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THE ROLE OF MULTIPLE COURTYARDS IN THE PROMOTION OF CONVECTIVE COOLING

By

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Abstract

This study is set out to confirm the phenomenon commented on by Hassan Fathy (1986) that the temperature difference between courtyards has a role in the promotion of convective cooling through transitional spaces in a multiple-courtyards building in semi arid regions. The transitional spaces situated between courtyards are identified with specific titles such as *Takhtabūsh* in the Egypt; and *Tablinum* in a Roman Domus. However, despite the historic significance of these spaces, most studies have mainly focused on the climatic performance of buildings with a single courtyard. Empirical and numerical study has not been conducted on the nature of this phenomenon. In order to confirm this conjecture, this thesis is set out to conduct fieldwork and theoretical investigation.

This thesis is a single case study of the Casa de Pilatos in Seville, Spain. The case study is used to develop a methodology for analysis of multiple-courtyard phenomenon. Field measurement and mathematical models are used to determine the drivers for yard-to-yard airflows. The fieldwork uses data logging equipment to record dry bulb temperatures, relative humidity, and air velocity through the transitional spaces. The amount of cooling attributed to yard-to-yard flows and implication to cooling requirements in a contemporary environment are evaluated. Adaptive criteria of Nicol and Humphrey (2001) and Brager and de Dear (2001) are used to predict the thermal comfort of subjects.

The drivers are determined through analysis of buoyancy 'stack' forces and local wind regime. The building mass introduces three hours delay with up to 2.5kW or 36W/m^2 variation in heat balance in the transitional spaces by 15:00h. The calculated volume flow rates through the transitional space are 5.3m^3/s (equivalent to 5kW or 71W/m^2 in convective cooling) at 15:00h. The DBT in the gardens are up to 11k below the WBT. It is shown that multiple-courtyards phenomenon is a robust strategy accommodating a large variation in temperatures. The study confirms that temperature difference is the driver for convective flows through transitional spaces.

This study presents an opportunity to investigate the applicability of this concept in the contemporary context. Findings of this study have direct application in the reduction of cooling energy in widely used courtyard concept in semi arid regions.

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LIST OF ABBREVIATIONS

DBT – Dry Bulb Temperature (^{0}C)

AH – Absolute Humidity (g/m^3)

RH – Relative Humidity (%)

Q – Volume flow rate (m^3/s)

DO – Discrete Ordinance

CFD – Computational Fluid Dynamics

ACH – Air changes per hour

CHAPTER ONE: **BACKGROUND**

1.1 Introduction

Buildings with multiple-courtyard can be found in hot and dry climate areas ranging from the Middle East through the Northern Africa and Southern Europe. This study suggests that, the multiple-courtyard concept was historically employed to optimize the building climate. This work is based on the conjecture made by Hassan Fathy (1986) that the historic multiple-courtyard buildings in hot and dry areas incorporated an environmental strategy which used temperature difference between courtyards to promote convective cooling through in-between spaces 'transitional spaces'. Cain et al (1976) and Konya (1980) have also commented on and illustrated this concept. Nonetheless, the evidence presented by Fathy and other authors is anecdotal. An empirical and numerical study has not been conducted on the nature of this phenomenon. Most studies have mainly focused on the climatic performance of buildings with a single courtyard. The goal of this study is to conduct field measurement in order to confirm the role of the multiple-courtyards in the promotion of convective cooling. This thesis is divided into eight chapters. The rationale for this study, methodology and objectives are presented in chapter one.

The environmental case for multiple courtyards is presented in *chapter two*. The chapter discusses the question 'what principles are exploited by the historic multiple courtyard buildings?' The traditional building practices in hot and dry climates are challenged by high temperatures and very low humidity. The environmental case for multiple-courtyards is made by discussing the empirical traditions, bio-climatic features, design concept, pragmatics and user considerations. These aspects will be used to show how multiple-courtyard buildings found their form.

Precedents from the Middle East, North Africa and southern Europe are presented in *chapter three*. These precedents are used to suggest a wide historical application of multiple-courtyard concept in the control of heat gains in semi arid areas. Precedents are important because architecture is learnt through a history of practice. In these precedents, garden-courtyard is used in conjunction with paved courtyard, and the transitional spaces in between have specific titles such as 'Takhtabūsh' in Egypt, 'Liwan' in the Middle East; and 'Tablinum' in a Roman Domus in Italy. These precedents are used to suggest that similar climatic strategy is applied to a range of environments and cultures.

The building and context to be investigated will be presented in *chapter four.* The influence from the Moorish 'Muslim' conquest of Spain is expounded. Southern part of Spain was named Andalusia by the Moors. The artful Moorish Architecture did later culminate in Mudéjar style. The climatic influences which set the context for Moorish garden-palaces, with the ingenious arrangement of materials and practical use of water and vegetation, are discussed. The Casa de Pilatos in Seville is used as an example of Mudéjar architecture that has demontrated the Moorish approach to multiple-courtyards building. The house is located in the narrow streets in the historic part of Seville in the Southern Spain.

The field data collected from the Casa de Pilatos will be presented in *chapter five.* Fieldwork was conducted between 10^{th} and 20^{th} August 2008 at the Casa de Pilatos, Seville, Spain. The primary collected data includes air temperature (DBT), relative humidity (RH), and air velocity (m/s). The selection of field instrument (data loggers, tiny-tags and tiny-talks) will focus on their ability to provide a continuous record of data. Air velocity transducers 'anemometers' will be used to record air velocity. All the data will be summarized into hourly intervals. The hourly data from six locations in the building will be tabulated, and presented in a graphical form.

Analysis and discussion of the fieldwork data will be presented in *chapter six.* The analysis will consider the impact of passive cooling in the Casa de Pilatos, the drivers for yard-to-yard airflows, thermal comfort and convective cooling in the transitional spaces 'Hall of Columns & Praetor Chamber'. The analysis will also consider the impact of sky turbulence, nocturnal cooling, and evaporative cooling from water outlets and vegetation, and radiant cooling from building surfaces. The analysis of thermal comfort will consider the practical application of window-seats and the cooling sensation of the airflows from the garden-courtyards.

Chapter seven has presented the CFD results from theoretical modelling of the Casa de Pilatos. Discrete Ordinance (DO) radiation model in Fluent software is used to model natural displacement flows by using field recorded surface temperatures. The surface temperatures that were recorded during fieldwork will be converted into fluxes of heat (W/m^2) for theoretical modelling.

Chapter eight presents summary and conclusions of this work. These are presented in four parts. The first part presents the hypothesis and historical precedents and principles. The second part summarises the field investigation and methodology. The third part reiterates results, and the fourth part provides conclusions and contribution to knowledge.

1.2 Objectives

General objectives:

(1) To use field data to determine the role of multiple-courtyards in the promotion of convective cooling across transitional spaces.

(2) To determine the drivers for air movement through the transitional spaces of the multiple courtyard buildings.

(3) To determine the thermal comfort criteria in the transitional spaces and multiple-courtyard environment.

Specific objectives:

(1) To use field measurements to determine the magnitude and direction of air movement through the transitional spaces.

(2) To use field measurements to determine the temperature variation between the multiple-courtyards.

(3) To use field data to compare and contrast the daytime and night time dynamics existing between the courtyards and the open sky.

(4) To determine the role of buoyancy forces as the driver for airflow through the transitional spaces.

(5) To determine the role of stack forces in the hot-grey courtyard on the movement of cool air from garden-courtyards.

(6) To determine the impact of prevailing wind pattern and urban layout on air velocity through the transitional spaces.

(7) To use theoretical modelling to confirm the impact of temperature differences between courtyards on the magnitude and direction of airflow through the transitional spaces.

(8) To determine the contribution of the building mass to heat balance in the transitional spaces.

(9) To determine the possibility for cooling from the conditions in the garden-courtyards.

(10) To determine the amount of convective cooling attributed to air flows through the transitional spaces.

(11) To determine the implication of additional heat loads on the convective cooling requirements in the transitional spaces.

(12) To determine the application of window-seats on the thermal comfort criteria in the transitional spaces.

(13) To determine the application of adaptive comfort models in the multiple-courtyards building.

1.3 Rational for the study

Until recently, very few scholars have attributed the history of human shelter to the quality of thermal environment and environmental comfort. Cain A, F. Afshar, J. Norton, and M. Daraie (1976) suggested that the era of rapid growth in the industrialised world linked the strategies employed by historic buildings with underdevelopment because their inherent strategy was employed by people who did not have access to technology and other sources of energy. Apparently, researchers have come to acknowledge that the organization of the environment in most historical settings did not come into existence through some form of accident, but all of them were preceded by creative processes that had ensured climatic survival.

Architecture as an evidence and source to the environmental aspects of history of human shelter has been explored in the works of Rapoport (1969), Heschong (1979), Konya (1980), and Fathy (1986). Their analysis of the relationship between building, culture and climate has shown the need for further investigation of environmental aspects of building. History is largely represented by human effort to shelter against the extremes of weather and climate through a variety of strategies and building forms. Particularly, following the comments by Fathy (1986) on the role of multiple-courtyards phenomenon in semi arid climates, no investigation has been carried out to verify this aspect of building design.

Unlike the multiple-courtyards strategy, a lot of studies have been conducted on thermal performance of single-courtyard buildings. Most of these studies assert that courtyard designs have historically provided the desirable heating and cooling without requiring other form of energy, with courtyard acting as a semi-outdoor space or transition between exterior and interior environment. The transition in courtyard buildings is an environmental event, where dust, noise, air-pollution and temperature is separated from the outer environment. Houses are built on the site perimeter in order to maximize courtyard space and provide calm and pleasing climate and privacy behind the hectic environment of an urban territory.

As the world is largely geared towards reduced energy consumption, the multiple courtyards strategy would provide an opportunity for regulation of the thermal environment and natural ventilation of built spaces. The investigation of the multiple-courtyards concept is important because the courtyard layouts are still widely favoured – they have not become obsolete. It is still possible to integrate this climatic strategy in the contemporary natural ventilated buildings. These buildings are also still widely used as architectural means to demarcate and intensify forms of social life (Tuan Y, 1977). If the anecdotal evidence provided by Fathy (1986) is confirmed, then multiple-courtyards phenomenon can be used to control the inflow and outflow of air through the spaces between courtyards and offer some advantages for control of heat gains and thermal comfort.

1.4 Research methodology

An improved understanding of this phenomenon will provide a more reliable theoretical basis. This study uses empirical evidence to confirm the anecdotal evidence provided by Fathy (1986) in order to make the results accepted within the research community. The study is primarily limited by inability to find the historic buildings in conditions that can produce convincing results. In order to confirm this phenomenon, this study has presented a general overview of three precedents and detailed analysis of one case study, all located in areas with semi-arid summer season. The four historic multiple-courtyard buildings referred to in this thesis are the following;

- Roman Domus, Italy
- Al-Suhaymi House, Egypt
- Beit Ghazaleh House, Syria
- Casa de Pilatos, Spain

Roman Domus is located in the city of Pompeii in the western part of Italy. This house is chosen because the Roman Empire did spread across the semi arid parts of North Africa, Middle East, and Southern Europe where Roman Domus could be found in all major cities. This places this house model in the period 44 B.C to 1453 B.C. when Roman civilization had influenced the region. The house is also chosen because it comprises two courtyards and a unique space entitled Tablinum as a transition between courtyards. It was a family house for the upper class Roman urban citizens. Since everybody wanted to own a Domus (mmdtkw.org), the house is likely to have a thoughtful environmental design. Information on the design of a typical Roman Domus is also widely available. However, the Roman Domus is only identified from excavated ruins; and it is unlikely for convincing data to be collected from such ruins.

Bayt Al-Suheymi (House of Suheymi) is built between 1648 – 1796AD and is located in the city of Cairo in the northern part of Egypt. The Al-Suheymi house is chosen because it was identified by Hassan Fathy as a surviving example of a building that has employed multiple-courtyards to promote convective cooling through a transitional space. The house is built in an area of 2100 square meters, and comprises of two courtyards and a unique space entitled Takhtabūsh as a transition between courtyards. However, the house suffered 350 years of environmental wear and poor maintenance until 1997 when restoration began under the auspices of Arab Fund for Economic Development. This was long after Fathy's conjecture, and some alteration, particularly the vegetation in the courtyards make this building not to be a viable case for field studies.

The third precedent presented in this study is Beit Ghazaleh house located in the city of Aleppo, 120km (75mi) inland from the Mediterranean coast in Syria. According to Edwards et al (ed.2006 pp148) the layout of this house is a typology of what used to be traditional houses in Syria. The layout of the house suggests that the transitional space 'Liwan' has benefitted from the thermodynamics between its two courtyards. However, due to political instability in the region and irresponsible alteration in some parts of this building, the spatial characteristics of this building are not in their original standards. The materials in the courtyards have been changes, and the opening which seems to exist in the original floor plan; connecting the Liwan space to the garden-courtyard does not currently exist.

Casa de Pilatos is chosen for field study because it is an exemplary multiple-courtyard building with well maintained and intact fabric and layout. The choice of the building is also influenced by the contact which was already available through research collaboration between the University of Nottingham and University of Seville. Contacts were necessary to facilitate access and rapport in a Spanish speaking country. The distance and duration of the fieldwork is also limited by available resources. Through various online resources, the layout of the building and images of its various spaces are confirmed in advance. As a result, it has been possible to plan the fieldwork and identify the location within the building for installation of equipment.

Empirical evidence from fieldwork and numerical investigation will be used to confirm the phenomenon. Field studies are widely accepted in the scientific community as a methodology of gathering research data. They have produced reliable results in a number of studies conducted in the built environment. The study by Nicol (1983) observes some thermal comfort trends that would not be evident in laboratory studies. In the study by Alcala (2002), fieldwork is used to collect data to help confirm the airflow pattern existing between patio, portico and tower in the palace of Alhambra. The results from their investigation would not be conclusively obvious through theoretical modelling. Field work will be conducted in the Casa de Pilatos, Seville, Spain in the summer season.

Fieldwork is carried out by installing some monitoring equipment and physical investigation of the site environment. The Casa de Pilatos covers around 100 x 70 metres ground around its four courtyards. Equipment is installed in three courtyards, two intermediate spaces, and roof top. The data loggers are used to collect data over 24 hours for a period of one week. Field measurement of air temperatures (DBT), humidity (RH) and air velocities (m/s) are collected from the investigated building and then summarized into mean hourly data. Correlation is made with meteorological data collected from Energy-Plus weather data. The data is used for analysis and graphical interpretation of building climate.

Predictive models are used to forecast the impact of buildings in their environment. Theoretical investigation of the phenomenon is conducted by using computational fluid dynamics (CFD). Theoretical model is made by using Gambit interface within Fluent software. The procedures held in CFD program have presented reliable results among researchers of natural displacement ventilation flows, because they can be used to calculate thermal radiation and diffusion as mechanisms for thermal transport (Howell and Potts 2002). The dimensions of the theoretical model are taken from field measurements. The thermal fluxes of heat (W/m^2) from field surface temperatures are used as an input data in order to determine the impact of the buoyant flow of air.

Field data is also used to identify the potential drivers. The DBT from the field data are used to determine the impact of buoyancy forces on air velocity through the transitional space and the outlet opening in the Main Patio. Convective cooling energy is calculated from the air velocity recorded at the inlet window and air temperatures recorded in the transitional spaces and adjacent garden-courtyard. The investigated spaces are also subjected to additional cooling loads to determine their adaptability to conventional requirements.

The variation of recorded temperature between the transitional spaces and outdoor air will provide an indication of the time-lag that is born out of building mass or capacitance insulation. Additionally, adaptive comfort principles will be used to determine the subjects' thermal sensation. The adaptive comfort models of Nicol and Humphreys (2002), and de Dear and Brager (2001) are used to evaluate the thermal conditions in the transitional spaces.

CHAPTER TWO: ENVIRONMENTAL CASE FOR MULTIPLE COURTYARDS

2.1 Introduction

This chapter presents an environmental case for multiple-courtyard buildings by evaluating the traditional building practices taken by these designs. The aim is to expound an environmental case for what is inherent in the multiple-courtyard designs located in semi arid regions in the hot summer Mediterranean climate (see fig.2.1). The climatic sophistication of multiple-courtyards design is evaluated by recounting the five aspects namely; empirical traditions, bio-climatic features, design concept, pragmatics and *apobetics*. These aspects are summarised from five levels of information provided by Gitt (2001). They help to fully explain how historic buildings found their form.

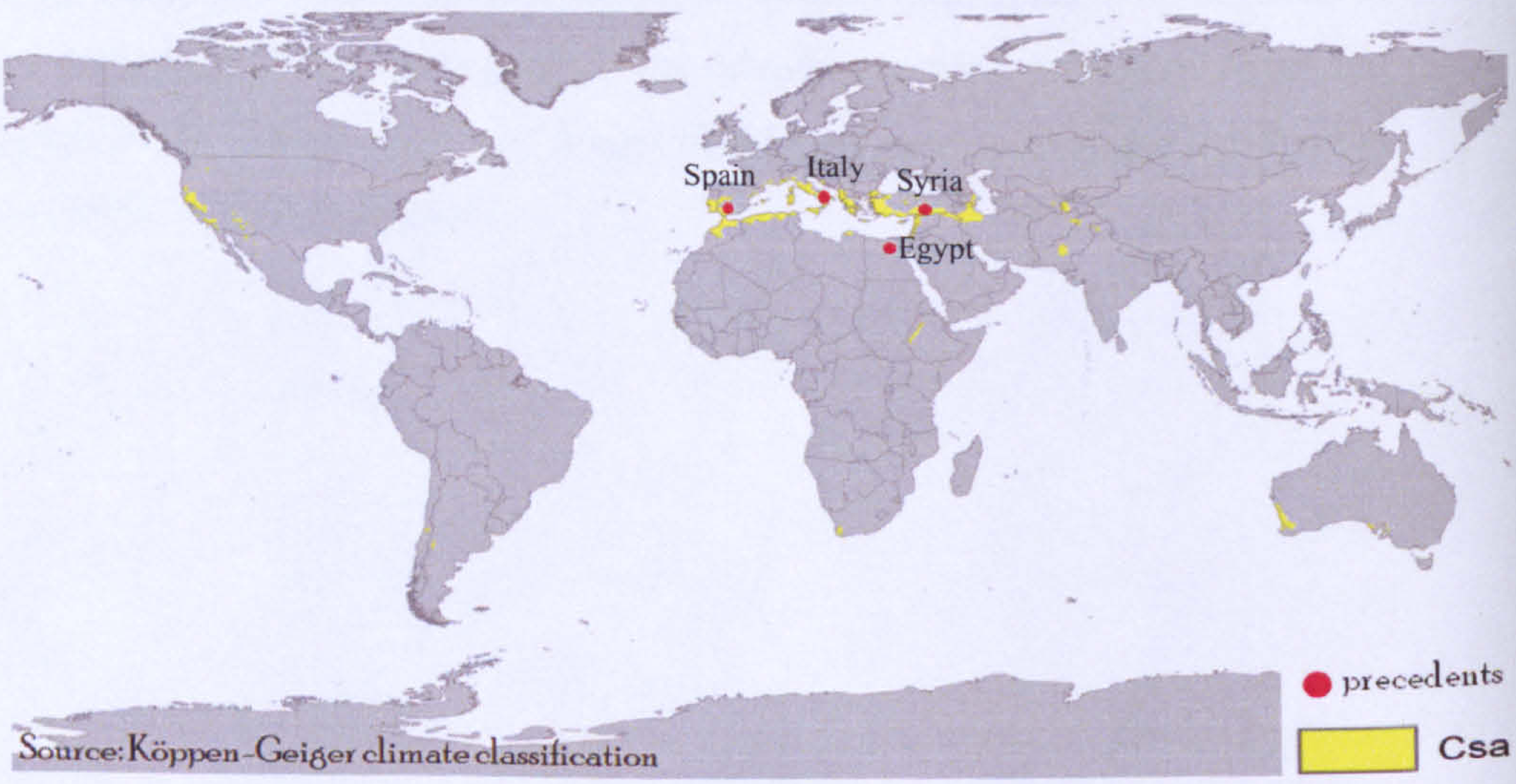


Fig. 2.1 The world map showing the location of the precedents in the hot-summer Mediterranean climate (Csa)

A complete characterisation of the multiple-courtyards phenomenon considers all the five aspects essential to both the designer and user. Multiple-courtyards architecture did firstly determined by empirical traditions which were handed down from generation of builders. An agreed upon bio-climatic features comprising individual devices such as vegetation and water fountains is used to determine the thermal environment. Then a number of bio-climatic features are purposeful organised to compose a unified strategy/technique (climatic concept). The design concept is made complete by incorporating the responses that are desired of the user (pragmatics), and experiences of the end user (apobetics).

