Climate-Sensitive Architecture, Is Natural Comfort Possible?

Carolina Ganem-Karlen

1 What Do We Mean by Comfort?

The image of Adam by Vitruvius, the first writer of western architecture, wisely rebuilt by Filarete in 1490, offers a tormented humanity that does not willingly commune with the environment to which it seems to be unswervingly thrown (Fig. 1a). Arms overhead would not so much indicate a mere reactivity deposited in the gesture of despair, but rather the tracing of a fine line that must separate a chaotic and untamed nature from the borders of that human interiority.

Indeed, the so-called ‘primitive hut’ of Vitruvius is nothing but the mimesis of that first body gesticulation, not so much because they try to replicate the action of the cover, but because, above all, it stands under the firm conviction of drawing the difference between an interior and an exterior in search for comfort (Fig. 1b).

The architect designs the limit between an inside and an outside. Interior and exterior are not fixed concepts in architecture. Sometimes buildings are barriers to rain and wind and sometimes subtle filters for light and heat [1]. There are spaces in architecture that cannot be considered interior or exterior and sometimes change in response to changing climatic conditions. If we were to represent interior and exterior environments as a positive-negative image, where the black surfaces represent the building and the white surfaces the exterior space, we would have to envisage grey areas, which appear as a blurring of the line that separates black and white [2] (Fig. 2).

These grey interior–exterior areas were developed over time in very diverse forms in several cultures and are keys in the search for natural comfort (Fig. 3).

C. Ganem-Karlen (✉)
CONICET – UNCUYO, Mendoza, Argentina
e-mail: cganem@mendoza-conicet.gov.ar; carolinaganem@gm.fad.uncu.edu.ar

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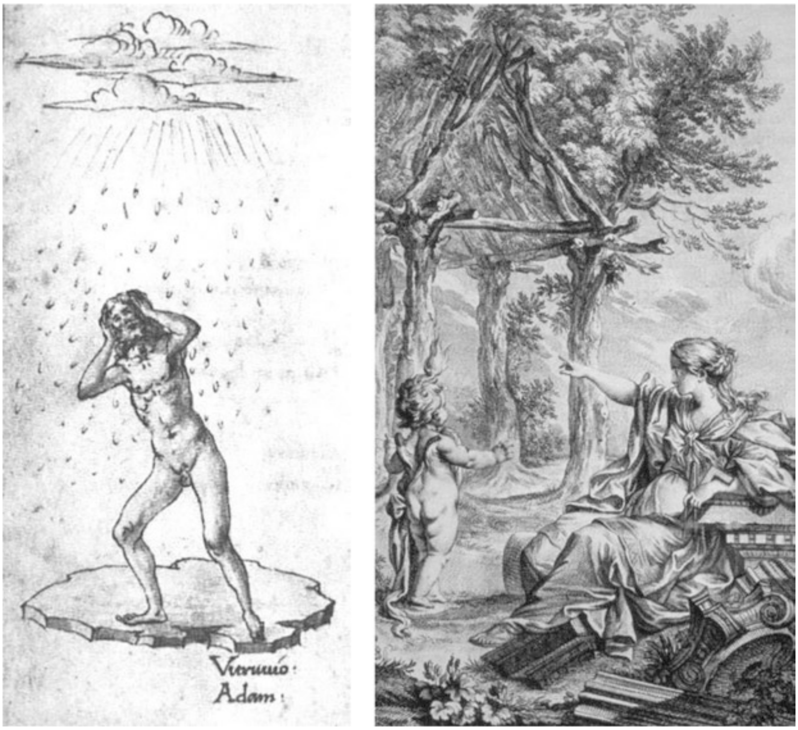


Fig. 1 From left to right. (**a**) –Adam by Vitruvius in Filarete's *Libro Architettonico* [3] (**b**) – Primitive hut by Vitruvius in Laugier's *Essai sur l'architecture* [4]

Surrounded by variable environments, where day and night, heat and cold, wind and calm, rain and sun change, buildings become havens of artificial conditions, like islands of tranquillity in an uncomfortable world [1].

Then, the question arises once again: What is comfort? Comfort in architecture is a subject that has been widely studied, although not always successfully. Many factors influence the appreciation of space. The simultaneous existence in time and space of different types and quantities of energy makes it very difficult to study them in an integrated manner, which would be the most appropriate approach in architecture. It is important to consider up to what point it is possible to study the concept of comfort objectively.

For Rybczynski [6], the simplest answer would be that comfort confines itself to human physiology. But that would not explain why – although the human body has not changed – our idea is different from that of a hundred years ago. But if comfort were subjective, one might expect a greater diversity of attitudes on the matter; yet, the opposite is true because in any specific historical epoch, there has always been demonstrable consensus.

