Bioclimatic design

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Glossary
Terms and symbols frequently used in building science and climatology

*Fahrenheit temperature* (°F) refers to temperature measured on a scale devised by G. D. Fahrenheit, the inventor of the alcohol and mercury thermometers, in the early 18th century. On the Fahrenheit scale, the freezing point of water is 32°F and its boiling point is 212°F at normal atmospheric pressure.

*Celsius temperature* (°C) refers to temperatures measured on a scale devised in 1742 by Anders Celsius, a Swedish astronomer. The Celsius scale is graduated into 100 units between the freezing temperature of water (0°C) and its boiling point at normal atmospheric pressure (100°C) and is, consequently, commonly referred to as the *Centigrade scale*.

*Dry-bulb temperature* (DBT) is the temperature measured in air by an ordinary (dry bulb) thermometer and is independent of the moisture content of the air. It is also called “sensible temperature.”

*Wet-bulb temperature* (WBT) is an indicator of the total heat content (or enthalpy) of the air, that is, of its combined sensible and latent heats. It is the temperature measured by a thermometer having a wetted sleeve over the bulb from which water can evaporate freely.

*Dew point temperature* (DPT) is the temperature of a surface upon which water vapor contained in the air will condense into liquid water. Stated differently, it is the temperature at which a given quantity of air will become saturated (reach 100% relative humidity) if chilled at constant pressure. It is thus another indicator of the moisture content of the air. Dew point temperature is not easily measured directly; it is conveniently found on a psychrometric chart if dry-bulb and wet-bulb temperatures are known.

*Humidity* is a general term referring to the water vapor contained in the air. Like the word “temperature,” the type of “humidity” must be defined.

*Relative humidity* (RH) is defined as the percent of moisture contained in the air under specified conditions compared to the amount of moisture contained in the air at total saturation at the same (dry bulb) temperature. Relative humidity can be computed as the ratio of existing vapor pressure to vapor pressure at saturation, or the ratio of absolute humidity to absolute humidity at saturation existing at the same temperature and barometric pressure.
Definition of the Subject

*Bioclimatic design* – combining “biology” and “climate” – is an approach to the design of buildings and landscape that is based on local climate. Bioclimatic design techniques include solar heating and sun shading, natural ventilation, and use of building materials for thermal time lag and storage.

*Resilient design* is an extension of bioclimatic design, adding precautionary measures to provide health and safety to prepare buildings, communities and regions for natural disasters and climate change.

1 Introduction

In adopting bioclimatic approaches, the designer endeavors to create comfort conditions in buildings by understanding the microclimate and resulting design strategies that include natural ventilation, daylighting, and passive heating and cooling.

Examples of bioclimatic designs are found in examples of indigenous and vernacular building throughout the globe, evidence of *genius loci*, the ways of living and working rooted in a particular place and time. Now an established topic of building science research and architectural practice, bioclimatic design can be applied to buildings, landscapes, urban and regional scales, as part of 21st century sustainability and resilient planning goals.

Techniques of sun-tempering, solar shading, and daylighting were amply represented in the early 20th century portfolios of Frank Lloyd Wright, Tony Garnier, and Augustin Rey, in 1920s Bauhaus manifestos of Hannes Meyer and Marcel Breuer, in late 1920s health-oriented designs of Alvar Aalto and Richard Neutra, and in “solar house” designs of the Keck Brothers in the Chicago area the late 1930s. [1]

Olgyay and Olgyay used the term “bioclimatic design” to define a methodology that matched local climate variables to achievement of human comfort, applicable to architecture and planning, promoted in a series of professional and popular publications in the late 1940s and 1950s. [2, 3]

When air-conditioning systems became widely available in the 1950s and electricity was considered cheap and available—it became possible “to cool a glass house in the desert.” Interest in bioclimatic design waned and became less evident in built work, although pioneering studies continued in academic and architectural research centers in Britain and the U.S. The topic revived in response to energy shortages of the 1970s. “Passive solar design” became the popular term to incorporate elements of bioclimatic design, at first emphasizing solar heating but soon broadened to passive cooling and daylighting. [4]
In the late 1980s, the United Nations Bruntland Commission and the Rio Earth Summit of June 1992 gave international focus to the concept of “sustainability,” including reduced reliance on non-renewable resources and threats to ecosystems and the biodiversity of environments and cultures. With emergence of such global environmental concerns, the scope of bioclimatic design was enlarged to include landscape, soil, water, and waste nutrient recovery, designed to mimic and restore the health of natural processes and ecosystems, characterized by the term “regenerative design.” [5]

At the beginning of the 21st century, the world confronts the evident trends of extreme weather and climate change. Bioclimatic design has gained additional relevance as the basis of applying climate science to “passive survivability”—defined by Alex Wilson as “a building’s ability to maintain critical life-support conditions if services such as power, heating fuel, or water are lost.” [6]

The challenge to reduce and eliminate where possible the use of fossil fuels for carbon reduction further supports bioclimatic design. Bioclimatic design provides the knowledge and inspiration of nature to design for sustainability and resilience in buildings, landscapes, cities and regions. [7]

2 Principles of bioclimatic design

Six key variables have been identified in research studies of human physiological comfort, in which volunteer subjects are asked to report level of comfort and discomfort: air temperature, ambient radiant temperature, humidity, air velocity, dress, and metabolic rate as a function of activity level [8]

Common responses across all these variables have established baseline conditions required for human comfort. Studies indicate that the “comfort zone” for humans does not vary, regardless of sex, age, place of origin and residence, skin color, and body form and weight. In other words, the human "comfort" zone is relatively universal independent of age, health, or sex. However, points where research subjects report discomfort and evidence thermal stress does vary, as a function of many variables, including age, health, and acculturation. Comfort studies are the basis of the design criteria of heating and cooling systems for buildings, also applicable to bioclimatic design.