Among the five aspects, the empirical traditions in multiple-courtyard buildings relied upon physical and botanical processes. Bio-climatic features include the application of vegetation, building mass, fountains, ponds and building surfaces. It is suggested that the design concept combines a cool garden-courtyard and warm grey-courtyard to promote convective flow of air through the transitional spaces. It is believed that the design considerations are primarily determined by pragmatic considerations of climate. The term '*apobetics*' is a teleological aspect; focused on the quality of the visible results and impact on the end user.

2.2 Empirical traditions

Multiple-courtyard buildings represent the vernacular traditions where knowledge was attained by the way of accumulated tradition of building design. Empirical traditions refer to the practices where building knowledge is accumulated by trial and error and handed down to generations. According to Hillier and Jones (1977 pp390), a traditional building practice is the encoding of technological wisdom, learnt by trial and error. Historic builders used experience gained from the environment they lived and interacted with. That way, the knowledge became very familiar to the native builders who participated in the design process. They had to master their environment over a period of time to know the inherent patterns of nature. Below is Hassan Fathy description of the innate engineering sophistication (see fig. 2.2) of Nubians in Egypt.

> *'It is remarkable to find that the builders ... were working ... with extraordinary intuitive understanding. ...they made the vaults in the shape of the parabola, conforming to the shape of the bending moment diagram, thus eliminating all bending and allowing the materials to work only under compression. In this way it became possible to construct the roof with the same earth-bricks as for the walls.'* (Steele, 1988 pp52)

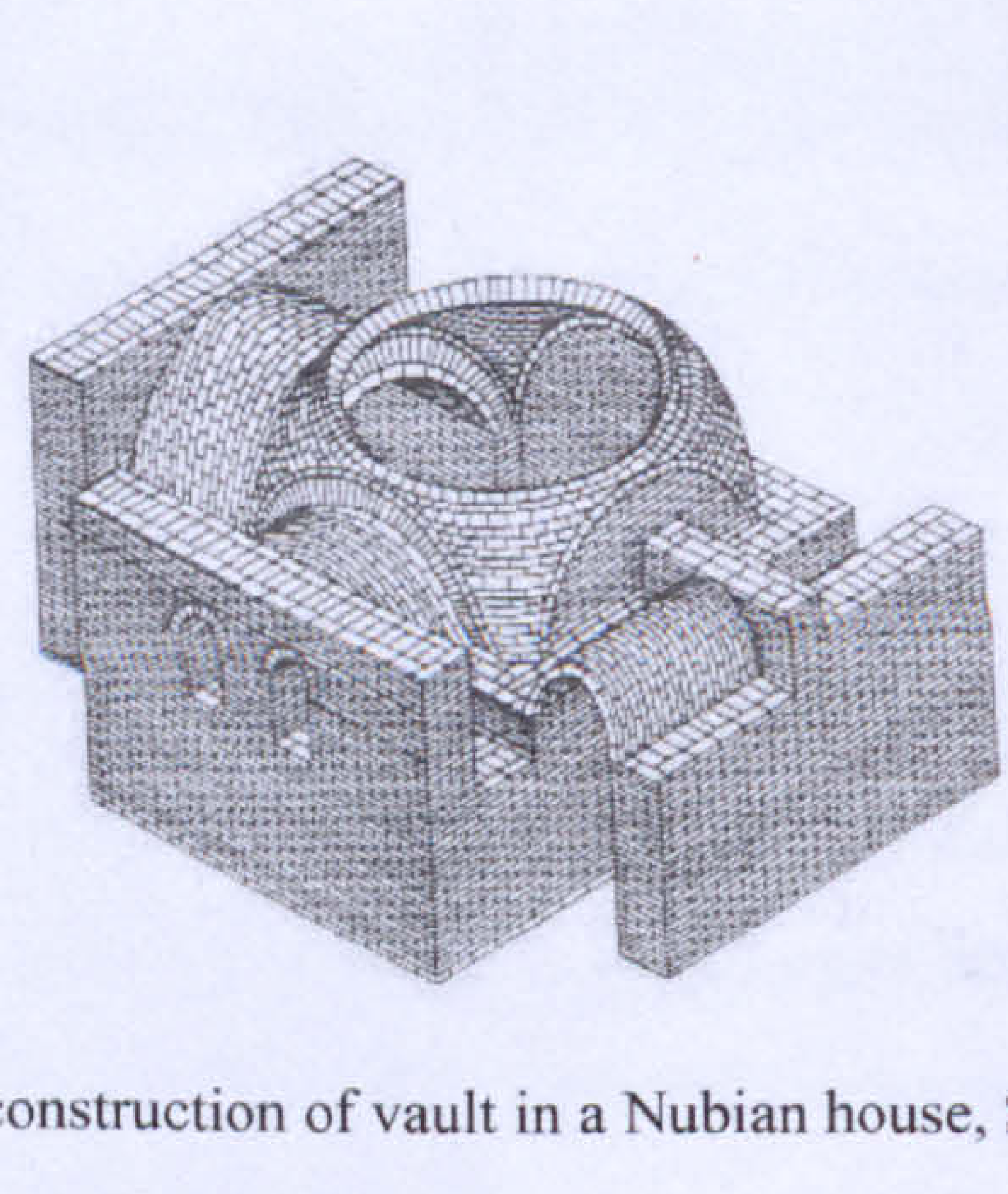


Fig. 2.2 Typical mud brick construction of vault in a Nubian house, Source: Steele (1988 pp52)

The precedents for multiple-courtyards buildings are taken from semi arid regions of the hot summer Mediterranean climate. All precedents lie between latitude $30^0 - 40^0$ North (see fig. 2.3). Historically, these regions are largely influenced by Romans and Islamic building practices. The Casa de Pilatos, Roman Domus, Al Suheymi house, and Ghazaleh house in Seville, Pompeii, Cairo, and Aleppo are suggested as precedents for this strategy. The buildings have strikingly similar layout, revolving around a warm main courtyard and a cool columned or colonnaded garden-courtyards.

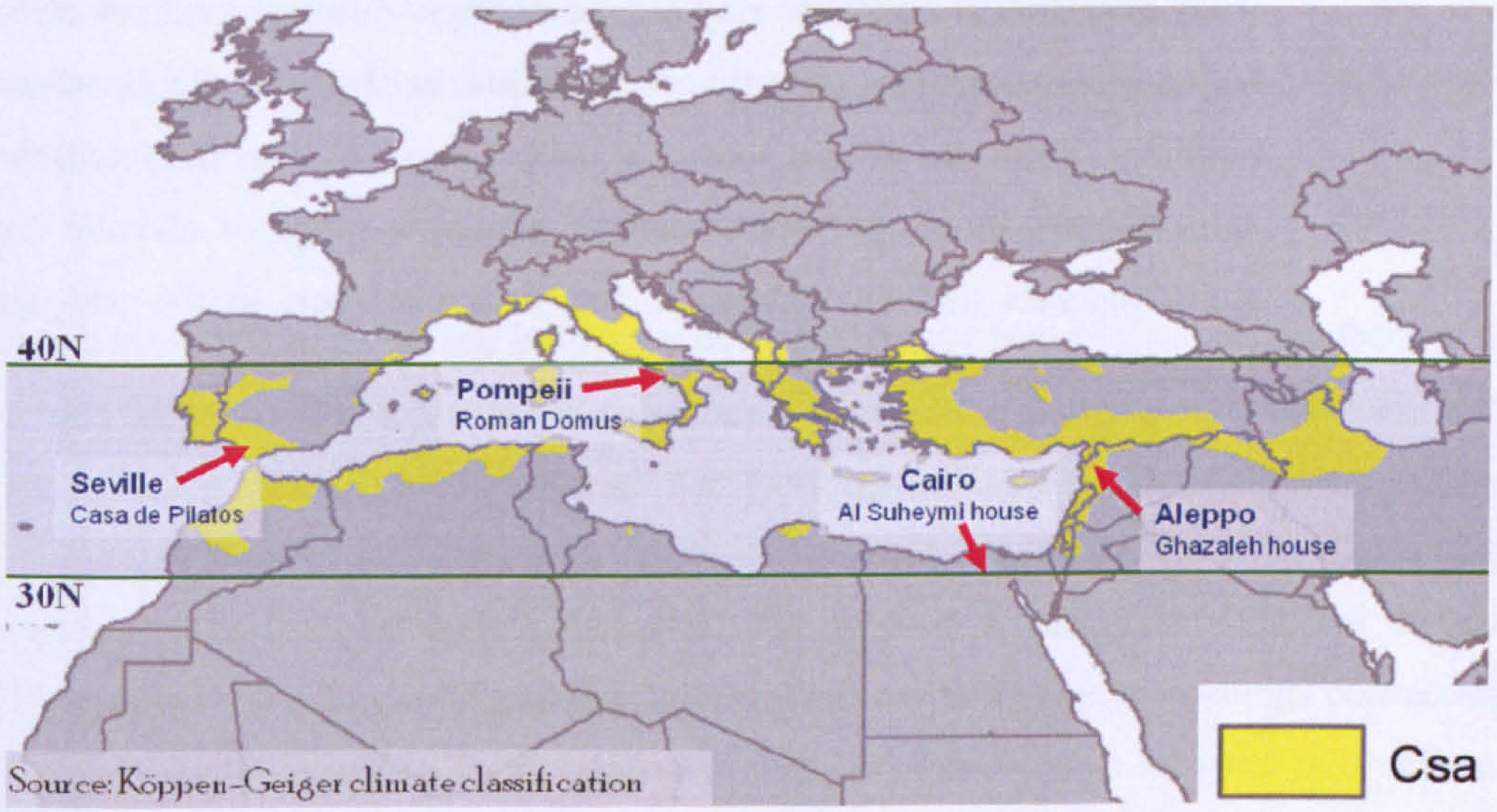


Fig. 2.3 The map showing the name and location of precedents in the Mediterranean region

Multiple-courtyard buildings combine physical and botanic processes. They used to rely on processes which occur in nature, some of them being technically realizable, while others like photosynthesis are yet to be realized technologically. Vegetation is used to alter the properties of air through evapotranspiration. Heat gains are reduced when dry air is humidified through the evapotranspiration process. Santamouris (2001 pp145) has shown that the latent heat transfer from vegetation can result in temperatures 6-8k cooler than exposed soil. The determination and description of growth, impact and cooling rates of botanic processes is complex, and does not form part of this study.

The study of climatic design of multiple-courtyard buildings requires quantitative knowledge of the magnitude of environmental data. The knowledge of the building microclimate requires the quantification of thermal properties and airflow. Historic builders accumulated this data from experience of the environment they have lived and interacted with. When hypotheses are proposed to explain the data and integrate explanations by studying evidence about the past, very complex and sophisticated reconstructions are possible (Hillier and Jones, 1977 pp390). Thus, the conclusions from study of historical buildings may require multiple different kinds of evidences to make major inferences. The climatic requirements in these buildings were different and buildings seem to accommodate a wide range of thermal environments; unlike contemporary buildings which consider a narrow range of climatic conditions. This study suggests that environmental data is a vital part in the understanding of the multiple-courtyard buildings.

2.3 Bio-climatic features

Bio-climatic features refer to a number of environmental elements employed to exploit the empirical traditions and particularly possibilities and capabilities in the local thermal environment. The available technology played an important part in the determination of the bio-climatic features for multiple-courtyard buildings. These features were also determined by their local environment. For example, the incorporation of cooling aids such as '*Maziara*' cooling jars which were located at the inlet windows. Other bio-climatic features to be found in these buildings include malkaf, salsabil, mushrabiyya screens, and loggia. The characteristic excessive heat and glaring sun in hot and arid climates require bio-climatic features designed to reduce heat impacts and provide shade and cooling.

The knowledge in traditional building was limited by the possibilities and capabilities of water, solar, botanic and physical processes. The available building techniques did play an important part in the choice of the bio-climatic features for multiple-courtyard buildings. Most of buildings with multiple-courtyards have employed building mass, garden-courtyards, vine-trellis, fountains, and pools in a variety of sizes and shapes. Most of these features are situated in the courtyards with an axis of openings connecting them to indoor spaces. It is suggested that the bio-climatic features in multiple-courtyards phenomenon required no other form of energy except the water, solar, botanic and physical processes.

- Water (fountains, ponds, jars next to the window)
- Solar (surface radiant heat, solar time)
- Botanic processes (garden-courtyards)
- Physical processes (Material thermal storage)

The following subsections discuss some bio-climatic features that require specific attention.

2.3.1 Vegetation

Vegetation is a bio-climatic feature that is widely featured in multiple-courtyard buildings. Botanical systems differ from other systems because their systems are naturally optimized, and have involved the extraordinary processes of photosynthesis and evapotranspiration. Evapotranspiration combines loss of water to the atmosphere by evaporation and transpiration. The positive impact of vegetation on energy saving has gained an increasing acceptance during recent years (Santamouris, 2001 pp146). To evaluate the possible decrease in air temperature due to evapotranspiration, it is necessary to know the exact latent heat absorbed by the ambient air during the evaporation of water by a tree.

The performance of vegetation is influenced by foliage geometry, disposition, height, air permeability, transmission of solar radiation and crown shape. Jones (1992 pp120) has reported the energy requirement of 680Wm^{-2} (which is equivalent to 10 mm/day or 1 mm/hour in the rate of evaporation) in arid environment. Evapotranspiration creates an 'oasis effect' which is responsible for a significant energy reduction of up to 50 per cent for buildings protected by trees (Barbera, 1991). Arcala (2002) has acknowledged a deep inter-penetration between architecture and gardens, citing examples from the Palace of the Lions and the Generalife in the Southern Spain. Garden-courtyards are desirable for their twin merit; cooling through evapotranspiration and shading.

In most multiple-courtyard buildings vegetation is kept and grown in the garden-courtyards to preserve against extremes of heat in semi-arid climates. The concept behind loggia was to create a platform to survey the paradise of greenery in the garden-courtyards. The *kheima* is a flat-roofed Egyptian loggia covered with palm leaves used as a sitting and sleeping area during the hot summer months (Steele 1988 pp46). Unlike mechanical ventilation, it is difficult to contain the impact of vegetation in garden-courtyards within a narrow temperature range. The vegetation in sunlit and shaded areas does have different energy balance. Thus, the choice and location of vegetation has impacted their performance.

2.3.2 Material thermal storage

Building mass is a bio-climatic feature common to historic multiple-courtyard buildings. Material thermal storage is more effective where the diurnal variation of ambient temperatures exceeds 10k (Balaras, 1996). This feature is widely used to regulate high diurnal and annual temperature swings in hot and arid climates. The storage material is the construction mass of the building itself. The volumetric specific heat capacity of a material is characterized as (ρ x c, density times specific heat). The energy available from high solar gains during the day is stored and then is slowly released into the indoor environment at a later time. Historic multiple-courtyard building in hot and arid climates used building mass to provide thermal delay between indoor and outdoor space temperatures.

This bio-climatic feature influences the life-style of inhabitants in multiple-courtyard buildings. If people wanted to withdraw from the hottest locations in the afternoon, they would retreat to interior spaces where the building mass has kept indoor temperatures below the outside air temperature. Outdoor activity would restart later in the afternoon when the outside temperature is past its peak (Konya, 1980 pp31). As indoor air temperatures continue to rise, people would then move into the courtyards or patios, and gardens.

2.3.3 Water features

Water is a bio-climatic feature most commonly used in historic multiple-courtyard buildings. Earth and water co-exist in a natural paradise (Steele 1988 pp50). The courtyard in hot and dry climate represent a delightful open-air sitting room to be kept cool from the intense heat of summer season using its fountains, ponds, vine trellis awning, and arcades. Below is an apt description of an Arab palace in Toledo, Southern Spain.

'In the centre of the lake rose a water pavilion of stained glass adorned with gold. Here the sultan could recline in comfort of the hottest day, encircled by the glistening shower falling from the dome' (Villiers-Stuart, 1994)

Maziara cooling jars are porous containers made from earth and then filled with water to promote evaporative cooling (fig.2.4). They were commonly used for air conditioning in the Middle East and North Africa. They were self regulatory and responded to climatic changes without the aid of a thermostat.

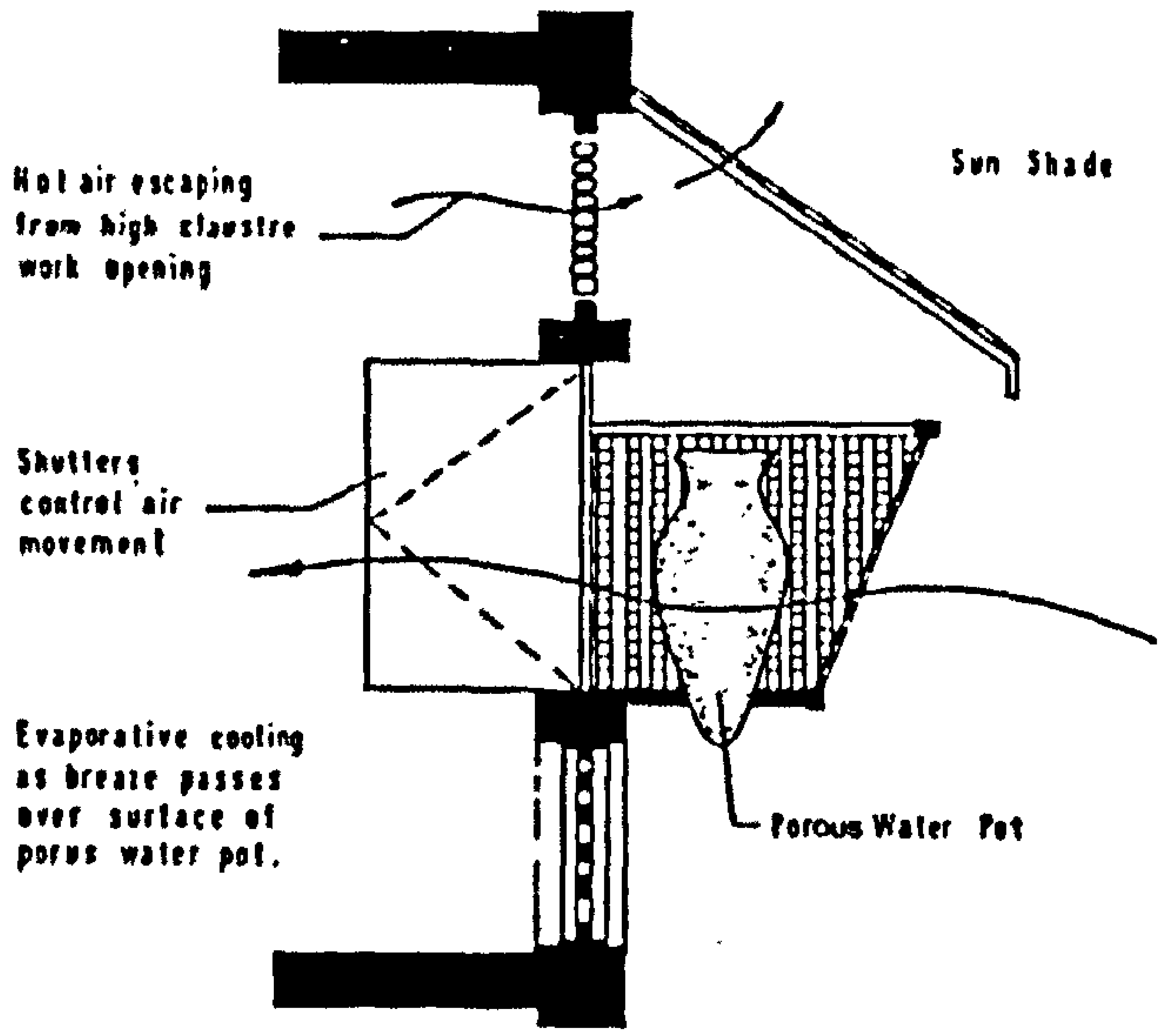


Fig. 2.4 Window mounted cooling unit, Source: Cain et al (1976)

2.3.4 Environmental time

Environmental time is the feature very significant in historic multiple-courtyard buildings. The properties, quality, and characteristics of spaces are influenced by the passage of time, from sunrise to sunset, all year round. Environmental time is primarily linked to solar time and seasons as the earth moves around the sun. According to Unwin (2005), time is amongst the modifying elements of architecture. Time becomes more complex when the variations in properties like heat, light, colour, sound become a positive part of the design process (Malnar and Vodvarka, 2004 pp259). In historic buildings, consideration of time would affect the scale, texture, smell, ventilation, temperature, colour, sound, and light.

This feature suggests that it is only through time as the fourth dimension of space, that we can comprehend the impact of the variation in the thermal characteristics in the multiple-courtyard buildings. Multiple-courtyard schemes have employed variable building heights for different parts of the form to cast shadow on each other as sun rise and set. It is most likely that this strategy is used to cut down on direct solar gain in the garden-courtyards. Field experience of time in these buildings is a necessary to evaluate the dynamics caused by solar path on the variation of air temperature, humidity and air speed.