While comfort is a subjective concept, it is also an objective fact. The most interesting point in all of this is that both assertions seem to be true at once, which leads

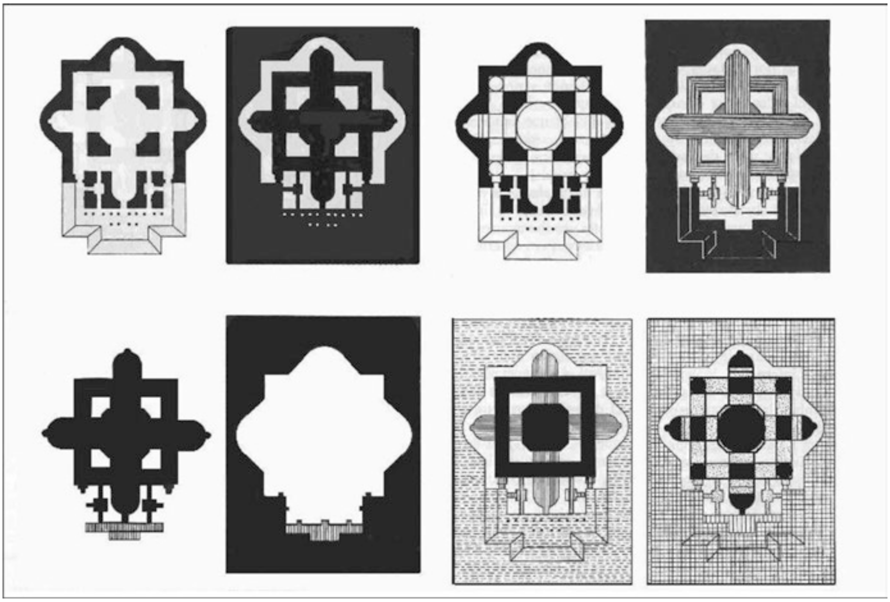


Fig. 2 Space analyses of St. Pietro Cathedral by Bruno Zevi in *Saper Vedere l'Arquitettura* [5]

Fig. 3 From left to right. (**a**) – *In a courtyard in Pompeii* by Luigi Bazzani (1878) (**b**) – *Coffee House in Cairo* by Konstantin Egorovich Makovsky (1870). (Source: Getty Images)

us to think that comfort may be both subjective and objective, without there being any contradiction in the statement [2].

Thermal comfort is defined in ISO 7730 [7] as '…that condition of mind which expresses satisfaction with the thermal environment'. In practice, the achievement of comfort is the result of a complex phenomenon in which objective space parameters – such as thermal, visual or acoustical – coexist with subjective physiological, sociological, cultural and psychological factors.

The comfort parameters are those objective characteristics of a given space which can be valued in energy terms and which summarize the actions that the people who occupy it receive in a given space. As such, these parameters can be analyzed independently of the users and are the direct object of environmental design in architecture.

The comfort factors, on the other hand, are those characteristics that correspond to the users of the space. They are therefore conditions external to the environment, but which influence the appreciation of said environment by these users. The comfort offered by a given environment will depend, in each case, on the combination of the objective parameters and subjective factors.

There is an analogy between comfort and an onion [8]. Like an onion, the notion of comfort has many layers, which were added historically. The image of the onion also conveys the elusive nature of comfort: If you take it apart and look at the layers one by one, you lose the overall shape, and yet the layers are still visible one beneath the other. These layers consist of ideas such as privacy or intimacy, convenience and physical ease. Each generation has added something to the definition, has added a layer without necessarily contradicting what came before.

2 Climate-Sensitive Architecture in Temperate Climates

In temperate climates, there are marked changes in conditions throughout the year. In these climates, architecture becomes more complex, having to be adaptable, even for short periods of time, to the entire spectrum of basic types of climate, such as hot humid, hot dry and cold climates.

The basic problem of these climates is not their harshness, but the fact that nearly in any period of the year and time of day, conditions of the opposite sign can occur. Cold in winter and heat in summer, and both can be almost as intense as in extreme climates, and also the problem of variable weather that, in the intermediate seasons, can generate cold or heat separated for short periods of time, even in the same day.

Although each individual constriction is not really critical, together they make the architecture of temperate climates have this greater degree of complexity, which makes it more difficult from a design point of view [1].

Air temperature, humidity, radiation and air movement all produce thermal effects and must be considered simultaneously. Each of these factors influences in some way the heat exchange processes between the human body and its environment; each one can favour or prevent the dissipation of superfluous heat from the body [9]. In the search to facilitate the understanding of the climate as a whole, analysis methods have been devised that relate climate variables in accordance with perceptual aspects of well-being.

Victor Olgyay [10] was one of the first to propose a systematic procedure to adapt the design of a building to human requirements and climatic conditions. His

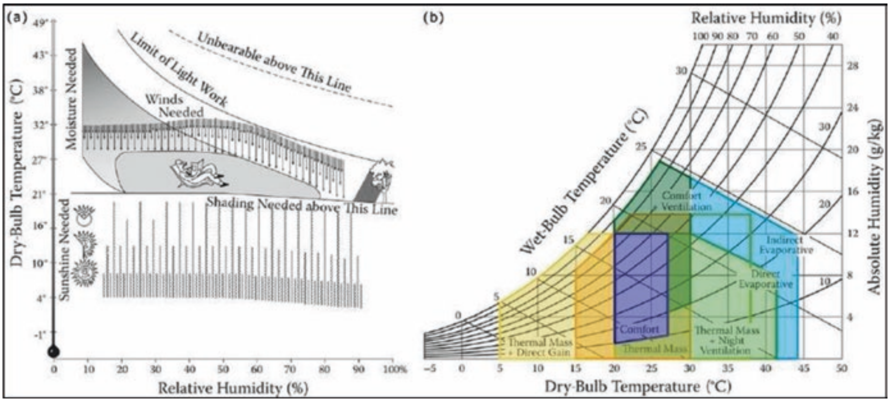


Fig. 4 From left to right. (**a**) – ‘Bioclimatic Chart’ by Olgyay in 1963 [10] (**b**) – ‘Psychrometric Chart’ by Givoni in 1988 [13]

method is based on a ‘Bioclimatic Chart’ showing the human comfort zone in relation to the conditions that surround it, such as ambient air temperature and humidity, average radiant temperature, air speed and solar radiation (Fig. 4a).