The “resources” of bioclimatic design are the natural flows of “ambient” energy in and around a building—the “microclimate” created by sun, wind, precipitation, vegetation, temperature and humidity in the air and in the ground. (Figure 1)
Figure 1. Paths of energy exchange at the building microclimate scale. Bioclimatic design is based upon understanding energy flows within and around buildings. (Reference 4)

- **Conduction**—from hotter object to cooler object by direct contact.
- **Convection**—by flow of air between warmer objects and cooler objects.
- **Radiation**—from hotter object to cooler object within the direct view of each other regardless of the temperature of air between, including radiation from sun to earth.
- **Evaporation**—the change of phase from liquid to gaseous state: The sensible heat (dry-bulb temperature) in the air is lowered by the latent heat absorbed from air when moisture is evaporated.
- **Thermal storage**—from heat charge and discharge both diurnally and seasonally, as a function of its specific heat, mass, and conductivity. Although not usually included alongside the four classic means of heat transport, thermal storage is helpful in understanding the heat transfer physics of building climatology.

The strategies can be set forth as:

- **Minimize conductive heat flow**
  This strategy is achieved by using insulation and thermal breaks. It is effective when the outdoor temperature is significantly different, either lower or higher, than the interior comfort range. In summer, this strategy should be considered whenever ambient temperatures are within or above the comfort range and where natural cooling strategies cannot be relied upon to achieve comfort (that is, whenever mechanical air conditioning is necessary).

- **Delay periodic heat flow**
  While the insulation value of building materials is well understood, it is not as widely appreciated that building envelope materials also can delay heat flows that can be used
to improve comfort and to lower energy costs. Time lag through masonry walls, for example, can delay the day’s thermal impact until evening and is a particularly valuable technique in hot arid climates with wide day-night temperature variations. Techniques of earth sheltering and earth berming also exploit the long-lag effect of subsurface construction.

• **Minimize infiltration**
“Infiltration” refers to uncontrolled air leakage around doors and windows and through joints, cracks, and faulty seals in the building envelope. Infiltration (and resulting “exfiltration” of heated or cooled air) is considered the largest and potentially the most intractable source of energy loss in a building, once other practical measures have been taken.

• **Provide thermal storage**
Thermal mass inside of the insulated envelope is critical to dampening the swings in air temperature and in storing heat in winter and as a heat sink in summer.

• **Promote solar gain**
The sun can provide a substantial portion of winter heating energy through elements such as equatorial-facing windows and greenhouses, that include other passive solar techniques which utilize spaces to collect, store, and transfer solar heat.

• **Minimize solar gain**
The best means for ensuring comfort from the heat of summer is to minimize the effects of the direct sun by shading windows from the sun, or otherwise minimizing the building surfaces exposed to summer sun, by use of radiant barrier and by insulation.

• **Minimize external air flow**
Winter winds increase the rate of heat loss from a building by “washing away” heat and thus accelerating the cooling of the exterior envelope surfaces by conduction, and also by increasing infiltration (exfiltration) losses. Siting and shaping a building to minimize wind exposure or providing windbreaks can reduce wind impacts and heat loss.

• **Promote ventilation**
Cooling by air flow through an interior may be propelled by two natural processes, cross-ventilation (wind driven) and stack-effect ventilation (driven by the buoyancy of heated air even in the absence of external wind pressure). A fan (using photovoltaic for fan power) can be an efficient way to augment natural ventilation cooling in the absence of sufficient wind or stack-pressure differential.

• **Promote radiant cooling**
A building can lose heat if the mean radiant temperature of the materials at its outer surfaces is greater than that of its surroundings, principally the night sky. The mean radiant temperature of the building surface is determined by the intensity of solar
irradiation, the material surface (film coefficient) and by the emissivity of its exterior surface (its ability to “emit” or re-radiate heat). This contributes only marginally if the building envelope is well insulated.

- **Promote evaporative cooling**
  Sensible cooling of a building interior can be achieved by evaporating moisture into the incoming air stream (or if an existing roof has little insulation, by evaporative cooling the exterior envelope such as by a roof spray.) These are simple and traditional techniques and most useful in hot-dry climates if water is available for controlled usage. Mechanically assisted evaporative cooling is achieved with an economizer-cycle evaporative cooling system, instead of, or in conjunction with, refrigerant air conditioning.