2.3.5 Building surfaces

The historical multiple-courtyards design encompasses radiant heating and cooling from surfaces. Since energy is dispersed from sun in the form of radiation, courtyards do process an environmental disposal of heat. The courtyard exposed to solar radiation contains hot and buoyant air while shaded courtyards contain cool and dense air. Hence, thermal convection takes place as a mechanism of restoring thermal equilibrium between spaces. Radiant heating and cooling cycles are believed to be the fundamental driver for air movement and comfort in multiple courtyards building.

The design goal is to relief occupants from extreme summer heat. Environmental conditions for thermal comfort and wellbeing need to be provided and maintained through mechanisms of heat transfer in the multiple-courtyard environment. It is believed that the multiple-courtyard concept has controlled the dispersion of heat through heating and cooling of building surfaces and as a result promoted natural convection.

2.4 Design concept

A design concept refers to a unified program of bio-climatic features set to deliver a specific environmental impact. For any entity to be accepted as architecture it must involve a meaningful design concept. According to Baker and Steemers (2000), environmental performance of buildings is determined, to a considerable extent, at the conceptual stage. The design concept in historical multiple-courtyard building is a spatial program involving a set of bio-climatic features. While the bio-climatic features are influenced by the level of technological development, the design concept is influenced by the available bio-climatic features. The design concept characterises the built environment in a way that it can take advantage of available bio-climatic features. The requirements and provisions for the multiple-courtyards concept are summarised in Table 2.1 below.

Table 2.1: The suggested requirement for yard-to-yard design concept

No.	REQUIREMENT	PROVISION
1	to have a heating source;	grey-courtyard (solar radiation)
2	to have a cooling source;	garden-courtyard (evaporative cooling)
3	to have a driver;	temperature difference
4	containment of the process;	multiple-courtyard design

The house and garden, for all intents and purposes are one, the water being a key feature used to exploit low humidity in the summer season. Grey-courtyard is exposed to solar radiation and therefore warmer, while the garden-courtyard is shaded and supplied with vegetation to create cooler environment. The following subsections distinguish two design concepts. Natural convection applies to kind of multiple-courtyards building which are the subject of this thesis. Conversely, wind driven flows apply to buildings which are not part of this study. This study suggests that multiple-courtyards concept connects a cool garden-courtyards and transitional space to a warm grey-courtyard.

2.4.1 Natural convection strategy

The multiple-courtyards concept is widely used in semi-arid climates. Garden-courtyard in most multiple-courtyard buildings helps to lower the temperature of air in one courtyard relative to others. Garden courtyards are incorporated in various approaches. In the example shown in Figure 2.5, the space '*Mwan*' in this Arabic building enjoys a flow of cool air from the garden-courtyard. In this case, the inflow of air from a wind-catcher is driven through the garden-courtyard. The air inlet 'wind-catcher' is normally installed with cooling pads or Maziara water cooling jars to reduce air temperature. Air would then descend into the functional spaces before flowing to the garden-courtyard for additional cooling from evaporation of water fountain and vegetation. Cool air is exploited by users in the Mwan while warmer air is allowed to escape through the openings at the top of the Mwan space (Fig.2.5c). The airflow through the Mwan space in this example is partly reliant on wind. However, it is likely that convective cooling flows through the Mwan space are promoted by the temperature difference between the garden-courtyard and the outer warm space behind the Mwan.

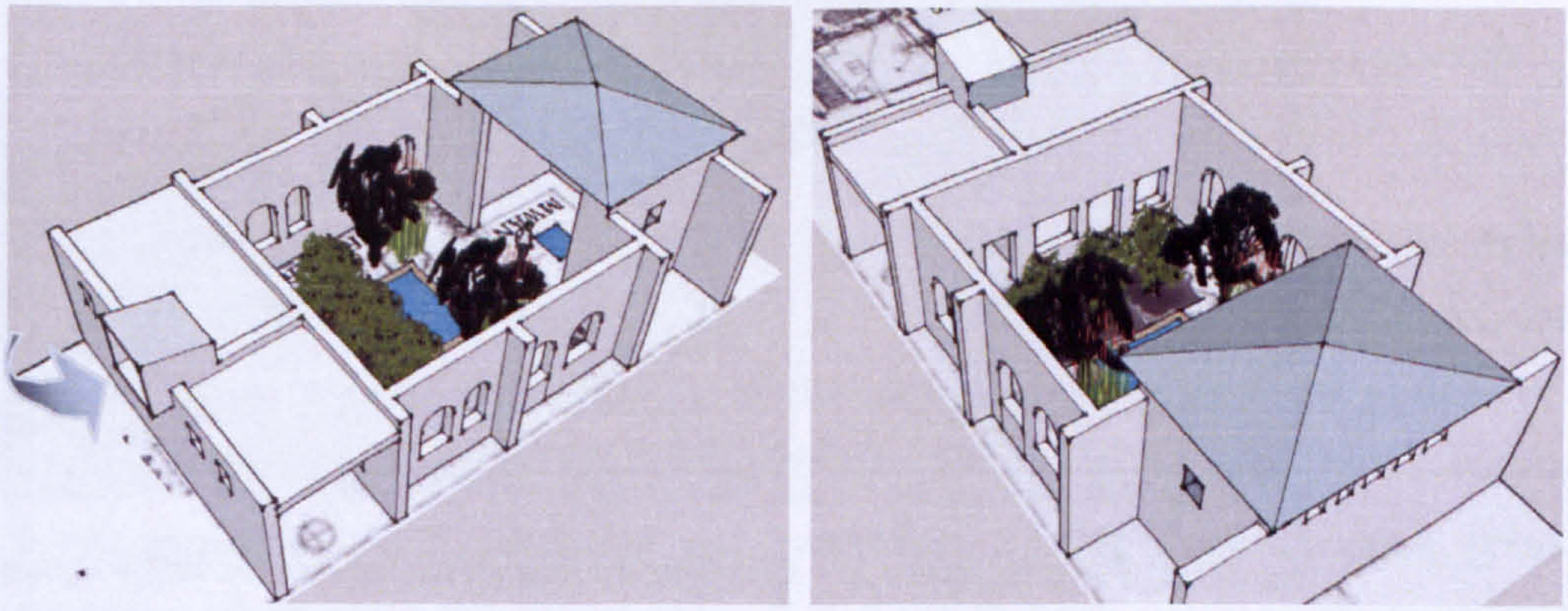


Fig. 2.5 (a) The 3D of Beit-Radwan, Marrakesh (reconstructed from Edwards (ed.2006 pp149)

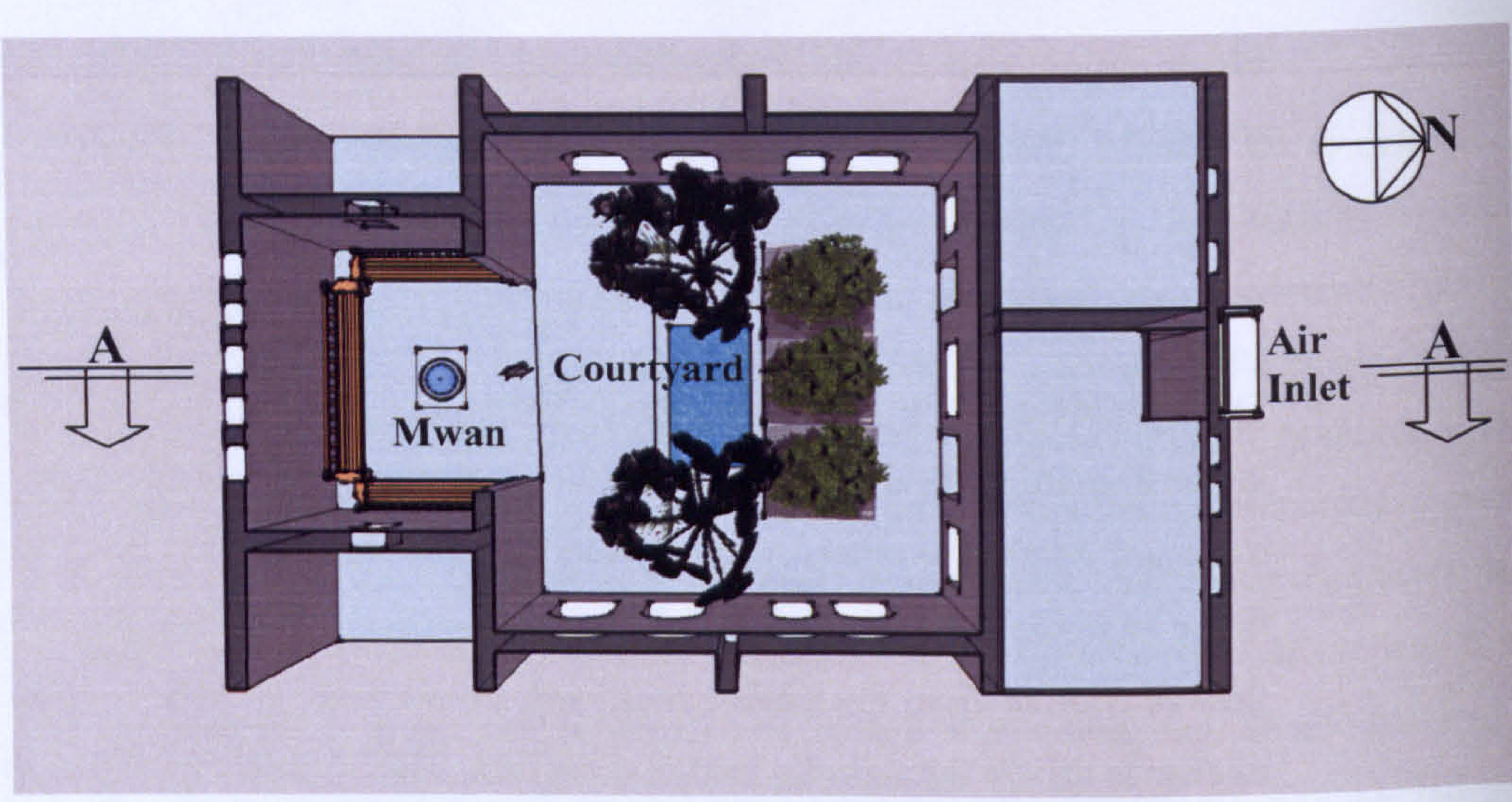


Fig. 2.6 (b) The layout and of Beit-Radwan, Marrakesh (reconstructed from Edwards (ed.2006 pp149)

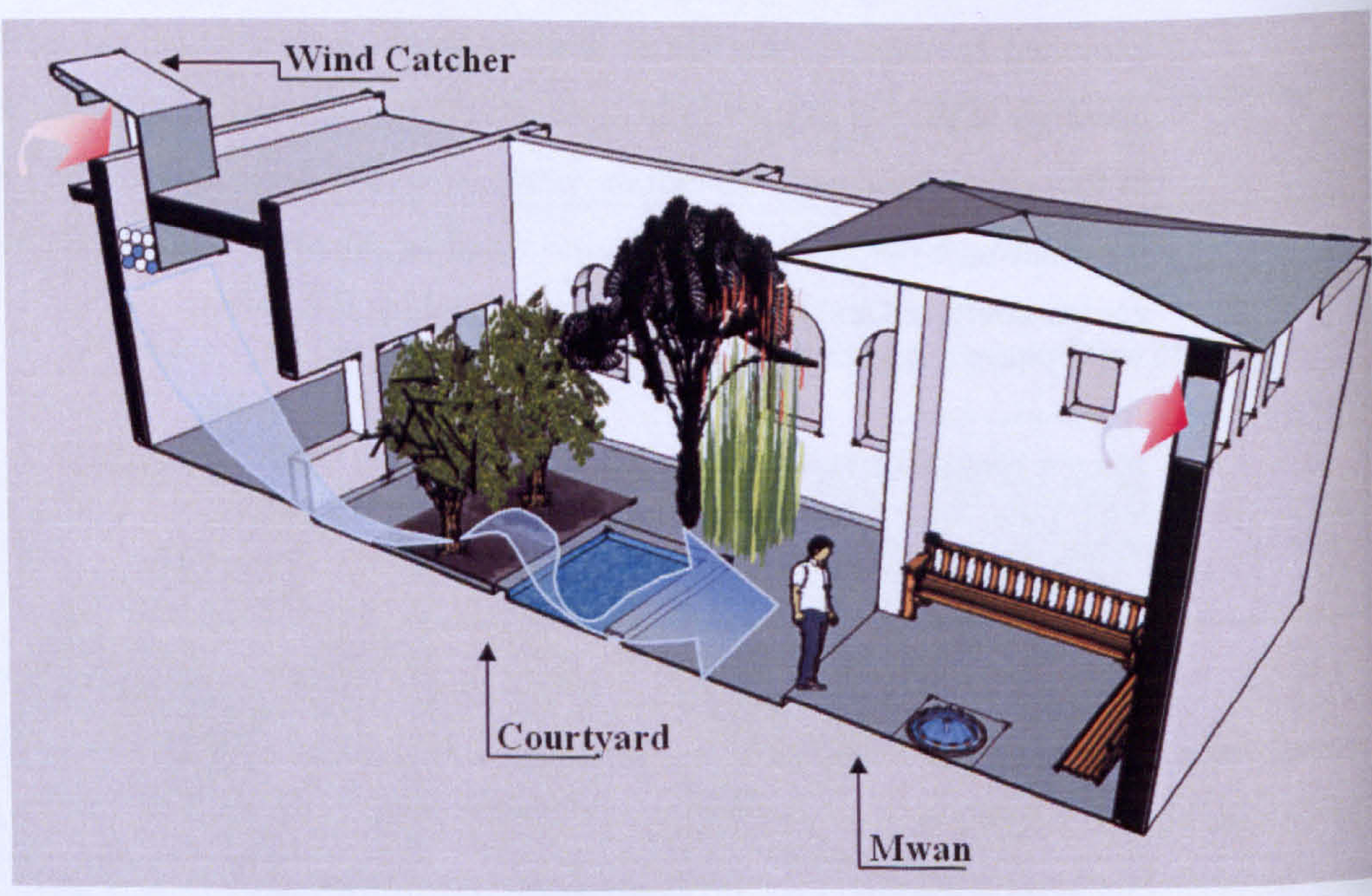


Fig. 2.7 (c) The cross section A – A showing the relationship between the airflow, vegetation and 'Mwan' space of Beit-Radwan, Marrakesh (reconstructed from Edwards (ed.2006 pp149)

However, in multiple-courtyards concept, garden-courtyards are used in conjunction with grey-courtyards. The grey-courtyard is exposed to solar radiation and therefore warmer, while the garden-courtyard combined shading and evapotranspiration from vegetation to create the cooler environment. Further cooling in the garden-courtyards is promoted by using fountains and pools of water. It is suggested that, in the summer, the moisture of air is increased as it flows through the garden-courtyard. Konya (1980) suggests that warm air in the grey-courtyard is evacuated by buoyancy forces for cool air in the garden-courtyard to be driven through the transitional space (see fig.2.6).

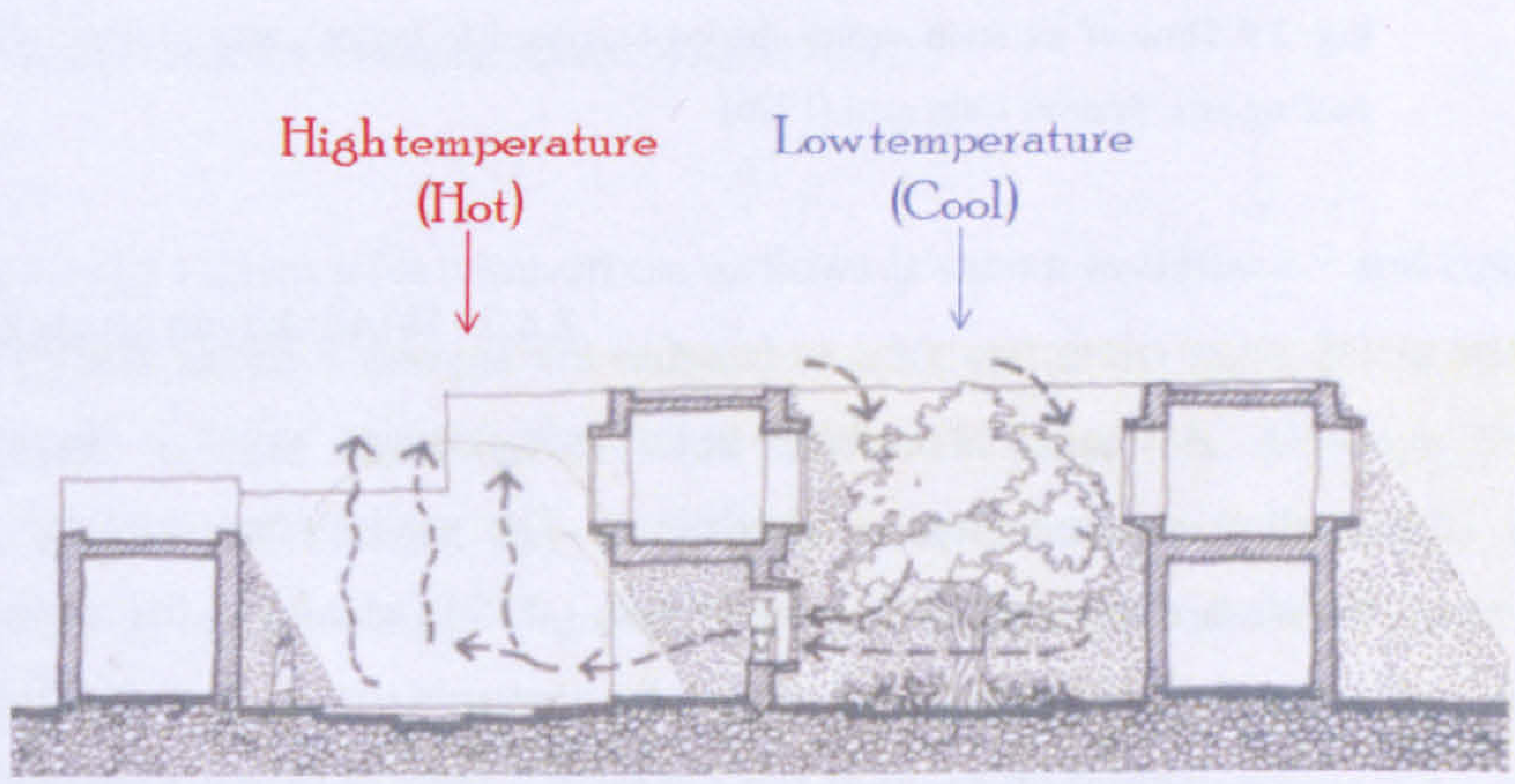


Fig. 2.8 Flow of air from a cooler shaded courtyard to a larger warm courtyard, Source: Konya (1980)

Where space is limited, the garden-courtyard is reduced to a small and shaded-courtyard. In some instances cooling aids are installed at the inlet to a functional space to promote further cooling (see fig.2.6 and fig.2.7). In this example (fig.2.7), the lower surfaces of a relatively smaller size courtyard are shaded from direct solar radiation. In the place of evapotranspiration from vegetation and evaporative cooling from fountains, porous water jars are placed at the inlet window. It is shown that subjects using the transitional space have exposure to the cooling sensation of airflow as they use the space or sit near the inlet window (fig.2.7). Although the location of this example is not mentioned, the reduced size of the cool courtyard is associated with site limitations, culture and affluence. Cain et al (1976) suggests that air movement is induced by temperature differences between the two courtyards.