Another well-known diagram is the ‘Psychrometric Chart’. In 1923, Richard Mollier [11] was the first to use enthalpy and moisture content as coordinates in the ‘Mollier i-x’ (Enthalpy–Humidity Mixing Ratio) diagram. The *ASHRAE Handbook of Fundamentals*, 1988, defines it as a graphic representation of the thermodynamic properties of humid air [12]. This means that each point on this chart will be defined by a value of the air dry bulb temperature (DBT), by a wet bulb value (WBT) and, therefore, by the ratio of both readings by a value of relative humidity (RH). The dew point temperature (DPT) is the temperature at which air with certain humidity becomes saturated and begins to condense the excess water contained in it.

Baruch Givoni [13] drew his bioclimatic diagram by incorporating the temperature and relative humidity of a place in the psychrometric chart. In this graphic, it is easy to recognize the relationship between climate and comfort and the demands to which architecture must respond to in a given climate. It is possible to define winter and summer comfort zones (Fig. 4b).

Givoni suggested the expansion of comfort limits from architectural performance through the application of bioclimatic strategies. These include passive heating, ventilation, thermal inertia with and without ventilation and evaporative cooling.

In winter, the effect of solar radiation on interior surfaces must be used in a certain way to balance the extreme minimum air temperatures. We can feel comfortable at low temperatures if the loss of heat from our body is counteracted by solar radiation.

In a climate with a majority of sunny days, the application of passive profit strategies is feasible. Direct Gain systems work from transparent surfaces oriented to the Equator (South for the Northern Hemisphere and North for the Southern Hemisphere). In this way, it is possible to capture the greatest number of hours of sunshine and those with the highest radiation intensity. These systems use the living spaces of the house to collect, conserve and distribute the solar gain. The building requires thermal mass to conserve heat during the day and to re-emit it at night.

Indirect systems work from the principles described for direct gain with the difference that the space into which the solar radiation enters through the transparent surface is attached to the space to be heated. Intermediate spaces such as greenhouses, glazed galleries and glazed balconies are very good architectural resources, and also specially designed walls such as trombe walls and solar walls. This space reaches very high temperature values, which are then transmitted to the interior by conduction in the case of indirect systems and by conduction and convection in semi-direct systems.

These systems must be combined with the presence of accumulation elements inside. That is, by building with materials with high thermal inertia like adobe, brick, stone and concrete. Thermal inertia is necessary because it allows maintaining higher indoor temperatures than outdoor temperatures during night-time periods in winter and achieving lower temperatures during daytime periods in summer.

To attend to the thermal conformation of the appropriate envelope is necessary to avoid losses by adding thermal insulation to the envelope, such as: cane, cork, cellulose, glass wool, expanded polystyrene and polyurethane. Also, to achieve an appropriate environmental regulation, the solar gain must be related to the reduction of the convective exchange of the glass with the outside. For this reason, the use of mobile night insulation on transparent surfaces is recommended, some examples are: shutters, blinds, lattices, roller blinds and sliding curtains.

In summer, the simplest strategy referred to passive cooling is in relation to the breezes of the place and the location of the practicable openings. The ideal position of the openings to favour ventilation in a space or in a sequence of spaces is to place them on opposite facades, that is to say, facing each other, in the direction of the prevailing breezes. This strategy is called cross ventilation.

Night cross ventilation is used in cases of continental climate, where the daily outdoor temperature differences are greater than 10 °C. The isolated thermal mass of the building must be kept closed during the day and avoid, by means of barriers and moderating filters, the entry of direct or indirect solar radiation. Given the construction characteristics, the insulation will prevent the entry of heat energy by conduction in the walls and the temperature will remain stable inside.

During the night, when the outdoor air temperature is lower than the indoor air temperature, the openings must be opened to promote nocturnal cross ventilation that will ‘sweep away’ – by convection from the inside – the heat accumulated during the day due to internal gains of its own related to the space use. If the openings are closed before the start of the sunny hours, the accumulated ‘cold’ will remain during the day, until a new cycle begins.

When high temperatures and low moisture content prevail in the air, the most viable design response is to raise the water vapour content of the outdoor air through the presence of moving water such as a fountain. This will produce an increase in the absorption of heat from the immediate surroundings, and thus reducing their temperature. The decrease in temperature caused by the evaporation of added moisture will restore the comfort temperature. This phenomenon will be influenced and modified by air speed, which will increase evaporation rates and with it the feeling of comfort.

Even though there is a consensus that climate-sensitive architecture is possible in temperate climates, the incessant search for what we call 'comfort', be it physical or psychological, has led to the evolution of the demands in all buildings. This process began to accelerate in the eighteenth century with the appearance of the first industries, massive production and new materials. Control systems, at first considered ingenious singularities created to provide some immediate benefit in the twentieth century, started to play a predominant role in architecture. Nowadays, comfort can be achieved by using auxiliary energy, usually from non-renewable and pollutant sources, that powers energy-intensive mechanisms with almost immediate response.

Comfort was repositioned and redefined as a 'product' sold by the HVAC industry [14]. The HVAC industry, therefore, needed to define 'comfort' in terms of the physical variables that could be controlled using the HVAC system. In such calculations, it is assumed that a thermal balance is needed between the environment and an 'average person', and this thermal environment is assumed to be constant. It, therefore, answers the needs of the engineering community in a way that allows them to size their plant. In doing so, it also dissuades them from addressing the shortcomings of the approach.