The “comfort range” as defined in research studies is within a small range of temperature and humidity conditions, roughly between 68-80°F (20-26.7°C) and 20-80% relative humidity (RH), referred to on the psychrometric chart as the “comfort zone.” Other variables include environmental indices—radiant temperature and rate of airflow—as well as clothing and activity (metabolic rate). While such criteria describe relatively universal requirements in which all humans are “comfortable,” there are significant differences in and varying tolerance for discomfort, that is, the limits in which stress is felt, which vary depending upon age, sex, health, cultural conditioning and expectations.

Givoni [9] and Milne and Givoni [10] offer a design method using the “Building Bioclimatic Chart,” modified by Arens. [11] (Figure 2)

![Figure 2. Building Bioclimatic Chart. The chart indicates parameters of climatic conditions favorable for bioclimatic design. (References 9, 10, 11)
Adopting the psychometric chart format, the Building Bioclimatic Chart displays the parameters for bioclimatic design strategies that can achieve human comfort in a building interior. If local outdoor temperatures and humidity fall within specified zones, the designer is alerted to opportunities to use specific bioclimatic design strategies to create effective interior comfort.

TMY (Typical Meteorological Year) summaries contain climatic data for all 8,760 hours in a “typical” year, available for most locations in the United States and increasingly available for major regions and cities worldwide. Each file contains one complete year of hourly data, including direct (beam) solar radiation, total horizontal solar radiation, dry-bulb temperature, dew-point humidity, wind speed and cloud cover. [12]

*Climate consultant* is a computer-based program that can be downloaded at no cost from the web. [13] Part of a career-long project of UCLA Professor Emeritus Murray Milne to develop public domain energy design tools, the software plots temperatures, wind velocity, sky cover, percent sunshine, beam and horizontal irradiation. It includes 3-D plots of temperature, wind speed, and related climatic data cross-referenced to bioclimatic design practices presented in Watson and Labs. [4]

[INSERT Figure 3 here]

**Figure 3. Climate Consultant display of the Building Bioclimatic Chart for Atlanta GA.**
Representative bioclimatic chart generated by Climate Consultant. The box “Design Strategies” tabulates the percent hours per year that bioclimatic design strategies are effective, compiling TMY3 data set. (Reference 13)
Climate Consultant graphs include the Building Bioclimatic Chart for Atlanta (Figure 3), with summaries of percent annual hours of heating and cooling requirements, along with effective bioclimatic strategies, listed below in rank order of percent annual hours of potential need and effectiveness. The designer can thus assess the relative effectiveness and priorities of options, also subject to local energy costs, reliability, and building uses.

26.8% Heating, add Humidification if needed (2346 hrs)
25.4% Internal Heat Gain (2223 hrs)
17.2% Dehumidification (1504 hrs)
14.0% Sun Shading of Windows (1228 hrs)
11.2% Cooling, add Dehumidification if needed (979 hrs)
11.1% Comfort (968 hrs)
09.9% Passive Solar Direct Gain Low Mass (866 hrs)
08.5% Passive Solar Direct Gain High Mass (747 hrs)
03.4% High Thermal Mass (299 hrs)
02.9% High Thermal Mass Night Flushed (252 hrs)
02.3% Two-Stage Evaporative Cooling (198 hrs)
02.2% Direct Evaporative Cooling (189 hrs)
02.0% Natural Ventilation Cooling (174 hrs)
01.2% Fan-forced Ventilation Cooling (107 hrs)
01.1% Wind Protection of Outdoor Spaces (94 hrs)
00.0% Humidification only (0 hrs)

3 Practices of Bioclimatic Design

Bioclimatic techniques can be set forth as a set of design opportunities, adapted from Watson and Labs (Reference 4):

3.1 Wind breaks (winter): Two design techniques serve the function of minimizing winter wind exposure
• Use neighboring landforms, structures, or vegetation for winter wind protection.
• Shape and orient the building shell to minimize winter wind turbulence. (Figure 4)

[INSERT Figure 4 here]
Figure 4. Sea Ranch, California. Landscape planting, roof slopes and fencing designed for wind protection. Esherick, Homsey, Dodge and Davis, Architects and Planners with Lawrence Halprin, Landscape Architect.

3.2 Thermal envelope (winter): Isolating the interior space from the hot summer and cold winter climate, such as:

- Use attic space as buffer zone between interior and outside climate.
- Use basement or crawl space as buffer zone between interior and grounds.
- Use vestibule or exterior “wind shield” at entryways.
- Locate low-use spaces, storage, utility and garage areas to provide climatic buffers.
- Subdivide interior to create separate heating and cooling zones.
- Select insulating materials for resistance to heat flow through building envelope.
- Apply vapor barriers to the warm side of building envelope assemblies to control moisture migration.
- Develop construction details to minimize air infiltration and exfiltration.
- Provide insulating controls at glazing.
- Use heat reflective or radiant barriers on or below surfaces oriented to summer sun.
- Minimize the outside wall and roof area ratio of exterior surface to enclosed volume. (Figure 5)

[INSERT Figure 5 here]
Figure 5. Analysis of building aspect ratio. Simplified building shapes are compared for ratio of exterior surface to enclosed volume. (Reference 4)