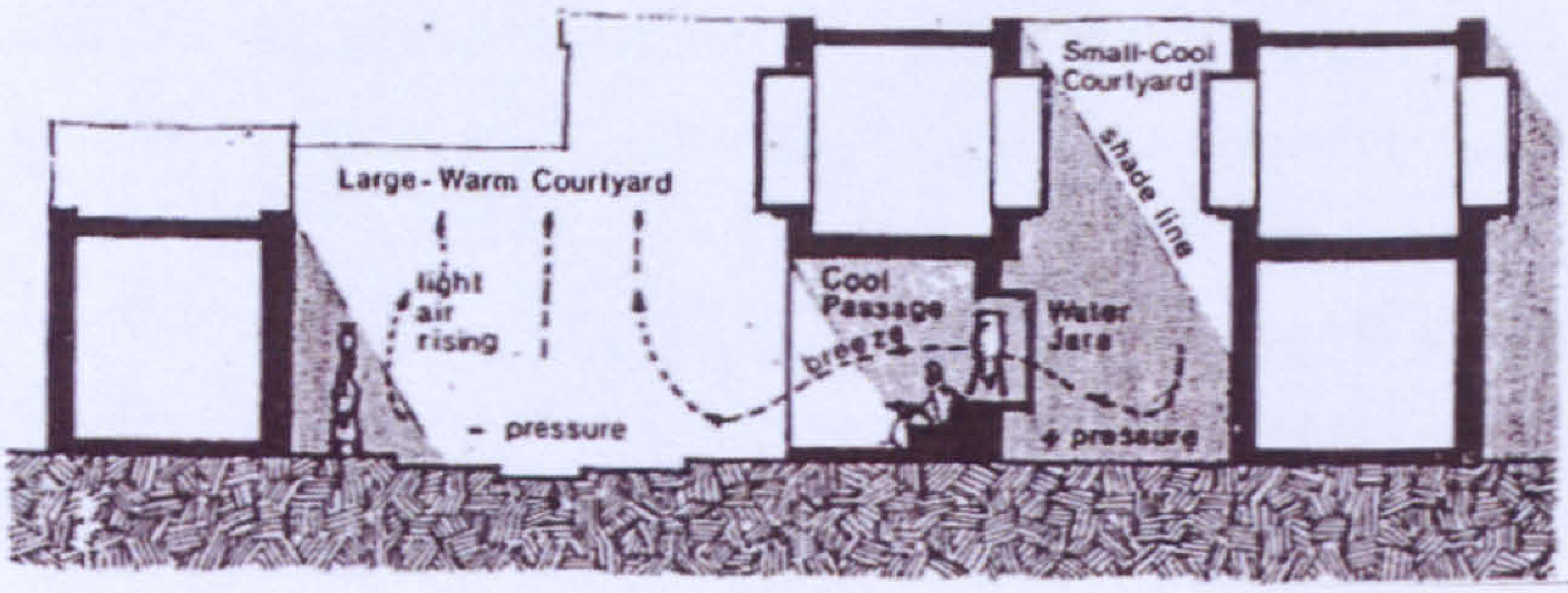


Fig. 2.9 Flow of air from cooler shaded courtyard to larger warm courtyard, breeze is drawn across the cooling jars, Source: Cain et al (1976)

2.4.2 Wind driven strategy

A variant of multiple-courtyards concept which is the subject of this study is applied to other historic buildings. The study conducted by Alcala (2002) at the Alhambra in southern Spain (1238 – 1354) identifies the application of wind driven strategy. Despite having a series of courtyards (see fig.2.8), a different strategy is used to move air through space at the Alhambra. Field measurements and theoretical modelling conducted by Alcala (2002) show the potential patio-portico-tower air movement across the Court of Myrtles, Salon de la Barca, and the Tower of Comares (or Hall of the Ambassadors). According to Alcala, cool air is driven from the court of Myrtles through the Salon de la Barca by the negative pressures from the wind forces at the top of the tower. Unlike, the warm dry-courtyard in the multiple-courtyards phenomenon, this design concept differs in a way that cool air from the Court of Myrtles is driven by the negative pressure in the tower.

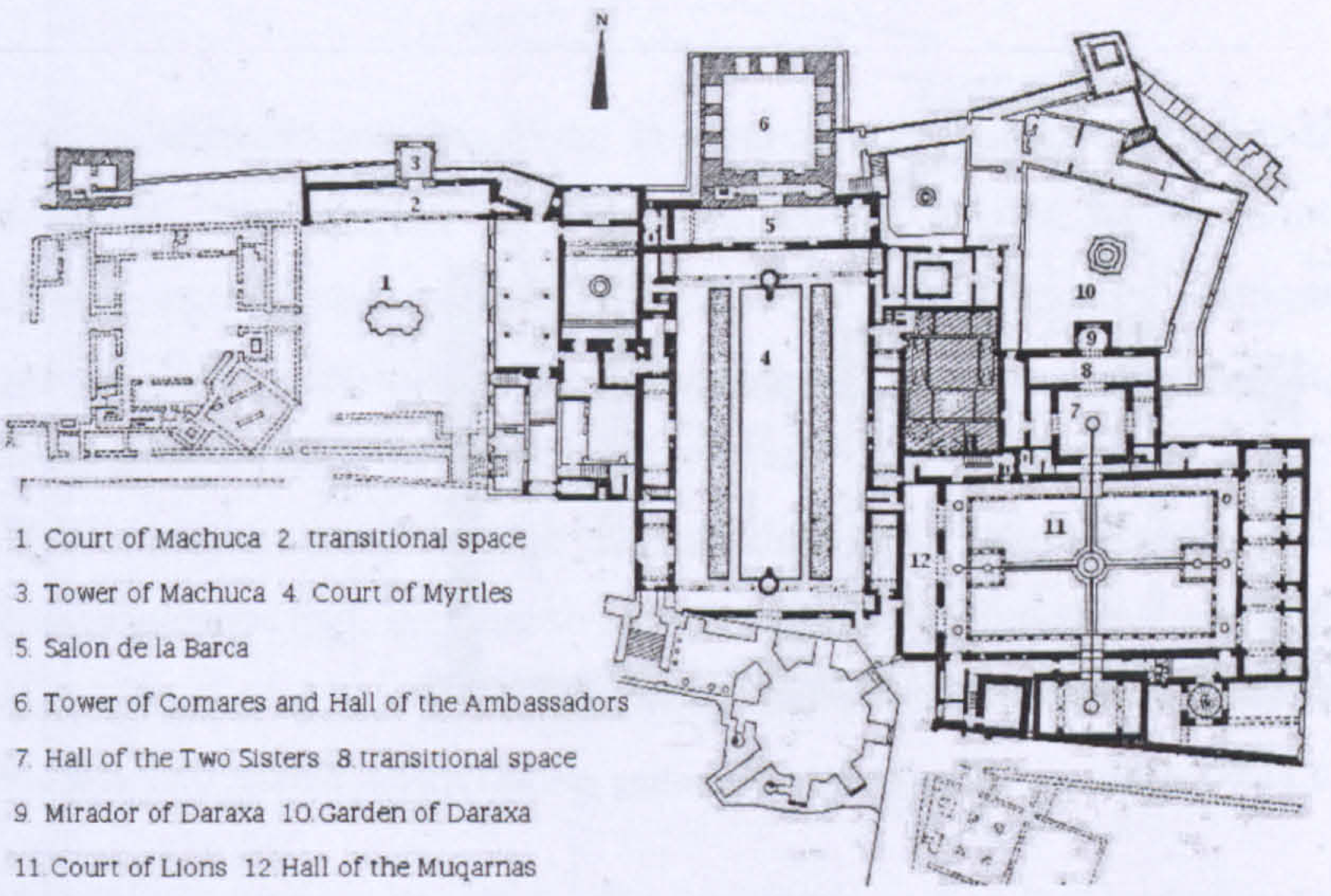


Fig. 2.10 The layout of the Alhambra, Source: Hoag J.D (1975)

Another design variant with wind-driven airflows is shown in figure 2.9 and figure 2.10. The courtyards in these designs are reduced to inlet and outlet halls. Inlets and outlets are designed to take advantage of wind forces and direction. Although the space organisation of this concept has similarities with the multiple-courtyards concept, fundamental differences exist. The study carried out at Mohibb al-Din showed that the builders of the wind catch or 'malkaf' oriented it towards the prevailing northerly breezes (Steele 1988 pp36). The duct sized space (see fig.2.9) is an inlet for outside air and porous cooling jars are installed for evaporative cooling in the malkaf. The intermediate space is enlarged to embrace the inlet duct space. Unlike the suggested yard-to-yard phenomenon in the multiple-courtyard concept, the transitional space in these designs is standing between a duct and a hall. The thermal convection in multiple-courtyards concept is reduced to wind driven air movement.

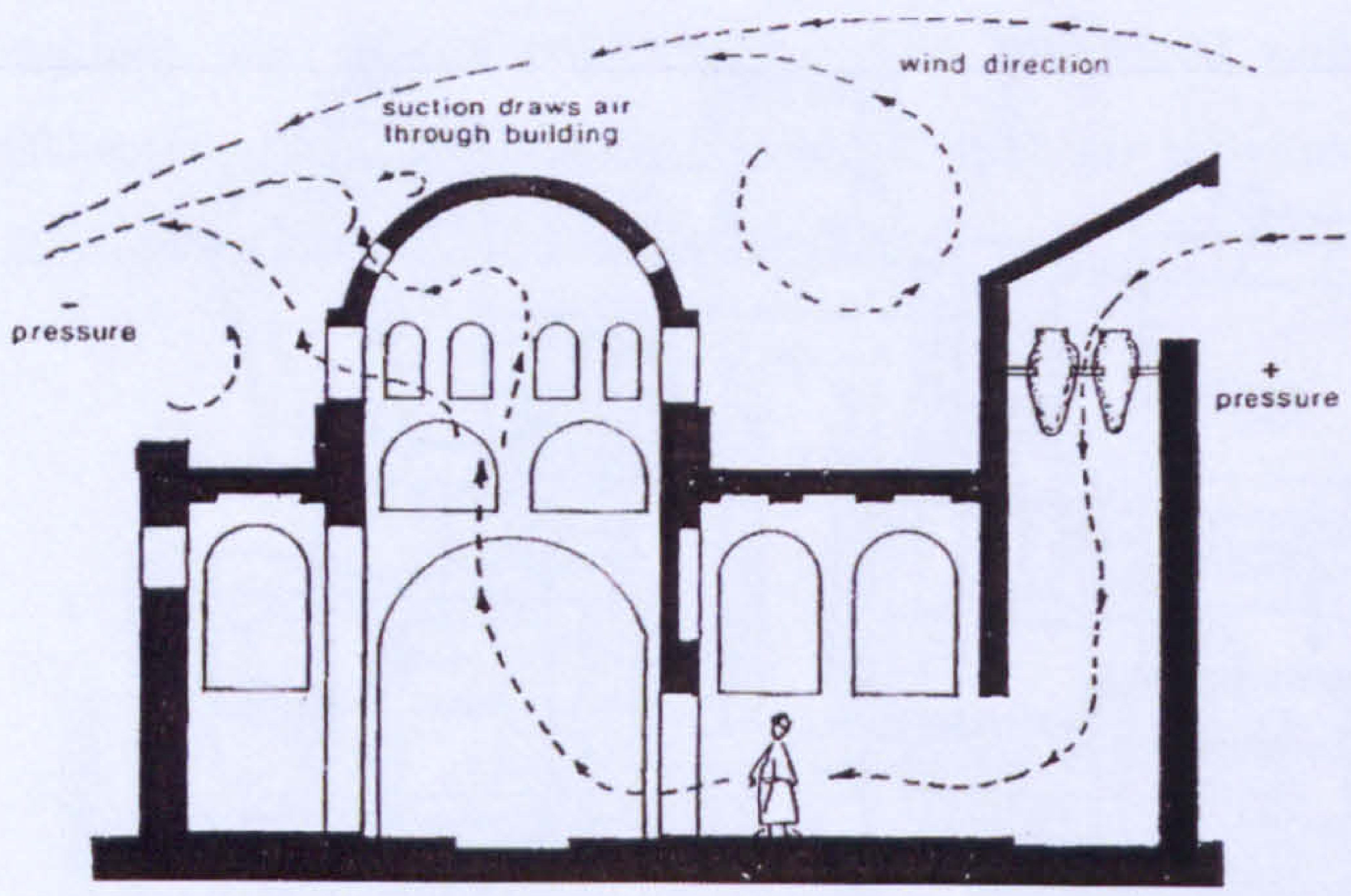


Fig. 2.11 Wind driven airflow through the cooling jars and spaces, Source: Cain et al (1976)

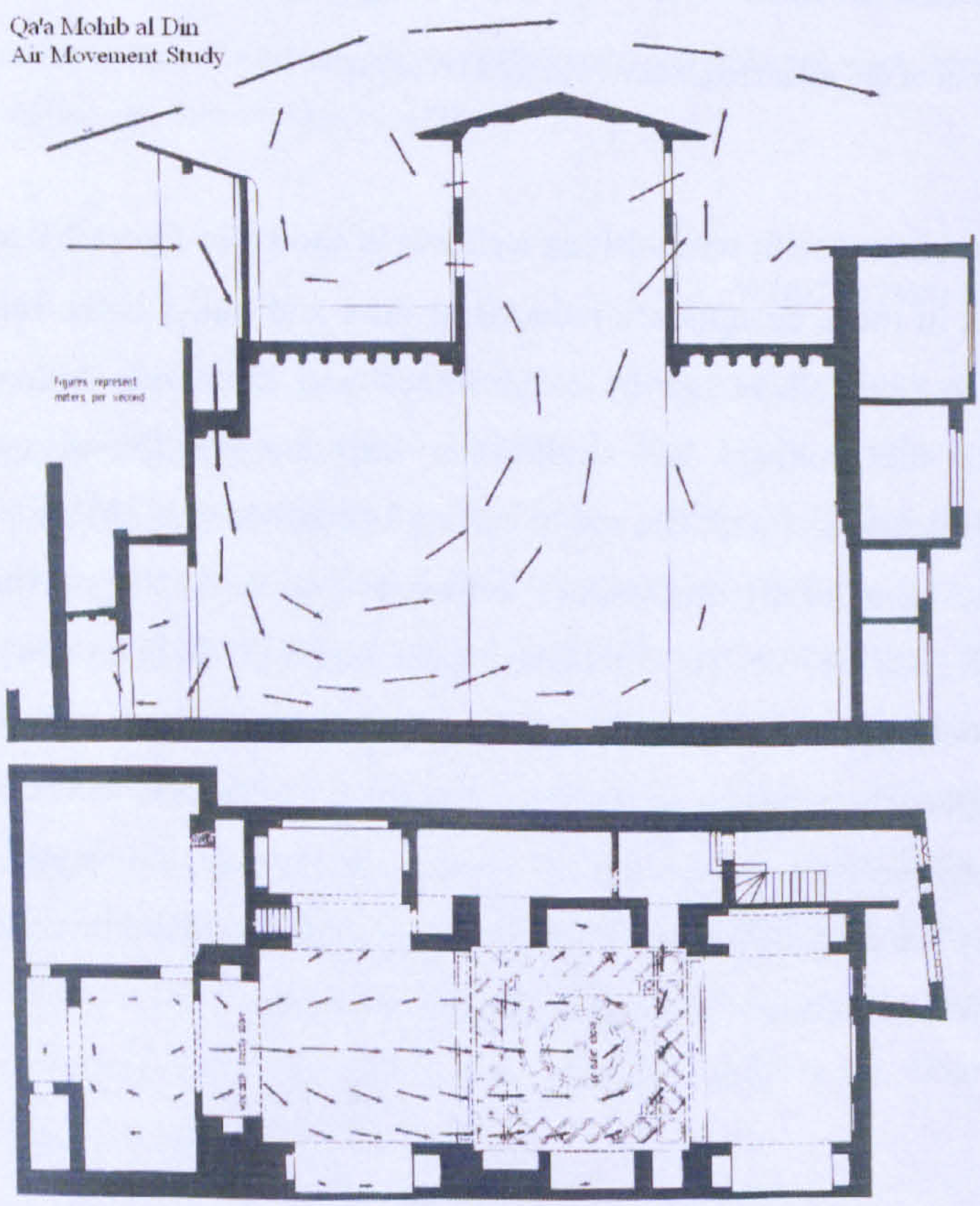


Fig. 2.12 Wind driven airflows through the House of Muhibb Al-Din Muwaggi in Egypt
Source: Steele (1988 pp37)

Similar attempts are also found in contemporary practice. As it is the case in low rise buildings, the current vertical development strives to accommodate the historic significance of pocket-spaces. A number of contemporary attempts have assimilated yard-to-duct, duct-to-duct or duct-to-hall concept. These attempts have claimed substantial increase in environmental qualities and significant reduction in energy use. This is implemented through the introduction of *pocket-spaces* such as atrium, ducts, wind-catchers, hall, concourse and courtyard. The functional use of these spaces varies from common spaces to all non-functional voids.

High-rise buildings like Swiss-Re or St. Mary Axe in London and Commerzebank in Frankfurt claims some climatic advantages from the introduction of a series of inter-connected pocket spaces in the form of atriums or gardens. Although these buildings are located in temperate climates (warm temperate, fully humid and warm summers according to Köppen-Geiger climate classification), a significant reduction in energy consumption is claimed. Air is received and contained in pocket spaces 'atrium' behind the building façade to reduce speed and alter its properties before being introduced into a usable space. However, this research focuses on yard-to-yard thermal convection in multiple-courtyards concept in hot and dry summer. The next section shows the significance of implementation strategy (pragmatics) on the performance of multiple-courtyards concept. The impact of the design concept is influenced by the sophistication of implementation.

2.5 Pragmatics

Pragmatics refers to the responses that are desired of the user. Criteria for evaluating the multiple-courtyard buildings are found both in the conceptual stage and in the sophistication of implementation (pragmatics). Any architectural design is bound to have functional requirements. Expected and implemented actions were part of historical multiple-courtyards designs. This study suggests that multiple-courtyard designs were primarily determined by pragmatic considerations of climate. By contrast, below is an apt description of a conventional approach.

> '*There is a problem with the pragmatic aspect of contemporary architecture. The recipient is tied within a strict routine, and there is very little degree of freedom for movement or exercise to the senses, most actions are either programmed or trained i.e. police dogs. This is unlike the humanly sensible actions and intuitive actions. Humans have some learnt activities and intelligent actions based on free will.*' Gitt 2001

The pragmatic considerations of climate in multiple-courtyard environments are influenced by the empirical traditions, bio-climatic features and design concept discussed previously. This is demonstrated in the variety of spatial characteristics and thermal environments provided in the multiple-courtyards design. Historic multiple-courtyard buildings were defined with respect to experience they were able to provide. That is how Fathy (1986) deciphered the cooling sensation of yard-to-yard airflows. This work divides the pragmatic considerations of climate in multiple-courtyard buildings into four categories.

- Contextual pragmatics (i.e. local climate, urban layout)
- External pragmatics (i.e. garden, fountains, envelope)
- Internal pragmatics (i.e. seasonal migratory lifestyle)
- Responsive pragmatics (i.e. open ended design)

Contextual pragmatics involves the capability of multiple-courtyards to respond to the climatic deviations from local and urban environment. This quality is evident in the applicability of multiple-courtyard design in various semi arid contexts ranging from the Middle East, North Africa and Southern Europe. Different environments lead into different contextual pragmatics depending on local vegetation, building materials, heat islands, urban structure, and culture. For example, Steele (1988 pp40) shows a connection between courtyards in the Al Suheymi House and heating and cooling patterns in the surrounding streets. In Southern Spain, inhabitants have responded to extreme summer temperatures by taking a midday sleep 'siesta'. While contextual pragmatics refers to the impact of the conditions outside the building boundaries, external pragmatics refers to the controls set by the built environment itself.

External pragmatics involves the responses that are desired from the user within built environment. This is highly influenced by the design provisions in the multiple-courtyards' building envelope, and the interface provided between a controlled interior environment and exterior environment. The garden-courtyards, fountains, balconies, arcades, dry-courtyards, and building facades have provision for external pragmatics of climate. Inhabitants use elements like operable window shutters and fountains to respond to their immediate environment. Building envelope is used to regulate external conditions (i.e. window shutters to admit and shade from solar heat in the winter and summer respectively). Fenestration is lacking on the outside of buildings in semi arid climate in order to isolate harsh outer environment from the regulated interior environment. While external pragmatics refers to what has been provided by the buy the building, internal pragmatics is more concerned with what is expected of the user life style.

Internal pragmatics refers to the climatic considerations to be taken by user in order to attain comfort in the multiple-courtyards building. These can be more frequent and independent of those required of its external envelope. For example, the migratory life style whereas people slept on the ground floor and upper floor in the summer and winter respectively. Another example is the user role in the management of indoor cooling aids.

Cain et al (1976) observed that a combination of six porous ceramic Maziara water cooling jars (refer fig.2.4) were able to deliver up to 1200watts in cooling. This is equivalent to a contemporary window-mounted air conditioning unit. However, user participation is highly required for operation of Maziara cooling jars than conventional air conditioning system. It is suggested that day to day internal pragmatics in multiple-courtyard buildings were fulfilled through migratory life style and provision of opportunity for inhabitants to respond to their environment.

Lastly, responsive pragmatics is the enabling of a multiple-courtyards building to response to climatic and socio-cultural changes over a long period. Historical multiple-courtyard models were constructed when building designs were mostly open-ended and incomplete. For example, the construction period (148years) for Al Suheymi House in Cairo (1648 – 1796AD) suggests that during the owner's lifetime or generation of owners, the building went through a process of elimination and adaptation. Hence, builders revisited the building they had built regularly to receive feedbacks and improve. Conversely, contemporary architecture assumes that buildings are optimised without continual relationship with the user. Buildings are expected to be finished and completed and ready for hand over. In historic times, builders engaged adaptive processes and responded to daily requirement of their users because they were part of the community.