By inverting the original terms of what was understood as architecture (Fig. 1), it now seems that the building concept can be formulated as a 'support structure and enveloping shell of a set of facilities'. From ancient architecture we have left the most resistant parts, the fixed parts and the flat representations of them. In contrast, service and conditioning facilities are present in today's architecture in an increasingly conspicuous way and help it to function better, but most of the time they are hidden from the users' eyes (Fig. 5).

The volume that these mechanisms need occupies an increasing percentage of the built surface, but it is not only space that they are occupying in the building. The

Fig. 5 From left to right. (**a**) – Florida Gallery Building (1964 – Bonta and Sucari Architects, Buenos Aires) with air conditioners equipment added in the facade after occupancy in search for comfort. [15]; and (**b**) – Bank Macro Building (2019 – Cesar Pelli Architects, Buenos Aires) with all the high technology conditioning equipment hidden from our eyes [16]

decision-making power over them is increasingly moving away from the human being and is delegated to central offices that manage the control of the building.

Therefore and despite the existing richness of solutions and possibilities, it is more often to find poor architectural skins with rigid envelopes in the trust to achieve comfort through mechanical devices. It is very important to take into account that just as the climatic action changes during days and seasons, so do the demands of users regarding interior habitability, especially in changing and complex climates such as temperate [17].

Building comfort by natural means should be our main goal in the twenty-first century to protect the environment for future generations. In this holistic approach, well-designed climate-sensitive architecture will play a very important role, but also occupant's expectations and willingness to adapt to architectural possibilities and its response times will be key.

3 Occupant's Expectations Meet Architectural Possibilities

The overall mechanization of architecture has led to a disconnection between the occupants and the building. The mentioned and widely acknowledged historical transformation over the past century, where technological innovation led to a shifting of design responsibility in comfort provision from architects to mechanical engineering consultants, shifted the control responsibility from occupants to technology. Increased faith in technologically sophisticated environmental control systems meant that building occupants played little or no role in shaping the interior comfort conditions or indeed had little awareness and understanding of the systems that did and the energy required to operate the building.

The terminology used by comfort researchers is that of engineering and physics: temperature, humidity and airspeed, clothing insulation and watts of metabolic heat/m^2 [18]. The predicted mean vote (PMV) is the best known of such thermal indices [19]. Based on a simple steady-state physiological model, it predicts the mean comfort vote on the ASHRAE scale of a group of building occupants from a value derived from the four physical variables of radiant temperature, air temperature, humidity and air movement, along with the insulation of their assumed clothing level and their metabolic rate.

Acceptable thermal comfort in buildings is attained when 80% of occupants are satisfied with the provided conditions. The recognition of variation in comfort levels of the remaining 20% of occupants suggests that the notion of 'absolute' comfort is a privilege [20].

'Absolute' in this sense relates not only to thermal comfort but also to a range of possible comfort determinants including indoor air quality, visual and acoustic conditions as well as important psychological, cultural and behavioural aspects.

When referring to how individuals experience comfort, rather than the collective, having the ability to choose, for example, in a home or personal workspace where adaptive opportunities tend to be higher, represents a different state of individual comfort than in a shared or group situation.

Adaptation is central to current comfort discourse and those with more opportunities to adapt themselves to the environment or the environment to their own requirements will be less likely to suffer discomfort [21].

The notion of 'liberty to choose' is, in part, related to this ability to engage in adaptation strategies and behaviour changes and tolerances, and these may need to become much greater in an increasingly carbon-constrained world. Moreover, if comfort is considered a privilege, then the provision and expectation of its delivery are not a constant – even assuming 'a liberty to choose'. In a similar manner that limitations on the availability of natural resources can influence and limit consumption patterns, there will be times that an individual or group will be uncomfortable – and this may have to become an 'acceptable condition' [20].

Variability is generally thought of as a 'bad thing' in centrally controlled buildings because occupants are adapted to a particular temperature. In buildings where the occupants are in control, variability may result from people adjusting conditions to suit themselves. A certain amount of variability then becomes a 'good thing' [21].

The process of building systems and inhabitants dynamically responding to changing conditions and needs has been described by Cole, Robinson, Brown and O'Shea [22] as 'interactive adaptivity' and refers to the ongoing, bidirectional dialogue between building and inhabitant in which the outcome is not predetermined by building design parameters or performance metrics, but is rather an evolving process.

In this evolving process, results are not instantaneous. There is a time-lapse between the user's action and the building's response. This is a very important concept to bring into discussion because occupants (and there is a significant difference in the commitment between the term occupant and the term user) are used to push a button and obtain the desired change in environmental parameters.

Bordass and Leaman [23] have demonstrated that there is more 'forgiveness' of buildings in which occupants have more access to building controls. By forgiveness, they mean that the attitude of the users to the building is affected so that they will overlook the shortcomings in the thermal environment more readily. This can be explained as a function of who is in control.

The flexibility in modifying the comfort conditions of the space allows variations so that the last adjustment can be made by the same user. In this way, we will attend to your individuality. According to the adaptation principle of Humphreys and Nicol, what leads to a reaction in people's behaviour is lack of comfort: If a change occurs that leads to lack of comfort, people react in ways that they try to re-establish comfort [24].

As time passes, the temperature that people find comfortable (the 'comfort temperature') approaches the average temperature they have experienced. This implies that the conditions that occupants find comfortable are influenced by their thermal experience and that they can be adapted to a wide range of conditions.

