-stream velocity of the air approaching a windbreak. If you have calculated that the wind approaching a windbreak. If traveling at 3 m/s, you simply multiply this value by the percentage offull wind as read off the graph or diagram (see, e.g., Figure 7.3 or 7.4). For example, if you are interested in the area that is labeled as having 50% of full wind, then the wind speed would be approximately 1.5 m/s, a value that can then be used to determine human thermal comfort.

C.3 In Heavily Treed Areas

If you are considering a site within a heavily treed area, you could use a graph such as Figure 7.6. Alternatively, there are some equations to assist you in making reasonable estimates of wind speeds within the canopy using only wind measurements at a nearby weather station. This is a two-step process.

Step 1 involves determining the wind speed at a point at 20% of the height of the canopy or above, using:

$$W_z = W_{CT} \text{ x } [3 \text{ x } (1- (z/CT)\,]^{-2}$$

where z indicates the height at which the calculation is being made, and CT is the height at the top of the canopy.

From the 20% point to the ground the wind speed can he calculated using:

$$W_z = W_{CT/5} \text{ x } [\ln(z/z_o)/\ln\,(CT/5 \text{ x } z_o)]$$

Where z_o is typically around 0.05 m.

Suggested Readings

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