It is also shown that pragmatic aspects are able to either allow a limited freedom of choice or considerable freedom of action on the part of user. In order to achieve the intended results the multiple-courtyard buildings consider/projected user actions over a period of time. It is believed that the pragmatic aspects of multiple-courtyard buildings show that the designer had in mind some purpose for the user. The migratory living patterns, the garden-bench for the daytime heat, and refilling of water jars for cooling at the inlet openings are part of pragmatics considerations of climate. It is suggested that the multiple-courtyards design have considerable projection of what is expected from their users. The relationship between design purpose and end utility is presented in the next section.

2.6 Apobetics

'To enjoy being warmed or cooled we need some awareness of the process. Clearly, it is impossible to enjoy consciously what we don't notice (Heschong, 1979 pp25)'

The multiple-courtyard designs are not limited to the pragmatics considerations of climate, but an understanding of the limitation of human adaptability to built environment. Apobetics is derived from the Greek *apobeinon*, meaning results, success, and conclusion (Gitt, 2001 pp76). The term '*apobetics*' is the teleological aspect referring to the relationship between design considerations and end utility (Ibid). Just as the way media industry would collapse as soon as it starts to disseminate information without due regards of the recipient, the design of historic multiple-courtyard buildings are believed to be a dialogue and not a monologue. This study suggests that the design strategy was intentional and with an unambiguously formulated purpose.

The historic multiple-courtyard design presents a combination of purposely created thermal environments. For example, a person seated next to a fountain may experience a cool and humid environment, while someone seated under a tree may experience relatively cool and dry conditions. Spenser (2006) presents human brain as a biological forecasting machine, with pleasure that consists of taking gambles. A spatial journey across these buildings gives user the choice to diverse environments. This is not the case with contemporary architecture, where thermal neutrality is promoted and functional spaces have to adhere to strict thermal code. The anecdotal evidence given by Fathy (1986) refers to such experiences in historic multiple-courtyards design and particularly the environment in the functional spaces situated between the warm courtyard and cool courtyard. It is suggested that the multiple-courtyard building environments make allowances for user responses that are not derived from the builders.

Although ASHRAE and ISO standards have acknowledged the variability in the comfort criteria in different climates, they do not address the human desire for diverse thermal environments provided in multiple-courtyard building. Clement- Croome (ed.1997 pp25) has shown that thermal stress does not directly relate to specific conditions, but the inability to adequately respond to thermal conditions. According to Brager et al. (2001), psychological adaptation is the likely explanation for the acceptability of higher temperatures in naturally ventilated buildings. On the contrary, ISO 7730 & ASHRAE 55 approach seek to reduce the percentage of people dissatisfied (PPD). It is believed that comfort conditions in multiple-courtyard buildings were decided by the users and not the building given that the environments has provided users with freedom to migrate within a range of micro-climates.

The quality of the visible results and impact on the end user in multiple-courtyards designs is far different from contemporary building. According to Malnar et al (2004) and Unwin (2005), contemporary architecture has more detailed implementation action and less understanding of expected user's responses and experience. The focus on energy savings, solar energy, or productivity has consistently isolates some design aspects which have direct relationship with human comfort. Strong (2008) observes that the human adaptive tendencies are restrained by inclination among professionals to focus on specific design aspects. The architectural spaces in historic multiple-courtyard buildings were created with solar-time in mind and as a result provided endless micro-climatic circles. Unlike the contemporary architecture, empirical traditions suggest that multiple-courtyard buildings evolve from everyday user's experience.

Despite the suggested use of field studies in this study, it is no longer possible to use direct observation of occupants to explore and confirm everyday living arrangements provided in historic multiple-courtyard buildings as most buildings lay in ruins. The eruption of Mount Vesuvius in AD79 buried the city of Pompeii where examples of Roman houses are being excavated. However, since historic multiple-courtyard buildings had unambiguously formulated purpose, a case should be identified for field investigation to be carried out.

2.7 Conclusion

The chapter has presented an environmental case for multiple-courtyards by referring to empirical traditions, bio-climatic features, design concept, pragmatics and *apobetics*. The multiple-courtyard strategy represents natural ventilated, bio-climatic and passive cooling architecture. It is shown that the empirical traditions for multiple-courtyard buildings developed from trial and error method over a long period of time. The bio-climatic features integrated physical and botanical processes, and choice of features was influenced by the available technology. Design concept has helped to explain how these buildings found their form. The garden-courtyard, dry-courtyard and building mass were combined to create a functional multiple-courtyard strategy. It is shown that the design is also influenced by pragmatic considerations of climate and user experience '*apobetics*'. It is believed that the multiple-courtyard strategy has promoted the convective flow of air from the cool garden-courtyard to the warm dry-courtyard through the transitional spaces. The next chapter presents the precedents and context to be investigated.

CHAPTER THREE: PRECEDENTS

3.1 Introduction

Architecture is learnt through a history of practice. This chapter suggests examples of buildings in hot dry regions employing multiple-courtyards to promote convective cooling. Three precedents are taken from areas ranging from the Middle East, North Africa and Southern Europe. The layouts and morphological characteristics of these buildings are discussed, whilst drawing attention to the characteristic transitional spaces between courtyards. These precedents are used to suggest that interface between two courtyards with different microclimates is characterised by transitional spaces exposed to convective flow of air from a cooler courtyard. Three historic precedents are presented in this chapter, namely;

- Al-Suhaymi House, Cairo, Egypt (Latitude 30^0 01'N, Longitude 31^0 14'E)
- Roman Domus, Pompeii, Italy (Latitude 40^0 45'N, Longitude $14^0$29'E)
- Beit Ghazaleh House, Aleppo, Syria (Latitude $36^0$20'N, Longitude $37^0$15'E)

The precedents are located in semi arid climate in latitude 30^0 – 40^0 North in the Mediterranean peninsula. The Köppen-Geiger climate classification refers the dry-summer subtropical climates (Csa and Csb) as Mediterranean (see Fig.3.1). These locations are characterised by warm to hot, dry summers and mild to cool, wet winters. Under the Köppen-Geiger system, the first letter consider the average temperature, hence "C" represents warm temperate; the second letter "s" represents dry-summer, meaning less than 30mm of precipitation in the summer month, the third letter "a" represents hot-summers, meaning the degree of summer heat gives an average temperature of above 22^0C in the hottest month. In some parts, hot summers are characterised by temperatures up to 45^0C, and as low as 20% RH. However, the precedents in Cairo, Pompeii, and Aleppo are located away from the coastline or Nile delta where humidity is high.

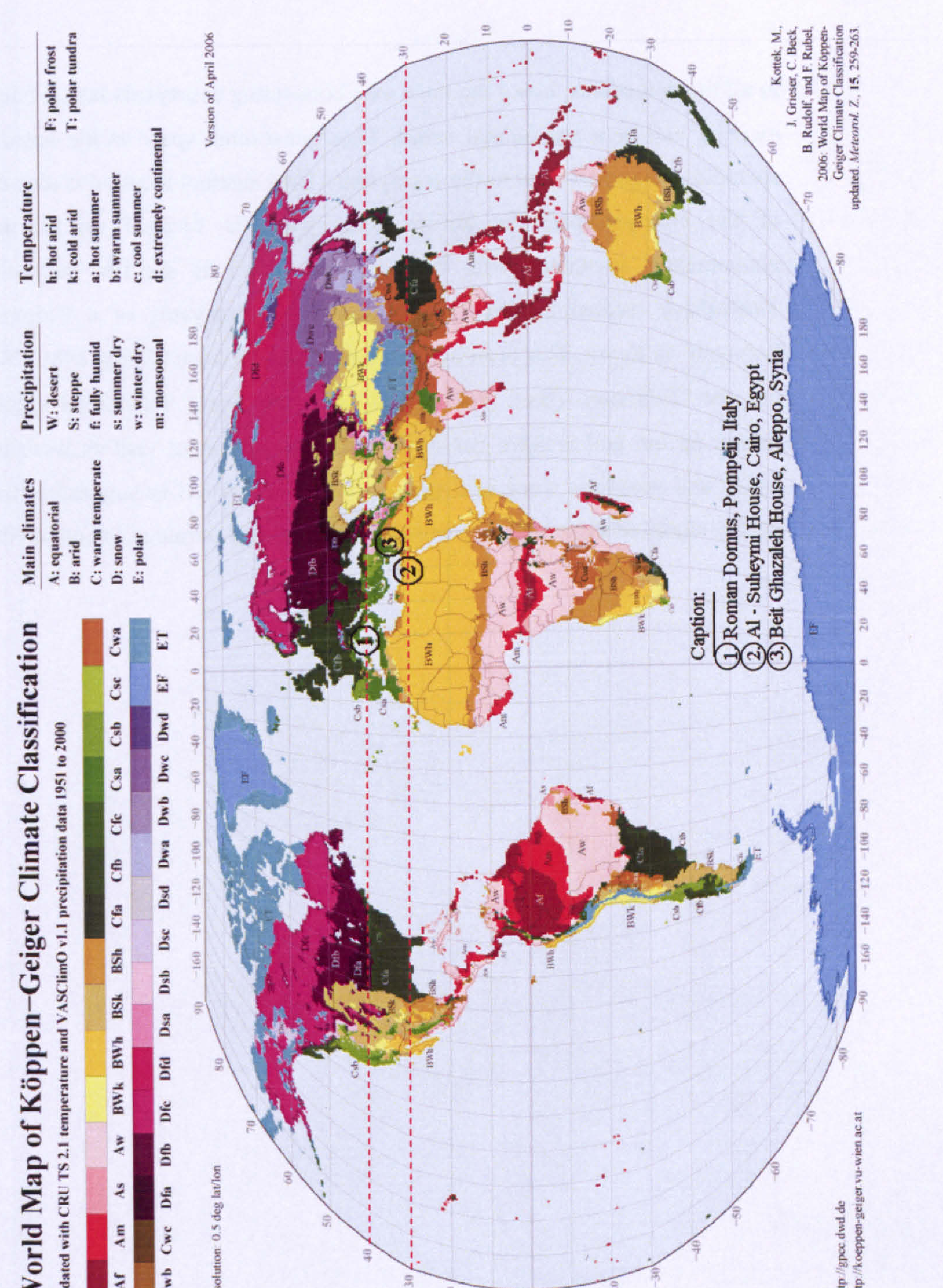


Fig. 3.1 World map showing the locations of precedents for multiple-courtyard designs (Source: Kopper-Geiger world climates http://koeppen-geiger.vu-wien.ac.at)

In all the precedents, along the main axis connecting courtyards lays a fine sitting room, meeting hall or a transitional space. This transitional space is the apsidal space with splendid design and view to the courtyards. Their distinct location is also the focal point of the courtyard/patio or atrium. This study is focused on the micro-climatic phenomenon associated with these spaces. There is specific microclimate in the *Takhtabūsh* located between the two primary courtyards of a Cairene house 'Al-Suhaymi' in Egypt. This is an important recreation terrace (Fathy, 1986). Roman Domus has the '*Tablinum*' (Ball, 2003 pp138) as a prominent transitional space between an indoor atrium and arcaded peristyle courtyard. Important visitors were invited to this space and meetings were held there (Carucci, 2006). It is suggested that transitional spaces signified the application of multiple-courtyards strategy in hot and dry climates.

3.2 Al-Suhaymi House, Cairo, Egypt

Al-Suhaymi house is a two courtyards building constructed in the Ottoman period in the historical part of the city of Cairo (30.13^0 North, 31.4^0 East). It was built between 1648 and 1796 (Jaffar et al, 1994 pp387), and is known by other names such as As-suhaymi house, al Suhaymi House, Suheimi House, al-Sihaymi House, Bayt al-Suhaymi, and House of as-Seheimy. It is named after its last owner, Sheikh Mohamed Amin El Suhaymi, and now owner by Egyptian government as a museum of architecture of Cairo. It is the largest and best preserved house in Ottoman Cairo. The house is built on an area of 2100 square meters and consists of halls (including seven *qa'as*), rooms, corridors and courts totalling 115 spaces (arabfund.org). The dry-courtyard and garden-courtyard separated from each other by a *Takhtabūsh*, with public (salamlik) and private (halamlik) zones carefully located so that each zone takes advantage of the building climate.

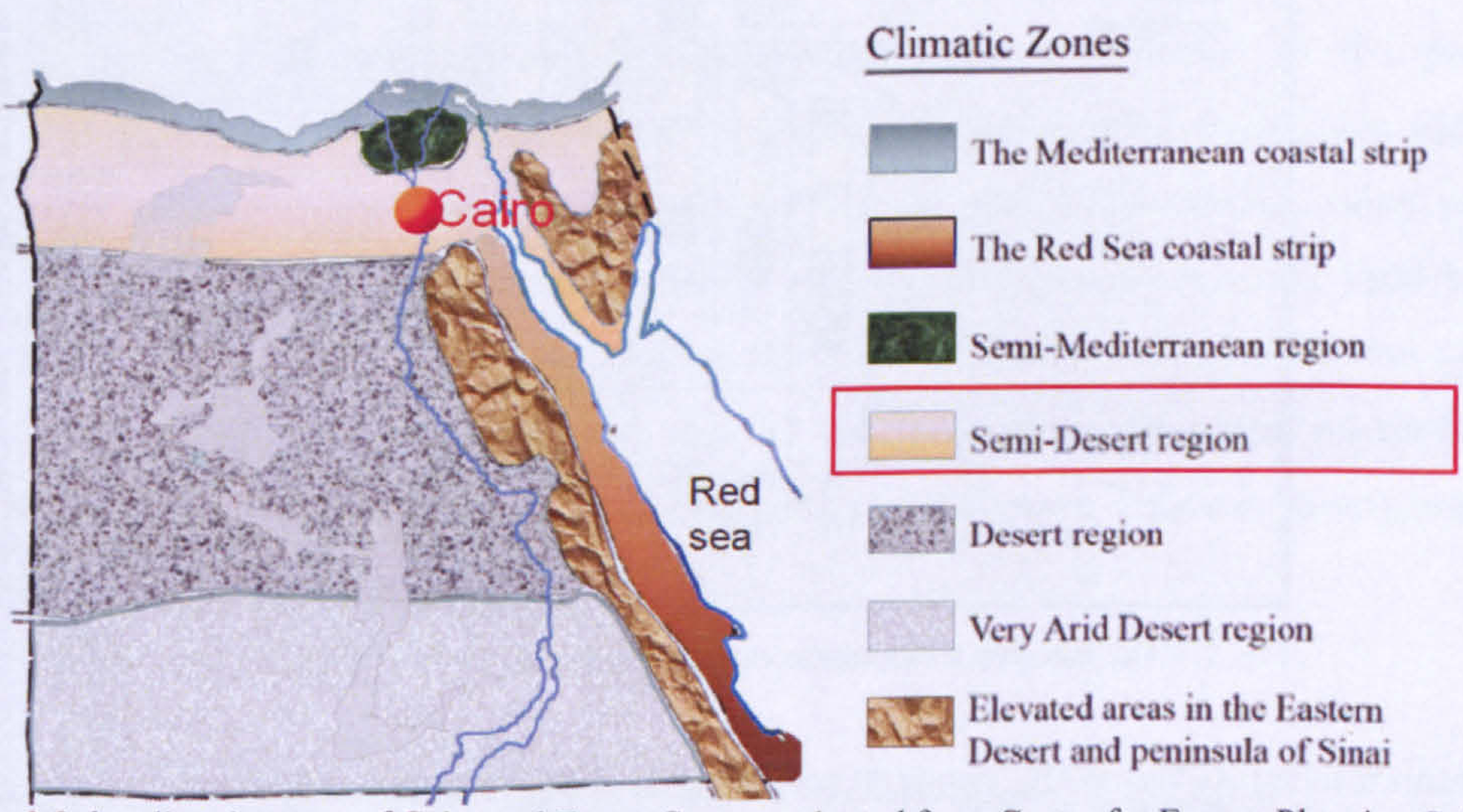


Fig. 3.2 the climatic zones of Cairo and Egypt, Source: adopted from Centre for Energy Planning Cairo (1998)

Al Suheymi is located in the semi-desert region of Egypt (fig.3.2). Semi-Desert region is a transitional zone between the northern coast and the Desert-Region. As a result the region records very high temperatures in the summer, while winters are moderate and cold (see fig.3.3). A record low humidity provides an opportunity for application of evaporative cooling i.e. water fountains and vegetation in the garden-courtyard when the daytime temperatures are high (see fig.3.4). Street patterns in the mediaeval Cairo were also not haphazard. The northwest prevailing wind direction has also influenced the building and the urban layout. Steele (1988 pp40) has shown a relationship between courtyards in the Al Suheymi house and heating and cooling patterns in the surrounding streets.

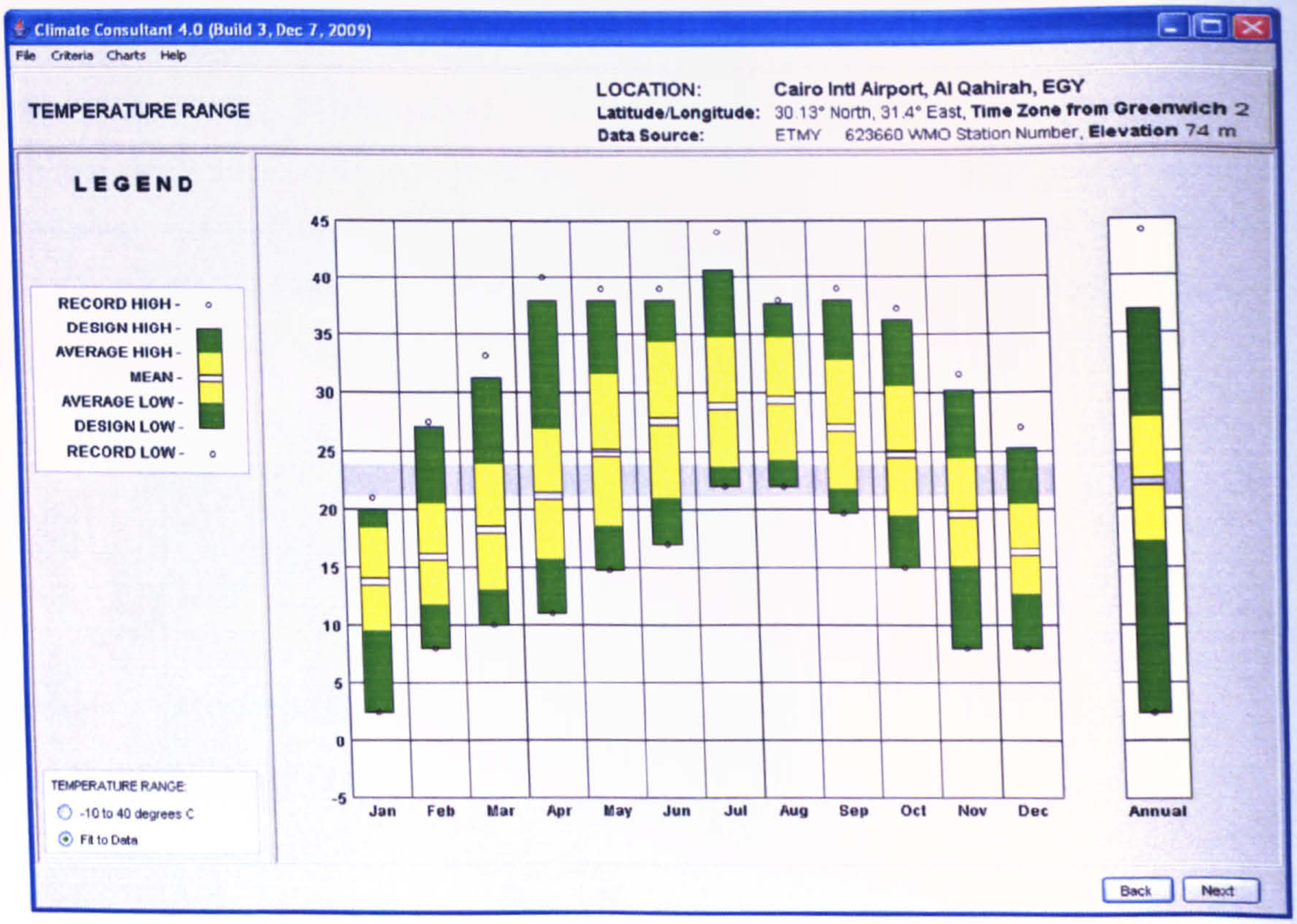


Fig. 3.3 The monthly temperature variation in Cairo, Source: Climate Consultant software

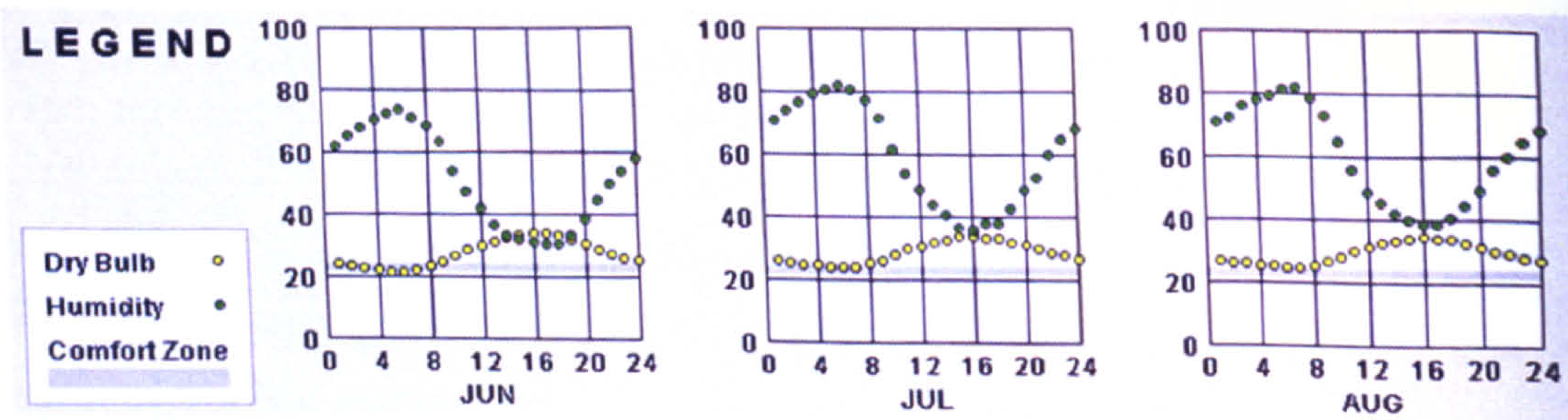


Fig. 3.4 RH and DBT in the hottest period from June to August, Source: Climate Consultant software

Al Suheymi house is the most elaborate example of how Cairene grand houses grew in size through external addition (Steele, 1988 pp39) in response to climate and socio-cultural needs. The building grew in phases with addition of *qa'as* to accommodate the growth of the extended family. The private areas of the house are reached by separate flight of stairs with openings concealed with fine *mashrabiyyas,* or wooden privacy screens, to allow women to enjoy the view without being seen by the guests in the courtyards (Jaffar et al 1994 pp387). Among other climatic features, the use of high mass construction and garden-courtyard suggest building's response to extreme summers in semi-arid climate.