The concept of acclimatization refers to the user's comfort factors. Although there are as many perceptions as there are users, generally particularities of the culture and climate of the region affect the expectations of comfort and therefore its standards. People put in place adaptation mechanisms and acquire more tolerance towards the most stressful aspects of the region's climate.

Popular architecture has always incorporated flexible solutions and systems, which components that can easily change their action according to climatic circumstances. Examples include mobile shading systems, which can prevent the access of solar radiation (hot weather in summer) or let it in completely if it is convenient (cold weather in winter); movable isolations in the openings, to allow night isolation; the same openings must be practicable for total ventilation; intermediate spaces located between interior and exterior, to generate favourable microclimates and be usable only in certain periods of time, among others. The components that make those changes possible can be an integral part of the envelope of the building (Fig. 6).

Therefore, the architecture in which natural comfort is possible takes time and space and engages the user as a part of its correct functioning, and that is a very different path to take when designing a building.

By accepting the adaptive hypothesis, it is argued that comfort is a 'social construction' – different societies, historically and geographically, have had different comfort temperatures. Therefore, previous experiences and cultural tolerance to change and education, among other factors, begin to participate in the equation of how architectural possibilities meet user's expectations – as the role of inhabitants

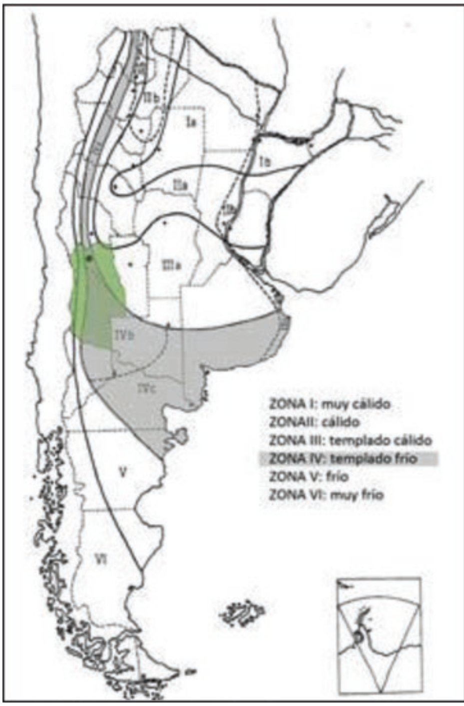
Fig. 6 Different shading devices. Sometimes buildings are barriers to Rain and wind and sometimes subtle filters for light and heat [25]

has shifted from occupants to users – engaged in a bidirectional dialogue with their buildings, reinforcing the idea that comfort is subjective and objective, without there being any contradiction in the statement.

4 Achieving Comfort by Natural Means: The User's Key Role from Theory to Practice

The adaptive model of thermal comfort rests on field-study research [26]. This research takes place in real buildings in everyday conditions, with the participants continuing their normal activities.

To assess the user role in achieving comfort by natural means, a case study of a free-running building in the city of Mendoza, Argentina is presented. A free-running building does not make any use of mechanical heating or cooling [27–28]. Its indoor temperature depends on the outdoor temperature and the total heat gains (from sun, occupants, lights and so forth) and the ability of users' 'interactive adaptivity' to adjust architectural devices to suit themselves.



Annual values	
Maximum mean temperature	24.5 °C
Minimum mean temperature	9.6 °C
Mean temperature	16.5 °C
Global horizontal irradiance	18.4 MJ/m^2
Relative humidity	56%
Relative heliophany	63%
July	
Maximum mean temperature	15.7 °C
Minimum mean temperature	0.8 °C
Mean temperature	7.3 °C
Global horizontal irradiance	10.2 MJ/m^2
Relative humidity	63%
Relative heliophany	58%
January	
Maximum mean temperature	32.3 °C
Minimum mean temperature	17.4 °C
Mean temperature	24.9 °C
Global horizontal irradiance	26.1 MJ/m^2
Relative humidity	49%
Relative heliophany	66%
Heating degree-days (T_b = 18 °C)	1384 °C
Cooling degree-days (T_b = 23 °C)	215 °C

Fig. 7 From left to right. (**a**) – Map: Location of the Province of Mendoza (green) in Argentina. The city of Mendoza is in climatic zone IV: temperate cold [29]. (**b**) – Table: Climate data for Mendoza, Argentina [30]

The city of Mendoza (32° 40′ South Latitude; 68° 51′ West Longitude and 827 masl) is characterized by an arid temperate continental climate, with strong thermal amplitude, low relative humidity, scarcity of rains and a high index of solar radiation and high heliophany (Fig. 7).

To obtain information about the thermal experience of real building occupants, a survey methodology was developed which simultaneously recorded room environmental conditions using conventional data loggers and sensors and the subjective feeling of warmth and preference for an individual together with a range of recent actions was recorded using a series of questionnaires.

The measurement period was of 59 days in the months of January and February, which is summer in the Southern Hemisphere. Temperature and humidity were recorded under pre-set conditions, testing the effect produced by different alternatives of occupation and envelope management by users. The information considered in the chart were: date, exterior and interior temperatures, rain, heliophany, hours of occupancy, closing/opening of windows, use of fan (the only device which required energy to function) and day/night comfort perception [31].

During the first measurement period, users opened all the windows during the night and closed them during the day. (Fig. 8) In a second period, users opened the window during the day and night (Fig. 9). Then in a third period, data were recorded for the dwelling without occupation, with all elements of the enclosure completely closed (Fig. 10).