3.3 **Solar windows and walls** (winter): Using the winter sun for heating a building through solar-oriented windows and walls is provided by a number of techniques:
- Maximize reflectivity of ground and building surfaces outside windows facing the winter sun.
- Shape and orient the building shell to maximize exposure to winter sun.
- Use high-capacitance thermal mass materials in the interior to store solar heat gain.
- Use solar wall and roof collectors on equatorial-oriented surfaces.
- Optimize the area of equatorial-facing glazing.
- Use clerestory skylights for winter solar gain and natural illumination.
- Provide solar-oriented interior zone for solar heat gain, with solar control for shading in overheated periods. (Figure 6)

![ INSERT Figure 6 here ]

Figure 6. Solar windows & walls.
L: Keck + Keck, Architects developed solar design principles in the Chicago area in the 1930s. The designs of Keck+Keck—in this example a prefab for Green Ready-Built Homes—included south-facing glass, exposed masonry floors with hypostyle (warm air radiant) heating, interior masonry walls, interior curtains and exterior shading. PHOTO: William Keck, Architect

3.4 **Indoor/outdoor rooms** (winter and summer): Courtyards, covered patios, seasonal screened and glassed-in porches, greenhouses, atriums and sun spaces can be located in the building plan for summer cooling and winter heating benefits, as in these three techniques:
- Provide outdoor semi-protected areas for year-round climate moderation. (Figure 7)

[INSERT Figure 7 here]
Figure 7. Protected courtyard. Buli Khelam Ihakhang Monastery, Bhutan. In the Himalayan tradition of building, an enclosed courtyard with sun exposed adobe walls and windows creates a wind protected microclimate, permitting a temperate planting regime to flourish within, in contrast to high mountain climatic conditions of its locale. PHOTO: Donald Watson

3.5 Earth-sheltering (winter and summer): Techniques such as banking earth against the walls of a building or green roofs provide thermal storage and damping temperature fluctuations (daily and seasonally), reducing envelope heat loss or gain (winter and summer). These techniques are often referred to as earth-contact or earth-sheltering:
• Use slab-on-grade construction for ground temperature heat exchange and thermal storage.
• Use earth-covered or sod roofs.
• Recess structure below grade or raise existing grade for earth sheltering. (Figure 8)

[INSERT Figure 8]


3.6 Thermally massive construction (summer and winter): Particularly effective in hot arid zones, or in more temperate zones with cold clear winters. Thermally massive construction provides a “thermal fly wheel.” Absorbing heat during the day from solar radiation and convection from indoor air, thermal mass can create comfort if it is cooled
at night, if necessary through nighttime ventilative cooling (if air temperatures fall within the comfort zone).
• Use high mass construction with outside insulation and nighttime ventilation.
• For selected climates (hot dry), use high-capacitance materials to dampen heat flow through the building envelope. (Figure 9)

[INSERT Figure 9 here]

Figure 9. Thermal mass appropriate for hot dry climate. Indigenous adobe block construction, with roof and window overhangs to shade and protect the walls. Tahono O’Odham Nation, Papago Indian Reservation, Arizona. PHOTO: Donald Watson

3.7 Sun shading (summer): Mid-day solar altitude angles are higher in summer than in winter. Thus, an overhang can shade windows from the sun during the overheated summer period and permit sun to reach the window surfaces and interior spaces in winter.
• Minimize reflectivity of ground and building surfaces outside windows facing the summer sun.
• Use neighboring landforms, structures, or vegetation for shading summer sun.
• Shape and orient the building shell to minimize exposure to summer afternoon sun.
• Provide seasonally operable shading, including deciduous trees.

3.8 Natural ventilation (summer and seasonal): Natural ventilation is a simple concept by which to cool a building.
• Shape and orient the building shell to maximize exposure to summer breezes.
• Use “open plan” interior to promote airflow.
• Provide vertical airshafts to promote “thermal chimney” or stack-effect airflow.
• Use double roof construction for ventilation within the building shell.
• Orient door and window openings to facilitate natural ventilation from prevailing summer breezes.
• Use wing walls, overhangs, and louvers to direct summer wind flow into interior.
• Use louvered wall openings for maximum ventilation control.
• Use roof monitors for “stack effect” ventilation. (Figure 10)

[INSERT Figure 10 here]
Figure 10. Shading and ventilation strategies. Built in an era well before air-conditioning, plantation manor houses such as the 1827 San Francisco Plantation House, New Orleans, combined a range of strategies for natural cooling in hot humid climates, including open understory and porches, cross-ventilation, and roofs designed to induce ventilation by thermal updraft. PHOTO: Robert Perron

3.9 Plants and water (summer): Many techniques provide cooling by plants and water near building surfaces for shading and evaporative cooling.