3.2.1 Environmental design features

There are various features and elements which have contributed to the positive microclimate in the Al-Suheymi house. In addition to the climatic advantages added to the *qa'a* through down drought of air through the *malkaf* 'wind-catcher', other natural environmental control devices such salsabil and mashrabiyya screens are used by the building. Fathy (1986) has commented on the *malqaf,* takhtabūsh, maq'ad, and qa'a in Al-Suheymi house. Takhtabūsh and Maq'ad are promoting distinctive microclimatic environments by taking advantage of temperature difference between courtyards and prevailing winds respectively.

Qa'a is a formal reception hall in Cairene houses (Salama, 2006 pp43). Its prominence is related to its indoor climate which is naturally warm in winter, and domed opening in the middle of its roof is an outlet for warm air in the summer season. Other features contributing to positive micro-climate in the qa'a include high ceiling, indoor water fountain, thick walls, marble surfaces, and *Mashrabiyya* screens. From the qa'a, the courtyard balcony '*Maq'ad*' can be accessed. This is an informal reception area used in the evenings as the main sitting place for owner and his guests (Jaffar et al 1994 pp387) (see fig.2.2b). It is located in the second-storey and has two arches that overlook the courtyard. It is Cairene equivalent of middle-eastern *iwan* and favourite area for evening entertainment (ibid). The Takhtabush is an environmental feature related to this study.

3.2.2 Takhtabūsh

The ground floor loggia known as 'Takhtabūsh' is a type of terrace or covered outdoor sitting area at ground level between two courtyards (Fathy, 1986) (see fig 3.5 – fig.3.6). It separates public and private courtyards. On the front side of the Takhtabūsh is a private garden-courtyard (green) while a larger drier courtyard area (grey) is public and located behind this space (see fig. 3.7). This feature has always maintained its closeness to the entrance, separated from the rest of spaces (Salama, 2006 pp51). Functionally, it was a space designated for the public visitors in the Ottoman domestic architecture of Cairo. It was allocated for receiving male visitors or low-ranking visitors, before they were allowed in other areas of the house. According to Steele (1998 pp40), the Takhtabūsh at the al-Suhaymi house is extremely elegant, with a long, low wooden bench flanking its three sides.

It is a flat roofed sitting space facing the garden-courtyard at the junction of two contrasting thermal environments, meaning the cool garden-courtyard and hot grey-yard. Behind the sitting space there are *mashrabiyya* screens for privacy and also to allow the flow of air between the two courtyards (see fig.3.7 and fig.3.8). The temperature difference between the two courtyards arises in part because the vegetation in the garden courtyard creates cooler environment, while absence of vegetation in the grey dry-courtyard promotes higher temperatures. The grey-courtyard was initially paved almost entirely in stone (Ibid pp40). It is believed that the temperature difference then promotes air movement through the Takhtabūsh. While this phenomenon has been commented on by others, the author is not aware of any studies which have attempted to quantify this effect.

Fig. 3.5 the view of the sky, and ceiling and windows in the Takhtabūsh space, Source: 3D Mekanlar.com

Fig. 3.6 the view of the Takhtabūsh from the garden-courtyard, Source: 3D Mekanlar.com

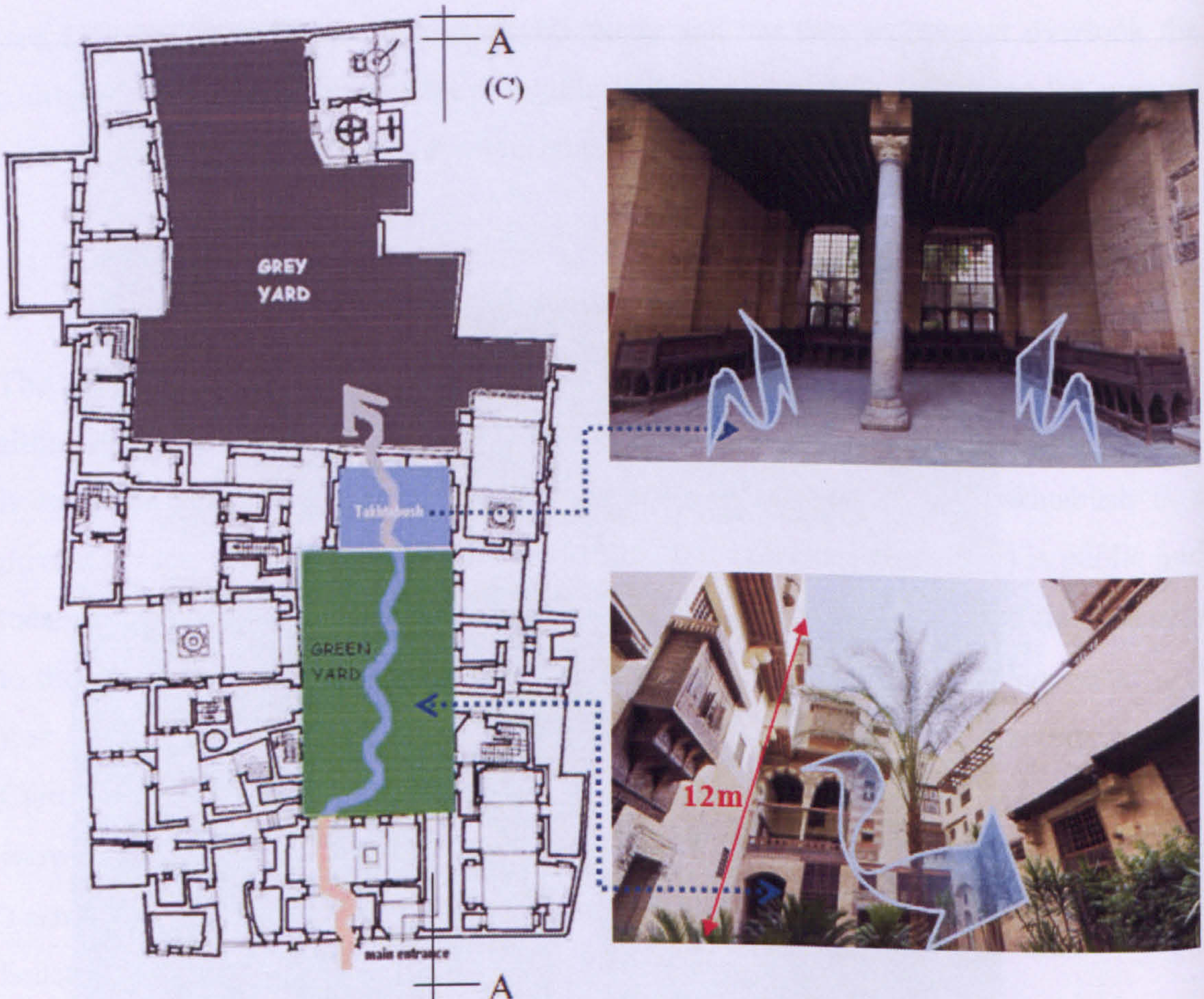


Fig. 3.7 (left and top right) Site layout of Al-Suhaymi house showing the Takhtabūsh between the garden-courtyard and grey courtyard, (bottom right) the view of the Maqad balcony from the garden-courtyard, Source: (right top/bottom) 3D Mekanlar.com

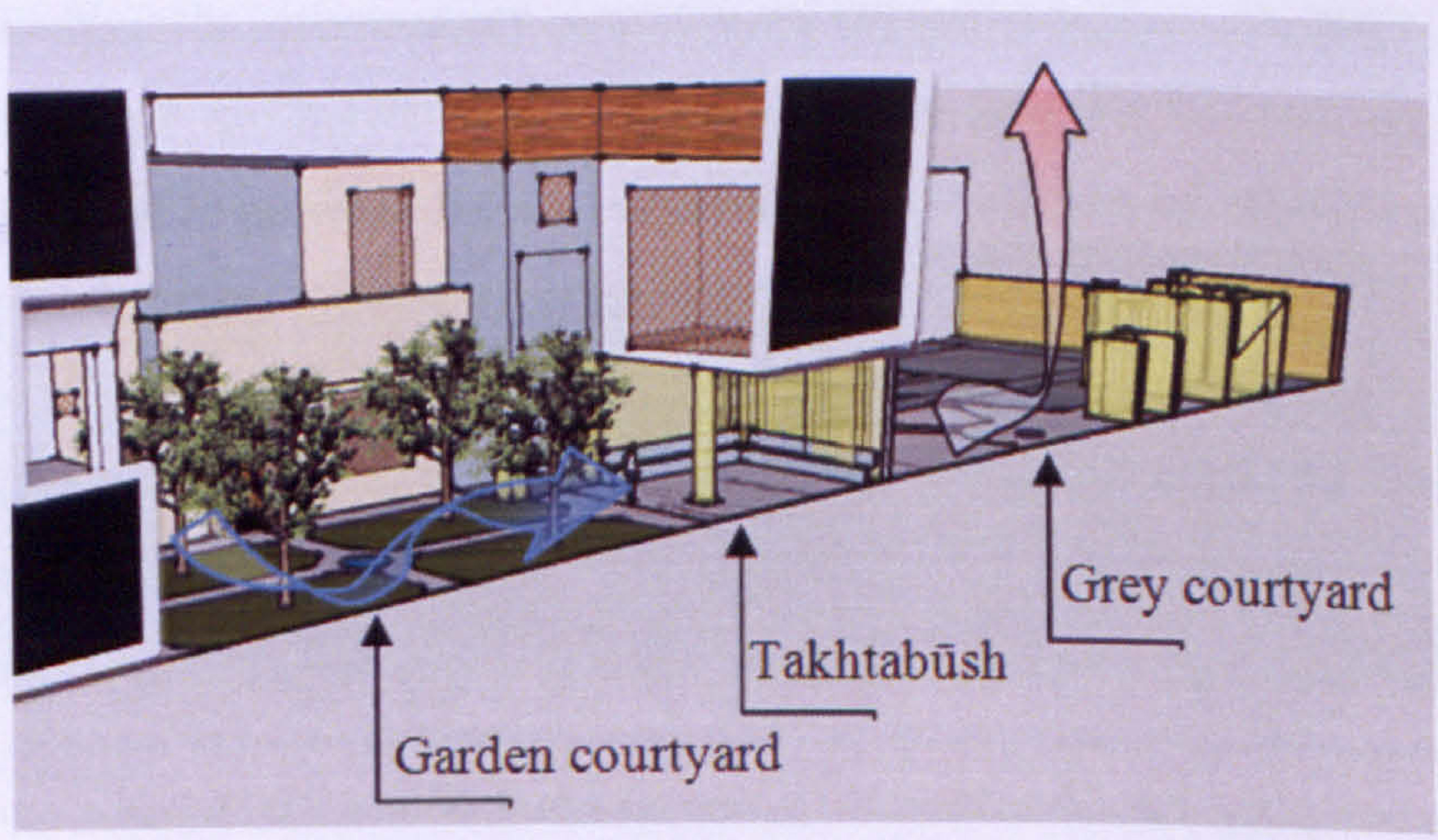


Fig. 3.8 Schematic diagram showing the cross section A-A through the Takhtabūsh in al-Suhaymi house

The microclimate in the garden-courtyard is being enhanced by the thermal mass of surrounding walls and evapotranspiration from the vegetation (see fig.3.9). According to Steele (1998 pp40), the formerly dry grey-courtyard had in the beginning not been planted as it is now. It was paved in order to heat up in the summer and draw cool air through the Takhtabūsh by natural convection (see fig.3.10). The Takhtabūsh does not only take advantage of existing air convection, it does reinforce it by maintaining the separation between the warmer and cooler environments (see fig.3.11). The users of Takhtabūsh would face the garden-courtyard and Mashrabiyya screens to separate from the hot grey-courtyard. It is believed that convective air movement is induced by the difference in the surface temperatures in the two courtyards. As a result, cool air is driven from the densely landscaped private garden-courtyard to the formal grey-courtyard in front of the house.

Fig. 3.9 The flow of air from the garden-courtyard to the Takhtabūsh in the Suheymi House, Source; modified from archnet.org

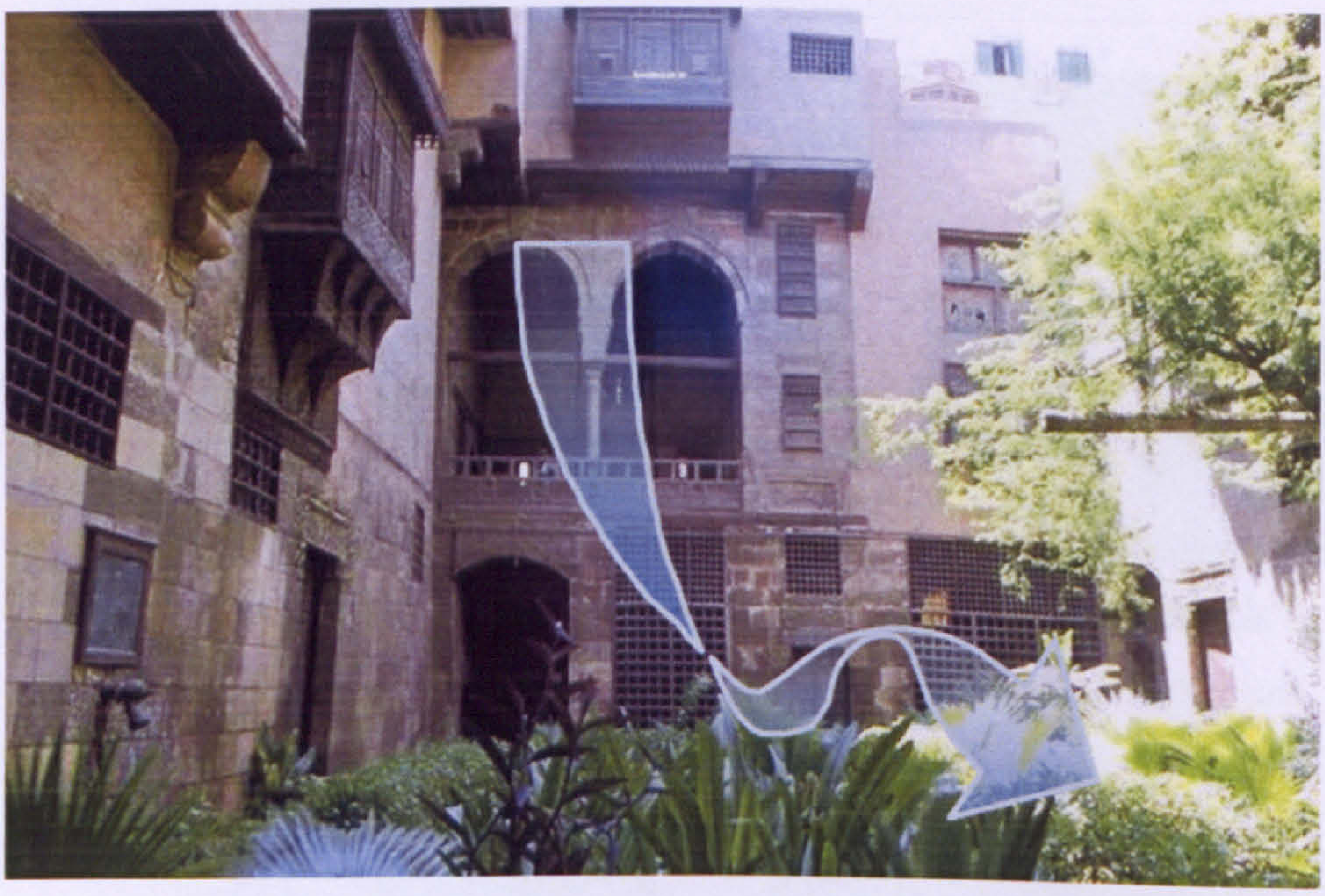


Fig. 3.10 View of the maq'ad balcony and garden-courtyard from the Takhtabūsh, source: modified from ocw.mit.edu

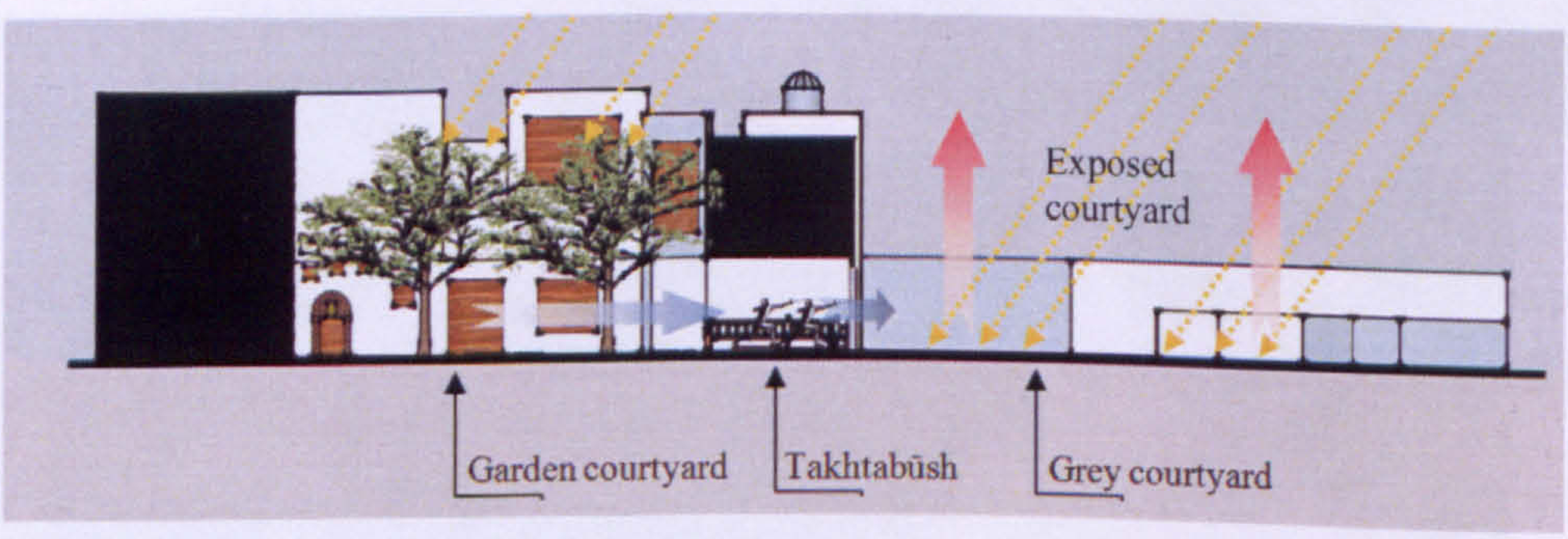


Fig. 3.11 Conceptual section across the Takhtabūsh

3.3 Roman Domus, Pompeii, Italy

The eruption of Mount Vesuvius in AD79 buried the Italian city of Pompeii and its citizens in volcanic ash, thus making Pompeii the best place to study perfect preserved examples of Roman courtyards (Keister, 2005). A typical house is variable in size and has a rectangular plan. It is almost totally devoid of windows on the outside, since all the rooms face onto the inner courtyards. It is designed so that anyone standing in the vestibule could see straight through the atrium and '*tablinum*' to the garden-gardens (McManus, 2007) (see fig.3.12). The multiple-courtyards concept in the Roman domus is mainly comprised of three parts; atrium, tablinum, and peristyle-courtyard (garden).