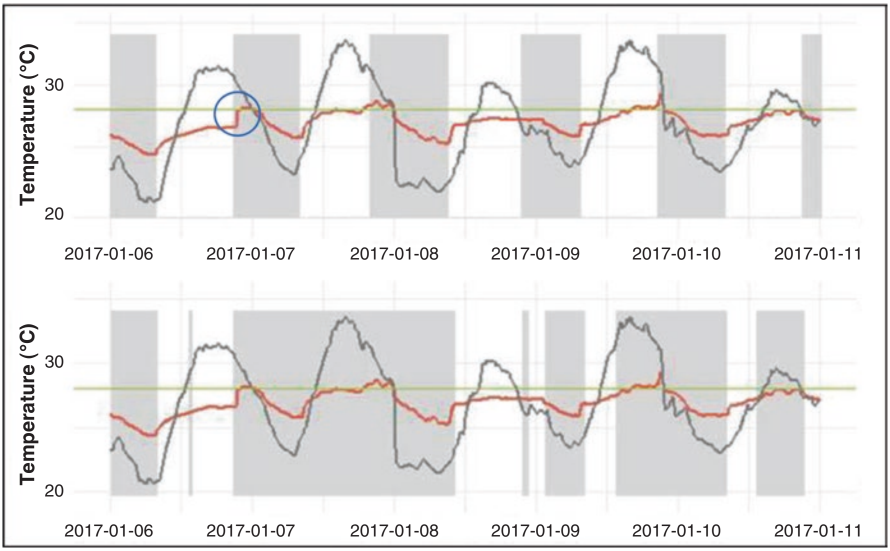


Fig. 8 Audit with occupation. Red: indoor. Black: outdoor. Green: 28 °C reference. From top to bottom: (**a**) – In grey: Windows opening to favour night-time natural ventilation. (**b**) – In grey: Space occupation [32]

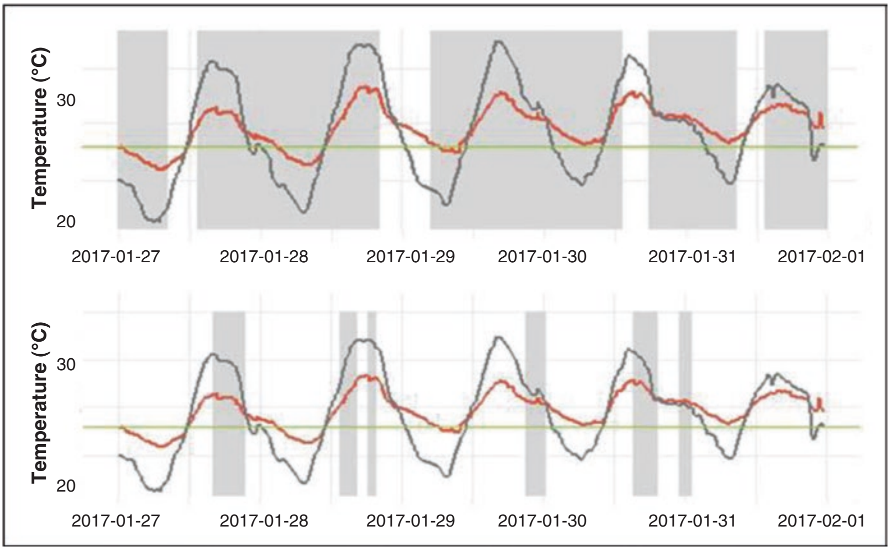


Fig. 9 Audit with occupation. Red: indoor. Black: outdoor. Green: 28 °C reference. From top to bottom: (**a**) – In grey: Windows opening day and night without any criteria. (**b**) – In grey: Space occupation with the use of a fan [32]

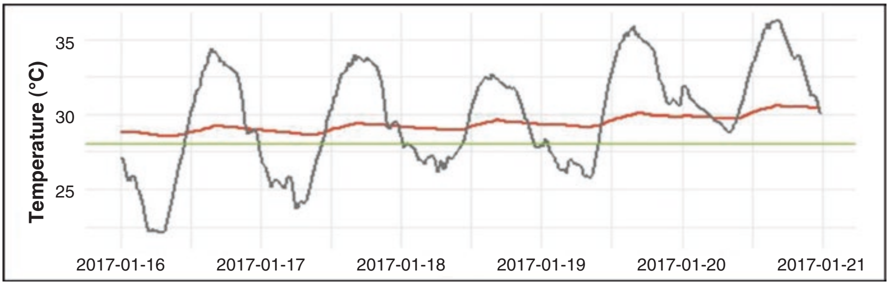


Fig. 10. Audit without occupation. Red: indoor. Black: outdoor. Green: 28 °C reference. Windows are closed during the day and at night [32]

Thermal performance was analyzed in relation to the compromised management of windows that users carried out to promote natural night ventilation, as well as the occupancy hours (Fig. 8).

The data from the record of occupation and management of openings graphed in grey bars (open/occupied) and in white bars (closed/unoccupied) in Fig. 8 show a general coincidence. We can assume that users are willing to manage the envelope of their homes while they are in them.

Note that the days in which the temperature exceeded the range of comfort correspond to an early opening of the windows (grey bars), which did not coincide with the drop in temperature outside. This can be clearly observed on 01/06 at 9:00 pm (marked in a blue circle in Fig. 8a), when the outside temperature exceeded the inside by 4 °C. Users arrived home and opened the windows probably assuming the correct hour to start (night) ventilation. As a consequence, the indoor temperature increased abruptly to meet the exterior temperature slightly above 28 °C.