• Use planting next to building skin (provided it does not interfere with ventilation).
• Use roof spray or roof ponds for evaporative cooling.
• Use ground cover and planting for site cooling.
• Maximize on-site evaporative cooling. (Figure 11)

[INSERT Figure 11 here]
4 Bioclimatic design of atriums

Atriums offer many energy design opportunities, depending upon climate variables, to provide natural heating, cooling, lighting and plants. Suggested by its Latin meaning as “heart,” or an open courtyard of a Roman house, the term *atrium* as used today to describe a protected courtyard or glazed large-volume space placed within a building. Modern atrium design incorporates many architectural elements—wall enclosures, sun-oriented openings, shading and ventilation devices, and subtle means of modifying temperature and humidity—suggested by examples that derive from 19th Century greenhouses and glass-covered arcades of Great Britain and France.

In northern Europe, especially Holland and England, from the 17th century on, south-facing orientation of indoor gardens, propagating sheds, orangeries, and conservatories revealed an understanding of bioclimatic design. Gardeners and greenhouse designers combined thermal mass, double glass, steep glass orientation, underground heating, shading and insulating devices in greenhouses. The greenhouse designs of J.C. Loudon, beginning circa 1820, had all of these elements evident in sketches and built examples through mid-century. Joseph Paxton’s Great Exposition Crystal Palace of 1851 demonstrated the possibility for large glazed-covered areas, inaugurating a proliferation of urban atrium designs across Europe and the world. [14]

Atriums offer many energy design opportunities: first, comfort is achieved by gradual transition from outside climate to building interior; second, designed properly, protected spaces and buffer zones create natural and free flowing energy by reducing or by eliminating the need to otherwise heat, cool, or light building interiors.

4.1 Solar heating guidelines

If heating efficiency alone is the primary energy design goal of the atrium, the following design principles should be paramount:

**Heating Rule 1**

To maximize winter solar heat gain, orient the atrium aperture (openings and glazing) to the equator. If possible, the glazing should be vertical or sloped not lower than a tilt angle equal to the local latitude.

**Heating Rule 2**

To store and distribute heat, place interior masonry directly in the path of the winter sun. This is most useful if the heated wall or floor surface will in turn directly radiate to building occupants.

**Heating Rule 3**

To prevent excessive nighttime heat loss, consider an insulating system for the glazing, such as insulating curtains or high performance multi-layered window systems.

Heating Rule 4
Heat recovery can be accomplished if the warm air is redistributed either to the lower area of the atrium (a ceiling fan) or redirected (and cleaned) to the mechanical system, or through a heat exchanger if the air must be exhausted for health and air-quality reasons. Because a large air volume must be heated, an atrium is not an efficient solar collector. A high space helps to make an overheated space acceptable, as the warmest air rises to the top. By facing a large skylight and/or window opening towards the equator, direct winter solar heating becomes feasible.

In cool climates, an atrium used as a solar heat collector would require as much winter sunlight as possible. In overbright conditions, dark finishes on surfaces where the sun strikes will help reduce glare and also to store heat. On surfaces not in direct sun, light finishes reflect light, especially welcomed under cloudy conditions. In most locations and uses, glass should be completely shaded from the summer sun. Movable insulation might be considered to reduce nighttime heat loss.

4.2 Natural cooling guidelines
Several guidelines related to the use of an atrium design as an intermediary or buffer zone apply to both heating and cooling. If an unconditioned atrium is located in a building interior, heat gain results from the warmer surrounding spaces into the atrium. In buildings with large internal gains due to occupants, lighting, and machines, the atrium may require cooling throughout the year. To design exclusively for cooling, the following principles would predominate:

**Cooling Rule 1** To minimize solar gain, provide shade for the summer sun. While fixed shading devices suffice for much of the summer period, movable shading is the only means by which to match the seasonal shading requirements at all times. In buildings in warm climates, sun shading may be needed throughout the year.

**Cooling Rule 2** To use the atrium as an exhaust air plenum in the mechanical system of the building. The great advantage is one of economy, but heat recovery options (discussed above) and ventilation become most effective when the natural airflow in the atrium is in the same direction and integrated with the mechanical system.

**Cooling Rule 3** To facilitate natural ventilation, create a vertical “chimney” effect by placing ventilating outlets high (preferably in the free-flow air stream well above the roof) and by providing cool “replacement air” inlets at the atrium bottom, with attention that the air stream is clean, that is, free of car exhaust or other pollutants.

The inlet air stream can be cooled naturally, best with cool air from a shaded area. In hot, dry climates, passing the inlet air over water such as an aerated fountain or landscape can facilitate evaporative cooling. Allowing the atrium to cool by ventilation at night is effective in climates where summer nighttime temperatures are lower than daytime (greater than 15°F difference).
Additional cooling capacity (to absorb and hold heat) is provided by materials such as masonry. However, as a general rule, if the average daily temperature is above 78°F (25.5°C), thermally massive materials are disadvantageous in non-air-conditioned spaces because they do not cool as rapidly as a thermally light structure. When stack ventilation is possible through a roof aperture, the space will ventilate naturally even in the absence of outside breezes, by the driving force of heated air. If air-conditioning of the atrium is needed but can be restricted to the lower area of the space, it can be done reasonably; cool air, being heavier, will pool at the bottom.