Fig. 3.12 The Roman Domus, Source: Modified from www.home.att.net; insert map from web.na.infn.it

Pompeii has a Mediterranean climate, meaning that summers are sunny and hot. The hottest months of summer are June to August. The Mediterranean climate does bring a lot of rain. On the average the west coast of Italy gets more rainfall that anywhere else in the country. There is high precipitation from November to February. The closest meteorological weather data presented by Energy-Plus is Napoli (see fig.3.13 and fig.3.14)

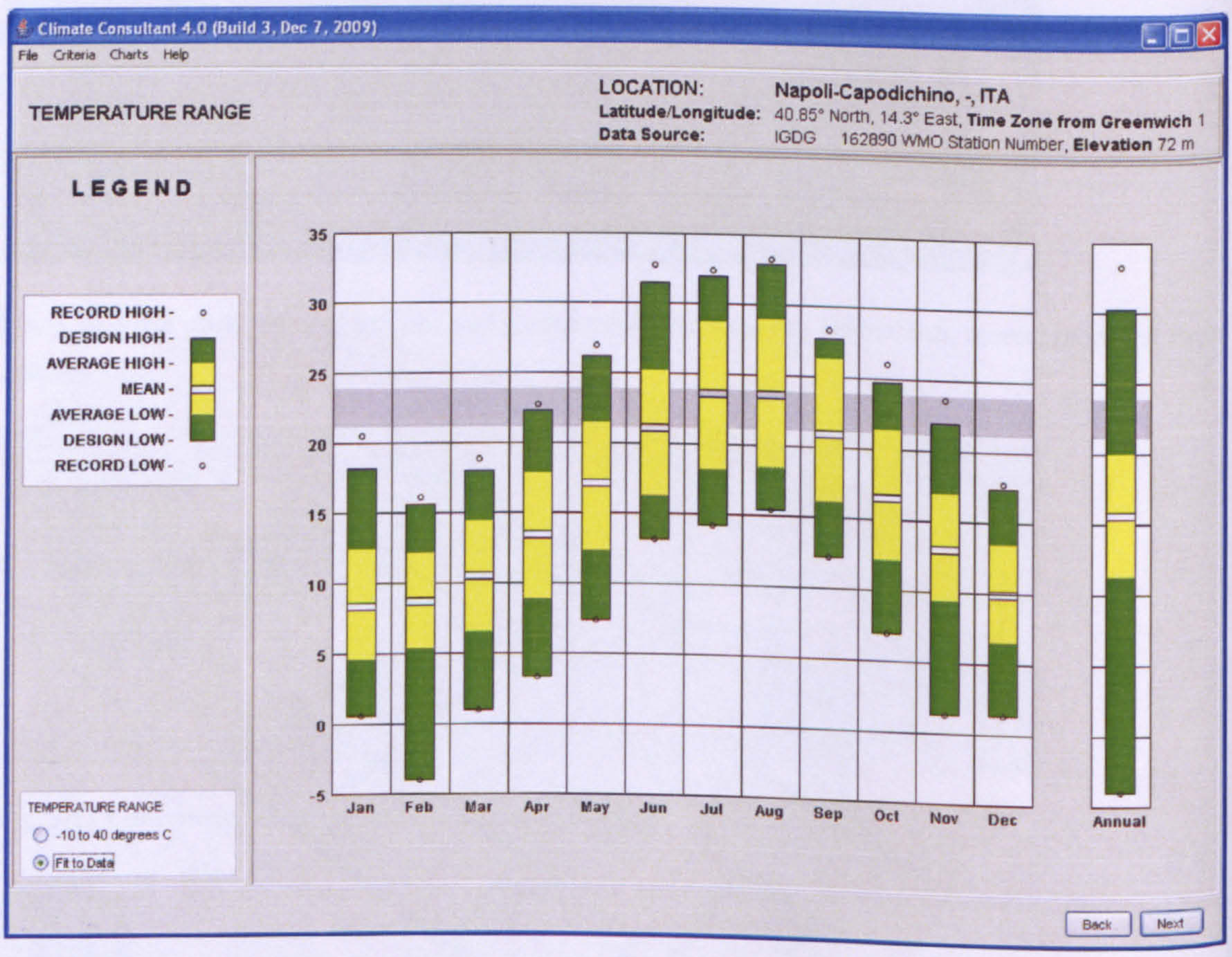


Fig. 3.13 Monthly temperature variations in Napoli, Source: Climate Consultant

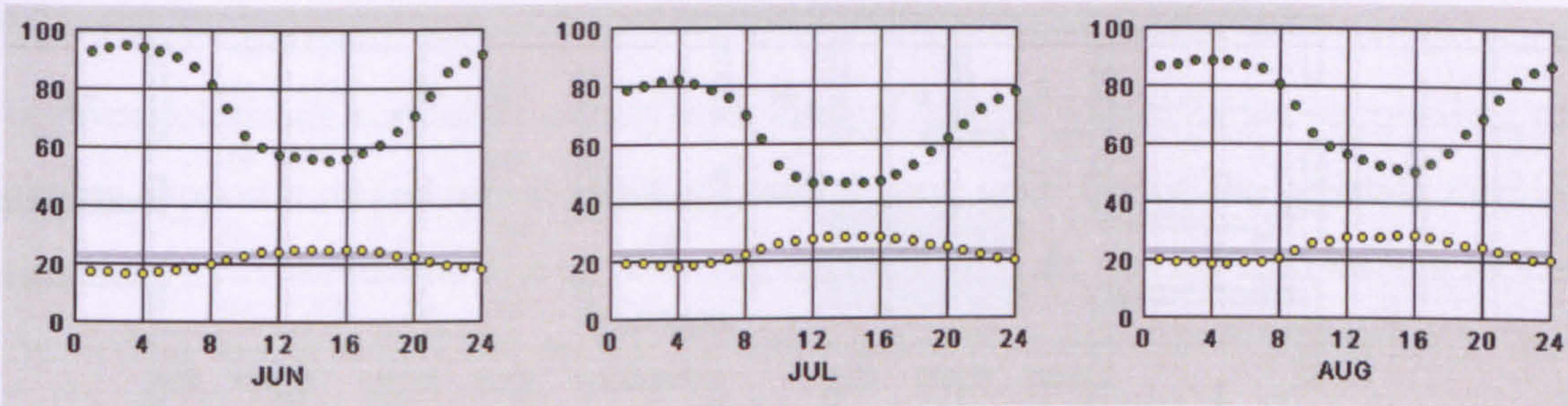


Fig. 3.14 Variation in DBT and RH in June, July, and August, Source: Climate Consultant

The atrium of the Roman domus was used for family occasions, and was also formal room where guests were received or clients assembled to wait for their customary morning visits to their patron. The garden-courtyard *'peristyle'* was the heart of the domestic building, and as much available space as possible was allocated to this space (Carucci, 2006 pp67). The tablinum is directly behind the atrium and open on two sides linking the peristyle-courtyard 'garden' to the atrium (see fig.2.6 and 2.7). In this room, the master of the house would greet his many clients while separated from other spaces with curtains or folding doors. Among other environmental features, this space is the focus of this study.

3.3.1 Environmental design features

The environmental design features for the Roman Domus includes building mass, two separated courtyards (atrium and peristyle), and yard-to-yard transitional space (tablinum). A typical layout is shown in Fig.3.15. Around the garden-courtyard, lay a series of galleries which were usually eliminated when additional space is required (Carucci, 2006 pp67). The tablinum located between the atrium and colonnaded garden-courtyard has a similar position as the Takhtabūsh, and it is believed to have functioned in a similar way, acting as a conduit for air moving from the cooler garden courtyard to the atrium.

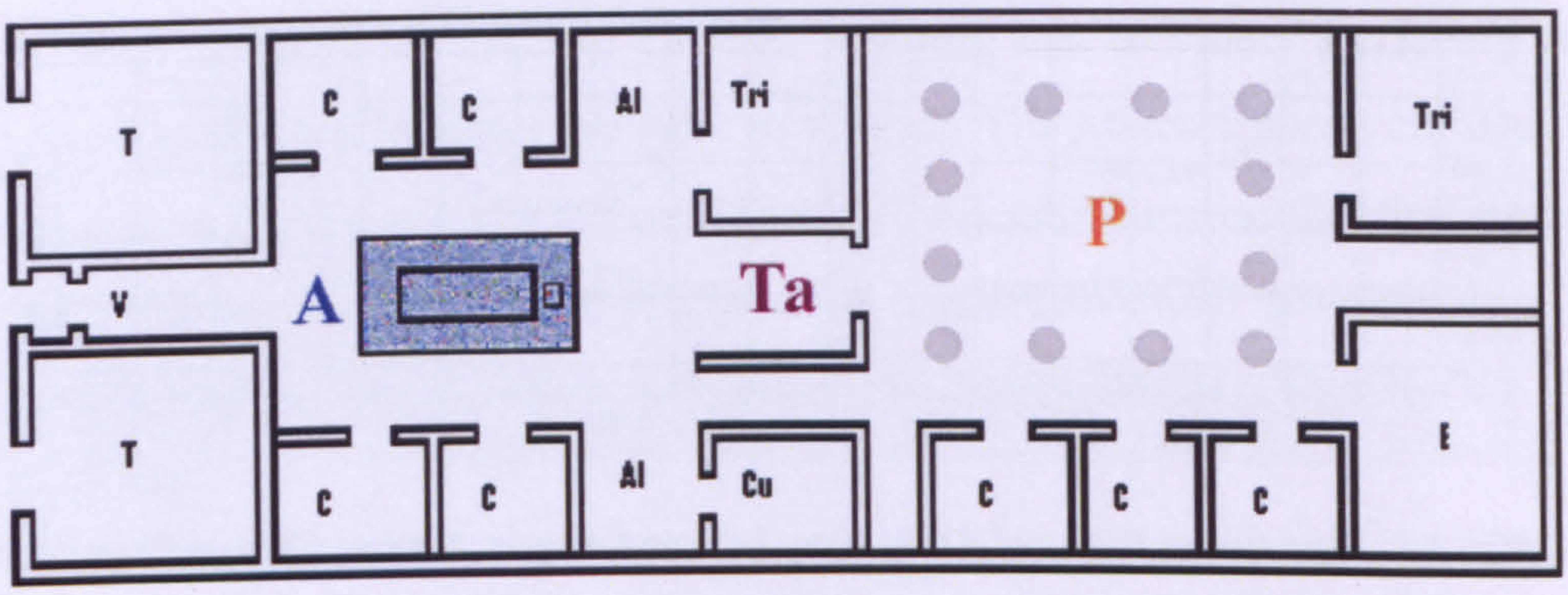


Fig. 3.15 A typical layout of a Roman Domus Source: http://www.vroma.org/~bmcmanus

A	atrium	formal entrance hall
Ta	tablinum	office; study
P	peristylium	colonnaded garden
V	vestibulum	entrance hall
Al	ala	"wings" opening from atrium
C	cubiculum	small room; bedroom
Cu	culina	kitchen
E	exedra	garden room
T	taberna	shop
Tri	triclinium	dining room

3.3.2 The Peristyle-courtyard 'garden'

The garden-courtyard is an environmental feature space in which a variety of activities would take place. According to Carucci (2006 pp88), it is a space where elaborate waterworks, decorative sculptures and fine mosaics are also symbolically used to display householder aspiration to taste and wealth. Kitchen, dining space and storehouses are located in this area. It created a lavish view for the guests looking onto the peristyle and therefore used for reception of guests in the elite household. This space would also contain features such as flowers and shrubs, vegetable patch, fountains, benches, sculptures and fish ponds (fig.3.16).

The garden-courtyard '*peristyle*' was the heart of the Roman Domus. A columned porch or open colonnade surrounds a court with internal garden. The columns surrounding the garden support a roofed arcade. With its central court open to sky, the peristyle fulfilled its primary environmental role by allowing light and cool air into the surrounding rooms. According to Carucci (2006 pp89), the environmental conditions in the peristyle area gave users a refreshing and cooling effect in very hot weather.

Fig. 3.16 (a) House of the Gilded Cupids, Pompeii, showing garden and household shrine in portico (b) Atrium in the House of the Silver Wedding, Pompeii Source: modified after www.arthiistory.upenn.edu

3.3.3 The atrium

Atrium is an important feature in any Roman Domus serving as the entry lobby. An area designed for reception of clients waiting to meet the patron. Large crowds of *clientes* packed in the entrance area of an influential aristocrat (Carucci, 2006 pp24). Conversely an empty atrium would characterise those who have forsaken ambitious life. In this space rain water is also collected for general use. The roof-opening in the atrium enables it to be well lit.

As air in the atrium becomes warmer it begins to rise and is allowed to escape through openings at the top of the atrium space. Atrium thus turns into a low pressure area, and by principle of convection, it begins to draw the air into it from the surrounding spaces (see fig.3.17 and fig.3.18). The building form suggests that pressure difference is also heightened by the difference in height between the atrium and the peristyle or colonnaded garden. It is believed that cool air from the garden-courtyard is driven to the atrium through the Tablinum.

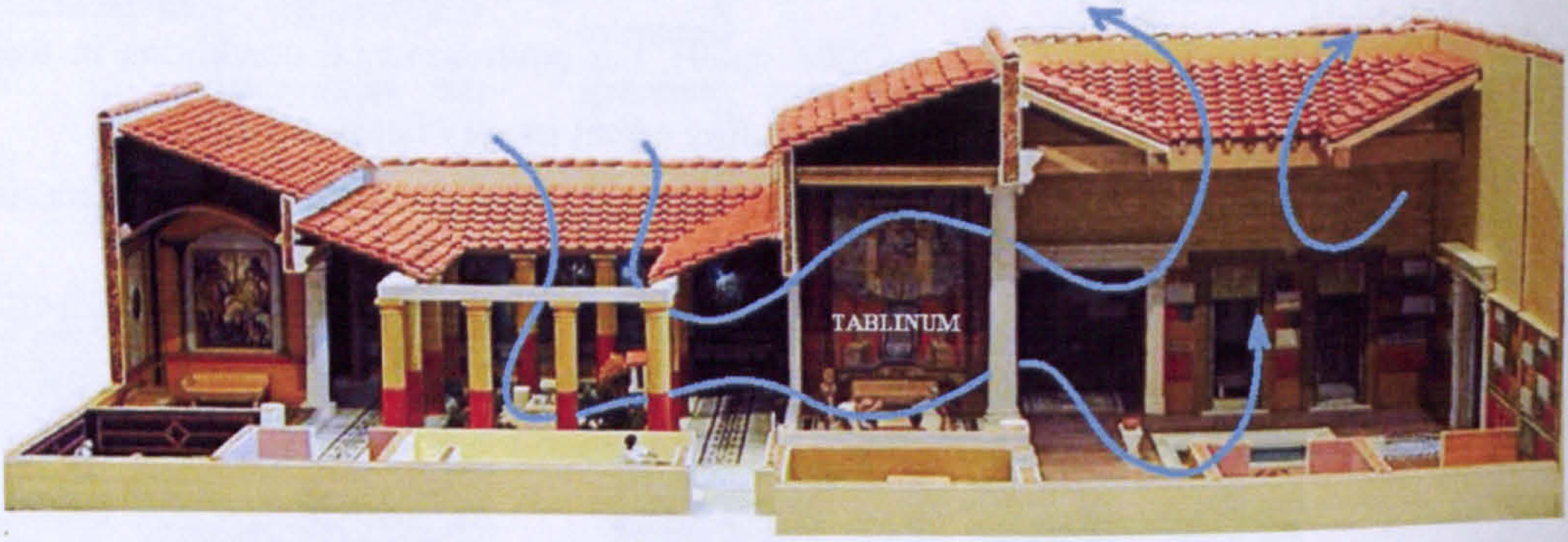


Fig. 3.17 the characteristic airflow in the Roman Domus, Source: modified after McManus, from composite model in the University of Pennsylvania Museum of Archaeology

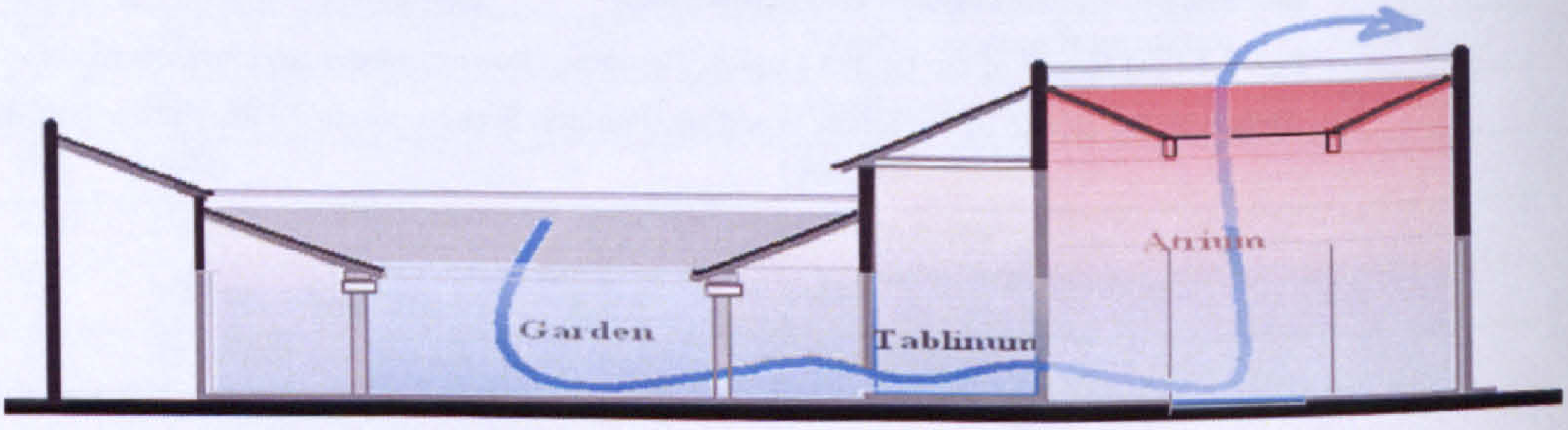


Fig. 3.18 Conceptual air movement in Roman Domus

3.3.4 The Tablinum

The environmental feature in this space is the focus of this study. Atrium houses, as Roman Domus were called, tend to have their great peristyle garden to light the Tablinum (Ball, 2003 pp138). It is a space where the owner met his guests on social occasions and displayed his status. The 'Tablinum' or assembly room was one of the most richly decorated rooms in the house (see fig.3.19). The rhythm of conversation in the Tablinum is accompanied by the sound of the water splashing into the marble basin in the atrium. Set in along the atrium-peristyle-axis opposite the entrance, the tablinum offered a fine stage for the appearance of the *dominus* receiving his *clientes* from the adjoining atrium (Carucci, 2006 pp25).

The Tablinum is simultaneously utilising the thermal conditions and views from the peristyle and atrium. In the summer, this space is effectively located to take advantage of the thermal dynamics between the atrium and colonnaded garden-courtyard. Similarity can be drawn from the Mohibb al-Din in the Medieval Cairo (refer fig.2.10), where studies have shown that the building tower was of light construction and relatively flat, causing it to heat up and accelerate the convective cycle, creating air movement in the interior even when the air outside is perfectly still (Steele 1988 pp36). It is suggested that the thermal environment in the Tablinum is influenced by a breeze caused by temperature difference between the colonnaded garden-courtyard and the atrium.

Fig. 3.19 (a) Views of the typical colonnaded garden – peristylium, (b) characteristic design of the original tablinum, Source: McManus, 2007

3.3.5 Similar layouts

Similar layouts are found across the Roman Empire. Regardless of site limitations, most of these buildings are a replica of the same concept, of rooms facing inwards towards the two inner courtyards linked by a Tablinum space. Roman Domus is believed to have evolved from a layout similar to the Domus Italica (see Fig.3.20). The garden-courtyard in this house is an exterior space situated next to the Tablinum. Equally, a sixth century BC house on the south eastern slope of the Palantine hill in fig.3.21 shows a variant of the same design. However, there was no real limit to the size to which a Domus or villa could grow (mmdtkw.org). A layout shown in fig.3.22 presents 2nd Century BC House with double Peristyle 'Casa del Fauno' in Pompeii. Most of these buildings lack fenestration on the outer wall. All designs suggest that the environmental condition in the Tablinum is influenced by the convective flow of air between atrium and peristyle courtyards.