Nevertheless, users perceived the space as comfortable without noticing the described ‘early’ opening. This is an example of the ‘tolerance’ users have towards temperature changes when they are in control of their living space. From this experience, users think their home is very comfortable and that they do not need to install any mechanical thermal conditioning.

In the second measurement period, users opened the window during the day and night. The direct influence that outside temperatures have over those of the interior was observed (Fig. 9).

Interior temperatures are above the comfort range throughout the observed period, with the exception of some night hours, the days in which minimum temperatures descended near 20 °C. In most cases, the accumulation of temperature in the interior mass materials during the day cannot be dissipated with natural night ventilation.

The lack of comfort manifested by users is evidenced throughout the period that they make intensive use of the fan, mainly in the hours of daily maximum temperatures. From this experience, users are willing to acquire energy-consuming mechanical equipment in order to condition their living space. Users do not know how to control their living space and therefore they think they need a machine to do that for them.

In the third measurement period, data were recorded with the dwelling without occupation, with all elements of the enclosure completely closed (Fig. 10).

The interior temperatures remain stable with a slight variation between 29°C and 30°C, staying above the range of comfort throughout the observed period.

Mass materials accumulate heat during the day, and by not ventilating inside spaces at night, heat builds up inside, which is reflected in a slight upward trend in interior temperatures. It is evident that even if temperatures are above the reference of 28 °C, they are stable. The fixed parts of architecture (material´s thermal mass and insulation) are keeping interior temperatures at a medium range.

Closed interiors won’t be at risk that daytime temperatures would rise to meet exterior temperatures. But this also implies that they won’t benefit from the night drop in exterior temperatures, also jeopardising the health and well-being associated with ventilation.

Opening windows are essential. All buildings should have opening windows and be habitable in natural ventilation mode [33].

Opening windows, along with all the architectonical devices and elements of the envelope in which the user can make changes and adjustments, lead to the fact that users add a level of uncertainty and unpredictability [34–36] and that it varies in relation to climate and customs. This fact must be seen as an advantage and not just a weakness – it is the means by which we manage risk and take advantage of opportunities by deviating from business as usual [37].

User behaviour has become key to reducing energy consumption. Many authors are starting to consider the education level of the user a differentiated point introducing management guides to give information on how to operate efficiently their homes, stating that a higher awareness and a better knowledge reinforce hazard prevention [38–39].

5 Building Natural Comfort for the Future

The existence of so many factors that influence the appreciation of architectural space makes the task of understanding space difficult. The simultaneity in time and of different types and amounts of energy makes it more complex to study this subject in an integrated way, which would be the most convenient in architecture. If we also consider the user interacting with architecture, the complexity rises even more. To these considerations we also need to add the future tense and a climate that is changing. Buildings are built not only for the present climate and the present user, but they will last over time. And even if the user remains the same, probably his preferences will evolve and change over the years.

Architectural design has an important impact on energy demand and efficiency. Decisions taken in the early stages of building design will influence and restrict the solutions for heating, ventilation and air conditioning in the present and also in the future. In this sense, the usage of the term 'resilient' has been increasing over the last decade, reflecting anticipated changes in our climate and resulting in necessary changes in our energy system and design practices.

Wilson [40] proposed a definition of resilience as the capacity of a system to absorb disturbance and reorganize while undergoing change to still retain essentially the same function, structure and identity. Resilience is measured by the size of the displacement the system can tolerate and yet return to a state where a given function can be maintained.

While referring to Wilson's definition, Roaf [41] states that it implies that the system should 'bounce back' to an original state and/or function and questions: Why not design systems that can 'bounce forward' to more failsafe states and functions? By designing systems that are enhanced by additional adaptive opportunities.

In the same direction, Trebilcock-Kelly, Soto-Muñoz and Marín-Restrepo [42] understand resilient buildings as designed and operated flexibly, so that the buildings can adapt to their occupants' requirements and promote the adaptability of the occupant.

Schweiker [43] establishes relationships between parameters and definitions of resilience and definitions and paradigms of comfort in the trust that connecting building resilience, human resilience, and paradigms of comfort opens several opportunities to scrutinise building design and operation practices together with research on thermal comfort (Fig. 11).