Design choices must balance between the requirements for sun shading and those for daylighting. The ideal location for a shading screen is on the outside of the glazing, where it can be wind-cooled. When the outside air ranges about 80°F (26.7°C), glass areas—even if shaded—admit undesired heat gain by conduction. In truly warm climates, a minimum of glazed aperture should be used to prevent undesired heat gain: a small amount of glazing should be placed where it is most effective for daylighting. Heat-absorbent or heat-reflective glass, the common solution to reduce solar heat gain, also reduces the illumination level, and also reduces desirable winter heat gain.

In temperate-to-cool climates, heat gain through a skylight can be tolerated if the space is high, so that heat builds up well above the occupancy zone and there is good ventilation. In hot climates, an atrium will perform better as an unconditioned space if it is a shaded but otherwise open courtyard.

4.3 Daylighting guidelines
In all climates, an atrium can be used for daylighting. Electric lighting cost savings can be achieved, but only if the daylighting system works; that is, if it replaces the use of artificial lighting. (Many daylit buildings end up with the electric lights in full use regardless of lighting levels needed.) Atriums serve a particularly useful function for an entire building by balancing light levels—thus reducing brightness ratios—across the interior floors of a building. If, for example, an open office floor has a window wall on only one side, typically more electric lighting is required than would be required without natural lighting to reduce the brightness ratio. A light court can provide such balanced “two source” lighting.

The following principles apply to atrium design for daylighting:

**Lighting Rule 1**
To maximize daylight, an atrium cross-section should be stepped open to the entire sky dome in predominantly cloudy areas. In predominantly sunny sites, atrium geometry can by based upon heating and/or cooling solar orientation principles.

**Lighting Rule 2**
To maximize light, window or skylight apertures should be designed for the predominant sky condition. If the predominant sky condition is cloudy and maximum daylight is required (as in a northern climate winter garden), consider clear glazing oriented to the entire sky dome, with movable sun controls for sunny conditions. If the predominant sky condition is sunny, orient the glazing according to heating and/or cooling design requirements.

**Lighting Rule 3**

Provide sun-and-glare control by geometry of aperture, surface treatment, color, and adjustable shades or curtains. Designing for daylighting involves compromise to meet widely varying sky conditions. What works in bright sun conditions will not be adequate for cloudy conditions. An opaque overhang or louver, for example, may create particularly somber shadowing on a cloudy day. Light is diffused by a cloudy sky, falling nearly equally from all directions; the sides of the atrium thus cast gray shadows on all sides. For predominantly cloudy conditions, a clear skylight is the right choice. Bright haze will nonetheless cause intolerable glare at least to a view upwards. Under sunny conditions, the same skylight is the least satisfactory choice because of overlighting and overheating.

Unless the local climate is truly cloudy and the atrium requires high levels of illumination, partial skylighting can achieve a balance of natural lighting, heating, and cooling. Partial skylighting (that is, a skylighting takes only a portion of the roof surface). This approach offers advantages of controlling glare and sunlight by providing reflecting and shading surfaces, such as by the coffers of the skylights. With less light intensity and contrast, a surface illuminated by reflected light is more acceptable to the human eye than a direct view of a bright window area. Movable shades for glare and sun control provide a further means to balance for the variety of conditions.

The design principles for heating, cooling, and daylighting can be selected according to building type and local climate. In the northern climates, the solar heating potential predominates, while the natural cooling potential predominates in the southern United States. In commercial and institutional structures, natural cooling and daylighting are both important. In this case, the local climate would determine the relative importance of openness achieved with large and clear skylighting (most appropriate for cloudy temperate-to-cool regions) or of closed and shaded skylighting (most appropriate for sunny warm regions). The design principles can be summarized as guideline principles. (Figure 12)

[INSERT Figure 12 here]
Figure 12. Bioclimatic principles for atrium design. Guidelines for design of atria and light courts in various climates. (Reference 15)

4.4 Garden atriums

Plants have an important role in buffer zones. If the requirements of plants are understood, healthy greenery can be incorporated into atrium design and contribute to human comfort, amenity and energy conservation. Plants, however, when uncomfortable, cannot move. Major planting losses have been reported in gardened atriums because the bioclimatic requirements were not achieved. A greenhouse for year-round crop or plant production is intended to create spring-summer or the growing-period climate throughout the year. A winter garden replicates spring-summer conditions for plant growth in wintertime by maximizing winter daylight exposure and
by solar heating. Plants need ample light, but not excessive heat. Although varying according to plant species, as a general rule planting areas require full overhead skylighting (essentially to simulate their indigenous growing condition). Most plants are overheated if their roots range above 65°F (18.3°C). Plant growth slows when the root temperature drops below 45°F (7.2°C). As a result, a greenhouse has the general problem of overheating (as well as overlighting) during any sunny day and of underlighting (in intensity and duration) during any cloudy winter day.