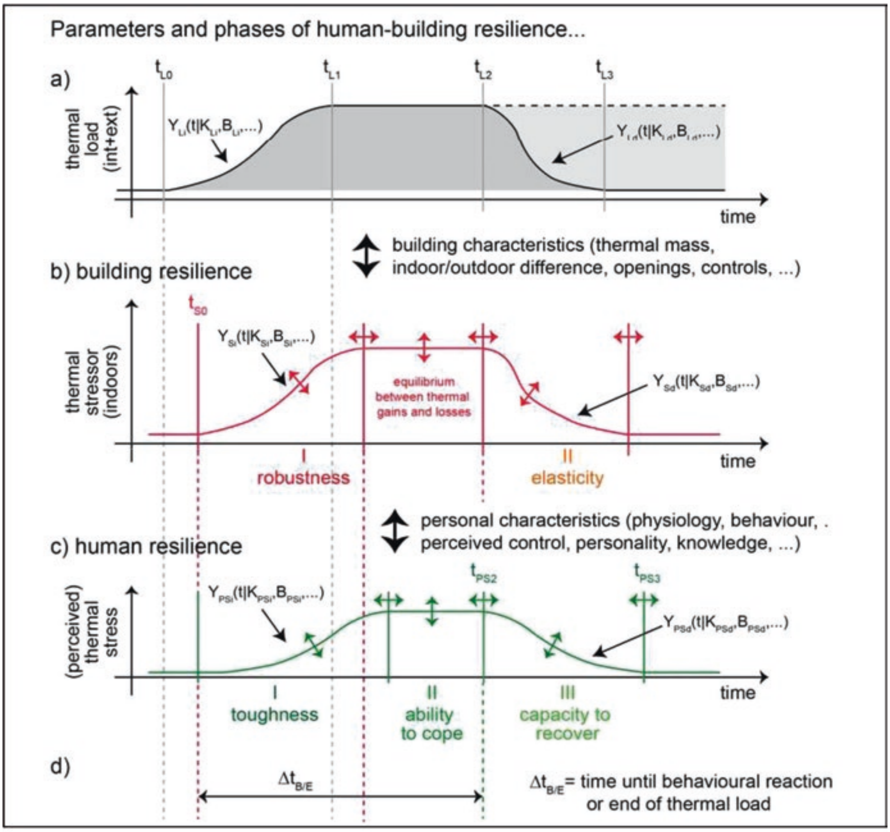


Fig. 11 Parameters and definitions of resilience in relation to comfort definitions and paradigms. Red and green arrows indicate that the position of the curve depends on building and personal characteristics [43]

Figure 11a presents the time course of a thermal load. This thermal load could be internal, meaning related to a high number of occupants or high equipment load, or external, such as high outdoor temperature or solar radiation. At times, the thermal stressor could be removed either by user action, for example switching on/off the equipment, closing blinds, or external conditions such as clouds or sunset.

Figure 11b shows the time course of a physical indoor thermal stressor, for example an increased operative temperature, as a result of the thermal load shown in Figure 11a. The relationship between thermal load and thermal stressor depends on the type of load and largely on the buildings' characteristics, such as thermal mass or window-to-wall-ratio. Different building concepts vary according to their robustness (increase) and elasticity (decrease). The values of these parameters can differ between robustness and elasticity. However, so far it hasn't been considered the effect on the thermal resilience of the user.

Figure 11c shows the time course of perceived thermal stress as a reaction to the thermal stressor shown in Figure 11b. While only one curve is drawn for reasons of clarity, note that thermal stress (e.g. physiological) can differ largely from perceived thermal stress. The relationship between thermal stressor and perceived thermal stress depends on personal characteristics such as the physiological constitution (e.g. level of fitness), behaviour (e.g. reducing workload to adjust metabolic rate) and perceived control, which was found to be related to perceived thermal stress and physiological reactions, personality or knowledge (e.g. that the stressor will end soon) [44].

The time course is split into three phases, each presenting a different parameter of human resilience: (I) toughness, (II) ability to cope and (III) capacity to recover. While the toughness related to thermal stress largely depends on physiological processes, the toughness related to perceived thermal stress might depend on other psychological influences. Phase II can be non-existing in case the occupant removes the thermal stressor before the thermal stress reaches its upper asymptote.

Thermal comfort is crucial in keeping building occupants safe, healthy, productive and happy. An unvarying environment may not just be psychologically boring, but may also reduce the ability of individuals to physiologically cope with environmental change. People adapt to a wide range of temperatures. Everybody is different. People habituate to the thermal environments they occupy over a day and year, and also their behaviours and expectations vary. Therefore, climate-sensitive architecture must vary too.

To achieve thermal comfort without a machine is the key to the success and resilience of a building. Architectural resources that users can use to adjust their spaces can collectively be described as adaptive opportunities, and their presence in a building may prove to be a key factor in the thermal satisfaction of the occupants.

The challenge posed is how to connect the work of comfort researchers to tangible improvements in the real world. In a future scenario that makes possible a more sustainable climate-sensitive architecture, comfort is not a given: Architectural adaptation possibilities must be conceived from the design, and users must be involved in the process of achieving comfort by interacting with their building over time.

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Carolina Ganem-Karlen is Professor and Senior Lecturer in the School of Design at the National University of Cuyo. (FAD-UNCuyo), Mendoza, Argentina and a Senior Researcher at the National ¬¬Research Council of Argentina (INAHE-CONICET). She is also the Academic Director of the Master in Sustainable Architecture at the Congress University (UC). Prof. Ganem-Karlen studied architecture at the University of Mendoza (FAU-UM) where she obtained her degree in 2001. That same year, she started her post-graduate studies in ABITA Centre at the Universitá degli Studi di Firenze (UNIFI), Florence, Italy with Professor Marco Sala. She holds a Ph.D. (2006) from the Universitat Politécnica de Catalunya (ETSAB- UPC), Barcelona, Spain under the guidance of late Professor Rafael Serra Florenza and Professor Helena Coch-Roura. Prof. Ganem-Karlen's research focuses are on energy efficiency; indoor environment and well-being; micro urban environments, occupants' thermal comfort and adaptive behavior, and energy assessment and certification of buildings. She has completed numerous research projects by a wide variety of resources. Prof. Ganem-Karlen has authored or co-authored many book chapters and more than 150 papers and research reports mainly presented in international journals or at international conferences with referee. Prof. Ganem-Karlen has been a member of the scientific committee and organization committee for many International Conferences. Referee for many international journals and international conferences in the field of energy and building. Prof. Ganem-Karlen is a Chartered Architect; a Fellow of the International Society of Building Science Educators (SBSE); a Fellow of the International Building Performance Simulation Association Latin-American Chapter (IBPSA-Latam) and a Fellow of the Argentinean Association of Renewable Energy (ASADES).