If the function of the atrium includes plant propagation or horticultural exhibit (replicating the indigenous climate in which the display plants flower), then clear-glass skylighting is needed for the cloudy days and adjustable shading and overheating controls are needed for sunny days. If the plant beds are heated directly, by water piping for example, then root temperatures can be maintained in the optimum range without heating the air. As a result, the air temperature in the atrium can be cool for people, in the 50°F (10°C) range, with the resulting advantage of providing a defense against superheating the space. People can be comfortable in lower air temperatures if exposed to the radiant warmth of the sun and/or if the radiant temperature of surrounding surfaces is correspondingly higher, that is, ranging above 80°F (26.7°C). Lower atrium temperatures have a further advantage to plants and energy-efficient space operation: evaporation from plants is slowed, saving water and energy (1000 Btu are removed from the sensible heat of the space with each pound of water that evaporates). Air circulation reduces excessive moisture build-up at the plant leaf and circulates CO₂, needed during the daytime growth cycle. (Figure 13)

[INSERT Figure 13 here]

**Figure 13 New Canaan Nature Center Greenhouse**, New Canaan, CT 1982. Buchanan / Watson Architects. (1) south-facing greenhouse (2) solar collectors (3) thermal storage (4) ceiling fans (5) roof monitor (6) operable sun-shade / insulating curtain (7) earth-contact floor (8) root-bed heating (9) grow-lights (10) earthberm (11) rainwater collection. ILLUSTRATION: Marja Watson

5 Large-scale applications

Figure 14 depicts site and building opportunities for energy collection, storage, and
distribution that may be integrated into larger buildings as combined passive and active measures of bioclimatic design. Applications may include on-site ecosystem services, green roofs, water collection, waste recycling, and biological diversity of sun and shade, warm and cool zones and energy storage, selected depending upon opportunities within each site and region.

Figure 14. Large building opportunities for microclimatic design integration. Bioclimatic design extends to larger scale for integrated heating, cooling and lighting systems.

William Lam [16] provides a detailed guidance for sunlighting large buildings, including documentation of case studies. A number of large scale building designs demonstrate exemplary applications of microclimatic design.(Figures 15, 16, 17)
Figure 15. Center for Interactive Research on Sustainability (CIRS) University of British Columbia, Vancouver. Designed as a “living laboratory” with multiple innovations to reduce energy and to capture and use rainwater. Busby Perkins+Will, Architects.

PHOTO: Martin Tessler

1 Daylighting / sun tempering
2 Photovoltaic collectors
3 Evacuated tube collectors
4 Greenroof / Rainwater harvesting
5 Displacement ventilation
6 Ground source heat pump
7 Heat recovery
8 Radiant heating
9 Deciduous living wall
10 Solar aquatic biofiltration
11 Stormwater to raingardens
12 Solar DHW
13 Rainwater cistern
14 Water purification
15 Gray and blackwater recovery
16 Greenspace irrigation

[INSERT Figure 16 here]

Figure 16. Solaire - 27-story residential apartment building in New York City
Passive solar, green roof, energy and water conserving features. Cesar Pelli & Associates Architects and SLCE Architects

6 Urban and regional scale

Many studies address microclimatic impacts at the urban scale. [3] Perennial topics have included solar access, evident in early 20th Century studies related to solar access and daylighting, as well as urban scale airflow,

6.1 Solar access
Ralph Knowles [17] in studies undertaken over many decades with students at University of Southern California developed the notion of assuring solar access to buildings, for sun tempering, daylighting and solar collection. His studies have demonstrated that solar access can be guaranteed in most urban areas while keeping within conventional medium to medium-high density Floor to Area Ratios (FARs). (Figure 17)
A study by FXFowle Architects [18] illustrates the feasibility of passive solar and improved insulation measures equal to Passivhaus standards. Strategies include shading, passive solar gain, shading, attention to thermal breaks in insulation and envelope, sun-oriented interior layouts, and energy-recovery within mechanical ventilation.

6.2 Urban heat islands and cool zones
Baruch Givoni [18] compiles a broad survey of urban bioclimatic data and design applications, with emphasis on measured data, along with discussion of challenges of data measurement at the urban scale.
Table 1 shows averages of air and surface temperatures measured at a height of 1 m (3.3 ft.) around noontime on the UCLA campus during a sequence of several clear days in summer. The lowest temperatures were in a space between a line of high shrubs and a wall of a building.

Table 1. Representative air and surface temperature averages measured during a sequence of several clear days in summer. (Reference 18)

<table>
<thead>
<tr>
<th>Location</th>
<th>Air Temperature °F</th>
<th>Surface Temperature °F</th>
<th>Air Temperature °C</th>
<th>Surface Temperature °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parking lot</td>
<td>79</td>
<td>122</td>
<td>26.1</td>
<td>50.0</td>
</tr>
<tr>
<td>Open plaza</td>
<td>78</td>
<td>107</td>
<td>25.6</td>
<td>41.7</td>
</tr>
<tr>
<td>Shaded walk</td>
<td>76</td>
<td>80</td>
<td>24.4</td>
<td>26.7</td>
</tr>
<tr>
<td>Grass lawn</td>
<td>75</td>
<td>88</td>
<td>23.9</td>
<td>31.1</td>
</tr>
<tr>
<td>Behind shrubs</td>
<td>74</td>
<td>73</td>
<td>23.3</td>
<td>22.8</td>
</tr>
</tbody>
</table>

Givoni’s research points to opportunities for continued research at the urban scale, supporting an approach to urban planning based on bioclimatic analysis and design. (Figure 19)

Figure 19. Pocket Park, New York City. Paley Park creates a small area of respite, with a cooling microclimate created by evaporative cooling, shading and wind protection, while water fountain sound helps neutralize urban clamor. PHOTO: Donald Watson

6.3 Urban air quality
Studies by Anne Whiston Spirn [19] have utilized research on urban wind effects to indicate design strategies to reduce pollution in city streets and public ways, principally by opening building forms and landscapes to less constrained airflow. (Figures 20 and 21)
Figure 20. Air Quality. The urban designer has opportunity to utilize strategies to improve air quality at the urban microclimatic scale. (Reference 19)
A - Street canyons lined with building of similar height, oriented perpendicular to the wind direction tend to have poor air circulation compared to B.
B - Street canyons lined with buildings of different heights and interspersed with open areas have better air circulation.
C - To promote air circulation in street canyons, step buildings back from the street, increase openings and vary building heights.
D - To promote air circulation in street side arcades, design them with high canopies and airflow outlets.

Figure 21. Comprehensive plan to improve air quality. Stuttgart, Federal Republic of Germany. Public gardens and open space atop the cities hills and hillside canyons are preserved as vegetated public stairways and watercourses. Hillside canyons funnel cool
nighttime airflow to center city streets and downtown parks. PHOTO: Dr. Michael Trieb, Urban Planning Institute, University of Stuttgart.

7 Future directions: design for resilience to climate change

The concept of resiliency applies lessons from natural systems to design for safety and protection in extreme conditions using strategies found in natural systems, such as buffering, zone separation, redundancy, rapid feedback and decentralization.

Extreme conditions include impacts of natural disasters, such as hurricanes, tsunamis, and earthquakes. It also includes mitigation and adaptation measures for longer-term risks of global warming and sea level rise through actions that reduce carbon emissions. As cities grow in size and density, risks to life safety and health increase.

The natural landscape that has evolved in response to climate and water regimes over millennia had adapted to long-evolving patterns of rainfall, aridity, heat and cold. Historical flood conditions were accommodated within the watershed ecology and its co-evolving plants and animals. When those patterns are disrupted and the natural landscape is altered, flooding risks and disasters increase.

Watson and Adams [7] and Watson [21] extend bioclimatic design to include resilience, to adopt precautionary principles in design of buildings, communities and cities. Resiliency is evident in natural systems strategies to adjust to shock, variable and extreme conditions. (Table 2)

Table 2. Lessons of nature for resilient design

<table>
<thead>
<tr>
<th>Principle from nature</th>
<th>Application to resilient design</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSORPTION</td>
<td>watershed planning and design (reservoirs, retention ponds, green roofs)</td>
</tr>
<tr>
<td>BUFFERING</td>
<td>breaks, riparian buffers, rain gardens</td>
</tr>
<tr>
<td>CORE PROTECTION</td>
<td>zoning, decentralization, self-reliant subsystems</td>
</tr>
<tr>
<td>DIFFUSION</td>
<td>meanders, wetland and coastal zone landscape, open foundations</td>
</tr>
<tr>
<td>WATER STORAGE CAPACITY</td>
<td>aquifers, wetlands, reservoirs, cisterns</td>
</tr>
<tr>
<td>REDUNDANT CIRCUITS</td>
<td>green infrastructure, wildlife corridors, and multiple service routes</td>
</tr>
<tr>
<td>WASTE/NUTRIENT RECOVERY</td>
<td>sustainable stormwater design and waste systems</td>
</tr>
<tr>
<td>RAPID RESPONSE</td>
<td>early warning, emergency responsive systems</td>
</tr>
</tbody>
</table>
Bioclimatic lifeline systems—green space, water, food, waste, mobility, and safe shelter—replicate the biological systems of water, vegetation, food, and biodiversity that protect the life, health and safety of cities. Ecosystems regulate the supply and quality of water, air, and soil. Urban parks and vegetation reduce the urban heat island effect. Urban green spaces help to regulate climate, reflect and absorb solar radiation, filter dust, store carbon, serve as windbreaks, improve air quality by oxygen emission and moistening, and enhance cooling by evaporation, shading, and air exchange. (Figure 22)

Figure 22: Lifeline systems, integrating bioclimatic principles as urban and regional scales. (Reference 21)

Bioclimatic techniques that contribute to lifeline systems at the urban scale include:
- **Greenspace**: walkways, pocket parks, playgrounds, wildlife, trees, plants, and soil protection.
- **Water**: stream daylighting, cleansing, water fountain cooling zones, and urban wildlife ponds.
- **Food**: local community gardens, farmers markets, other community market venues.
- **Energy**: protected utility and communication lines, district energy conduits, solar/wind structures.
- **Waste**: combined urban services, efficient waste collection, recycling and removal.
- **Mobility**: urban transit options, bikeways, pedestrian scaled vehicles, flexible use,
emergency service lanes.
Refuge: community shelters and safe zones, emergency communication, evacuation and materials staging.

Bibliography

[18] FXFowle Architects (2017) Feasibility study to implement the Passivehaus standard on tall residential buildings. New York State Research and Development Authority, Albany

Additional references


END OF ARTICLE