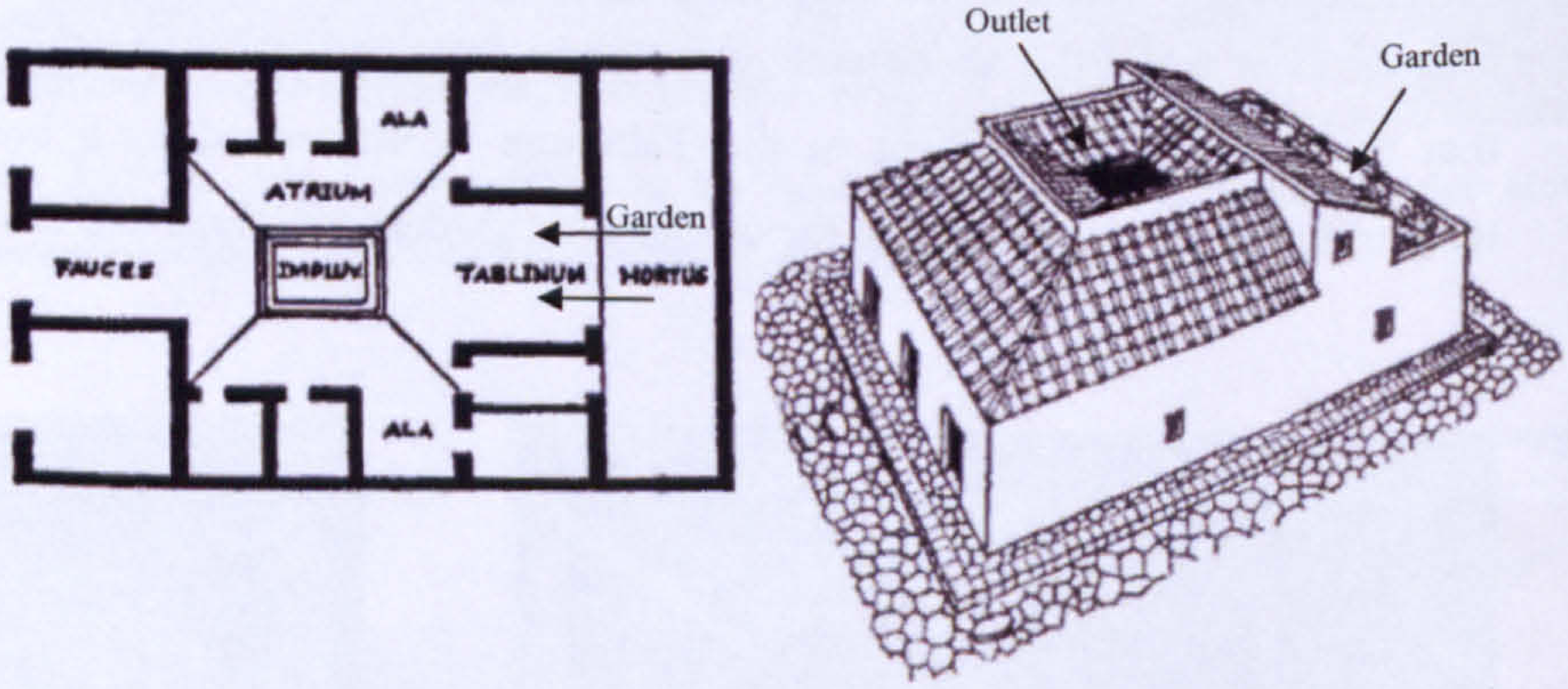


Fig. 3.20 Domus Italica, plan and 3D reconstruction, Source: modified after McKay, 1998

Fig. 3.21 A conceptual sketch predicting the air flow between the garden-courtyard and the atrium in one of the sixth century BC houses on the south eastern slope of the Palantine hill, Souce; modified from www.arthiistory.upenn.edu

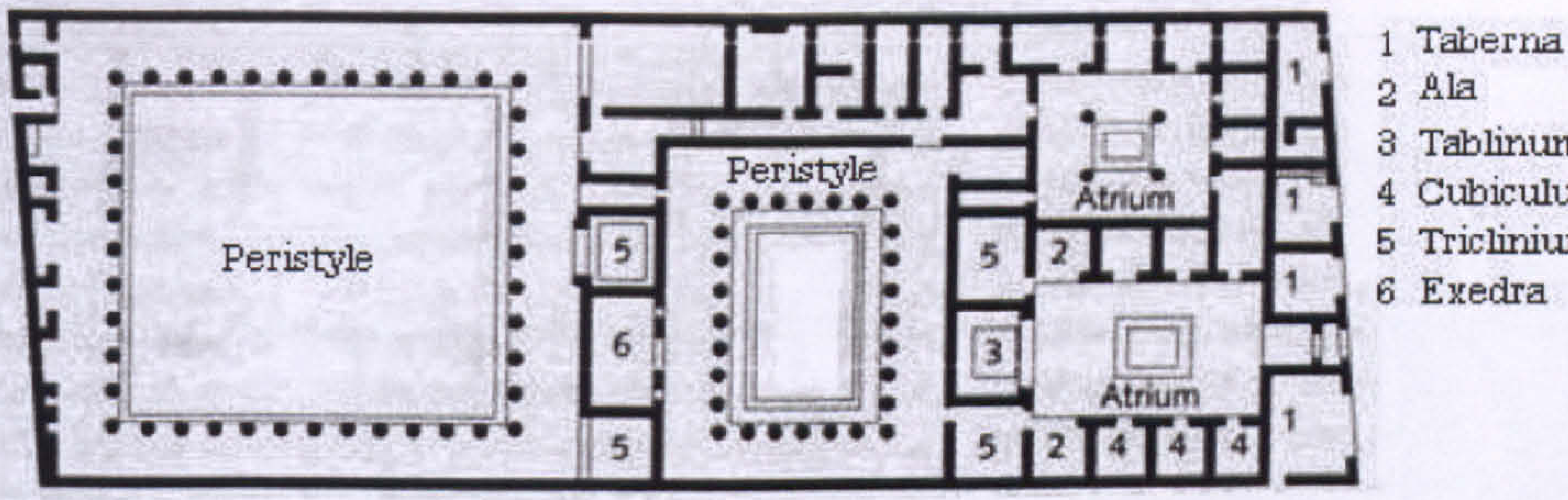
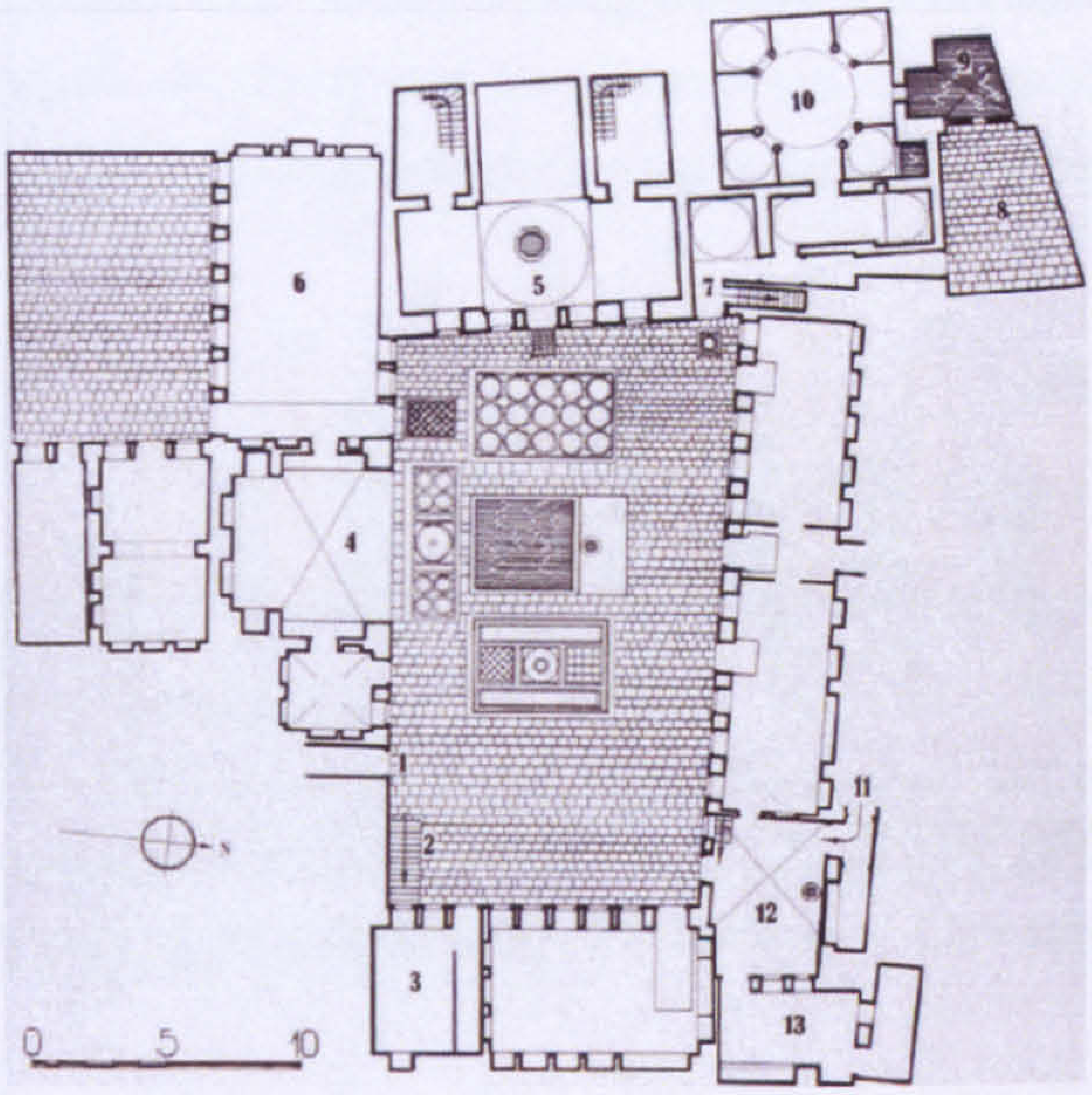


Fig. 3.22 Pompeii, House with double Peristyle, 'Casa del Fauno' 2nd Century BC

3.4 Beit Ghazaleh house, Syria

Beit Ghazaleh house is a 17th century historic mansion located in the city of Aleppo ($36^0$20'N $37^0$15'E) in semi arid climate in the Mediterranean region in Syria. The house is characterised with fine decorations and Armenian sculpture of Khachadur Bali in 1691. It is an example of a building in semi arid climate which has employed the multiple-courtyards concept (see fig.3.23). Various wings in the house are dedicated to different functions and seasons of the year. According to Edwards et al (ed.2006), the number and quality of inner courtyards in the traditional Arabic houses was affected by economic status and the size of the family. The Liwan space in this house rests between the front courtyard and back peristyle-garden.

Liwan houses have existed in different forms, but this particular house is a surviving example of this spatial device. According to Edwards et al (ed.2006 pp148), a slightly different tradition existing in Aleppo is to be found in the courtyards of Beit Ghazaleh house. Liwan is historically referred to as a city architectural element in Syria. Liwan houses have normally incorporated courtyards and are generally found in various shapes and sizes. The layout of this house is a typology of what used to be traditional houses in Syria (ibid). The house is typically designed so that anyone sitting in the Liwan would have direct access to the main courtyard and restricted view to the peristyle courtyard (fig.3.23). The study of this house is speculative and based on various assumptions. Physical investigation of this building cannot be carried out due to irresponsible alterations and political instability in the country.



1, Entrance, - 2, staircase terraces, - 3, housing the doorman - 4, Liwan. - 5, large reception room (Qa'a). - 6, open space with fireplace. - 7, Stairway - 8, service yard of the bath. - 9, boiler bath. - 10, bath oven. - 11 service entrance. - 12, Hall of service (with hole in the tank and access to the cellar-hut). - 13, kitchen.

Fig. 3.23 (left) the building layout, (right – top) The Iwan (source: ArchNet.org); (right-bottom) the view of the house from the street on the north façade, source: www.commons.wikimedia.org

The city of Aleppo (weather station – OSAP is located at an altitude of 393m) is characterized by strong daily and seasonal temperature variations (see Fig. 3.24 – 3.25). The summers are hot and dry with average highs of between 44°C and 28°C in July. Relative humidity is very low, ranging between 20 and 40% during daytime. This can be beneficial in extending the thermal comfort range up to 28°C. For most of this period the average rainfall is zero and the annual average precipitation is 16mm. Clear skies and intense solar radiation are the norm, and dusty north-westerly winds prevail. The short and fairly mild winter have a mean maximum of 15°C and min of 4°C in January, which is the coldest month. The perception of daytime temperatures, however, is heightened by high solar radiation.

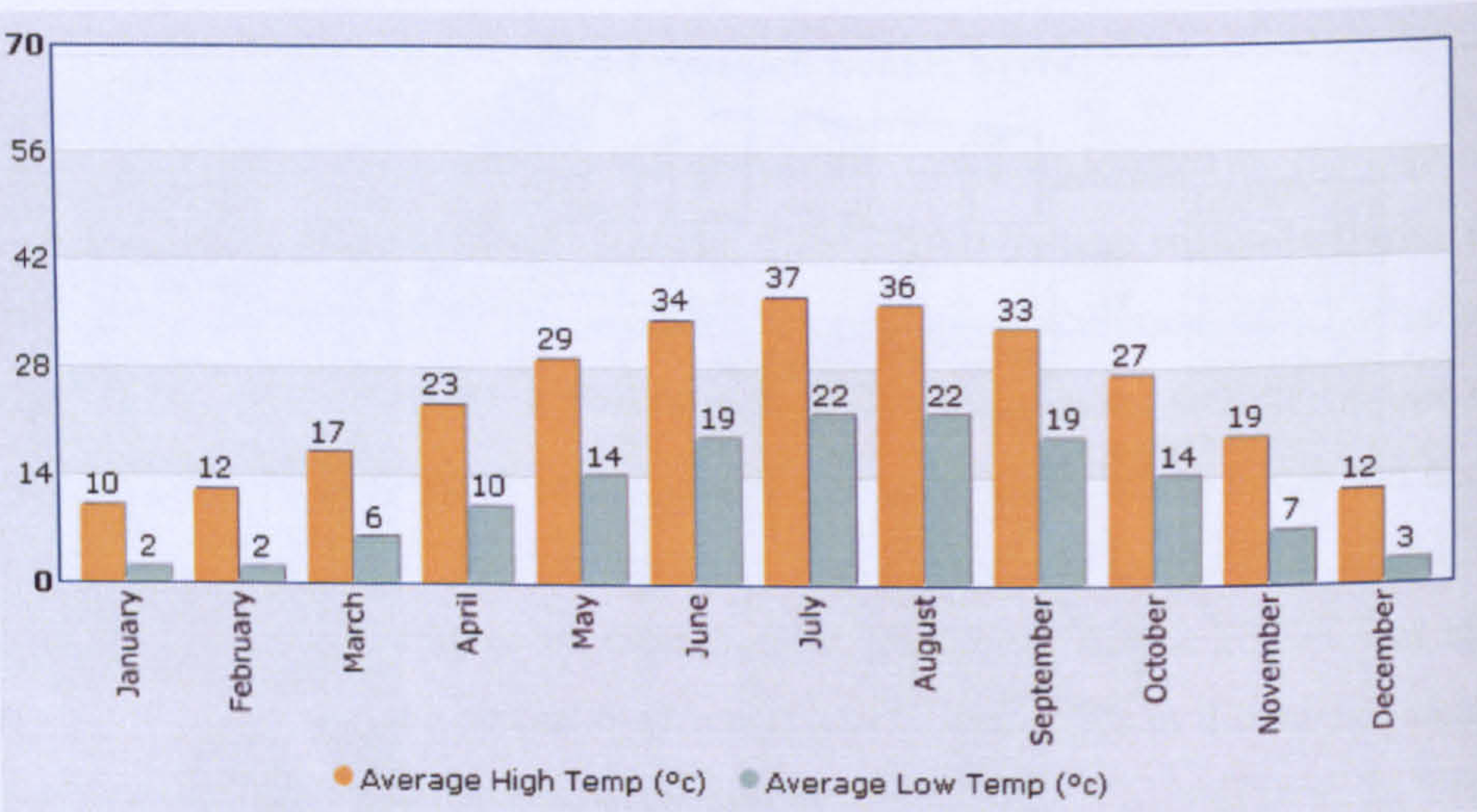


Fig. 3.24 The monthly average high/low temperatures in Aleppo (Source: www.worldweatheronline.com)

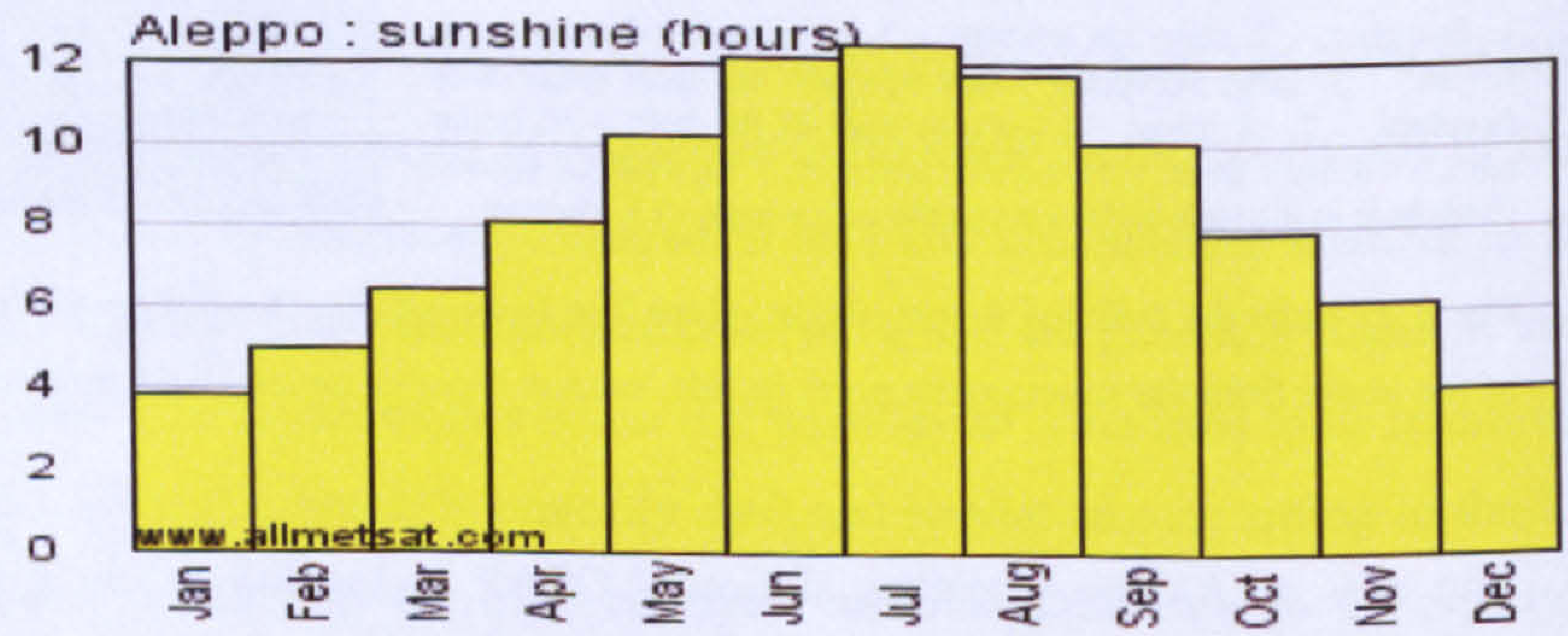


Fig. 3.25 Monthly average numbers of hours of sunshine per day, Source: www.allmetsat.com

3.4.1 Environmental design features

Similar to other historical precedents, Beit Ghazaleh house has a self regulating thermal environment. The building incorporates a supply of features such as vegetation, pools, water fountains, and building mass to help reduce the extreme summer temperatures. The building mass and orientation are used to insulate and stabilize the temperature swings which are characteristic of hot and dry climate, while the variable roof heights and protruding elements in the facade provide shade. The absence of window in the exterior walls helps the courtyards and interior spaces to be protected from extreme summer heat. This study suggests that the multiple-courtyards design is set to promote cooler environment in the Liwan space. The main courtyard, garden-courtyard 'peristyle garden' and Liwan space are the environmental design features which are of interest to this study.

3.4.2 Main courtyard

This Beit Ghazaleh house is entered through the main courtyard which is bigger and more exposed to solar radiation than other spaces in the building. Edwards et al (ed.2006) has shown that the un-shaded and half shaded areas represent 80 per cent of this house. The presence of a fountain in the main-courtyard helps to moderate extreme temperatures (see fig.3.26).

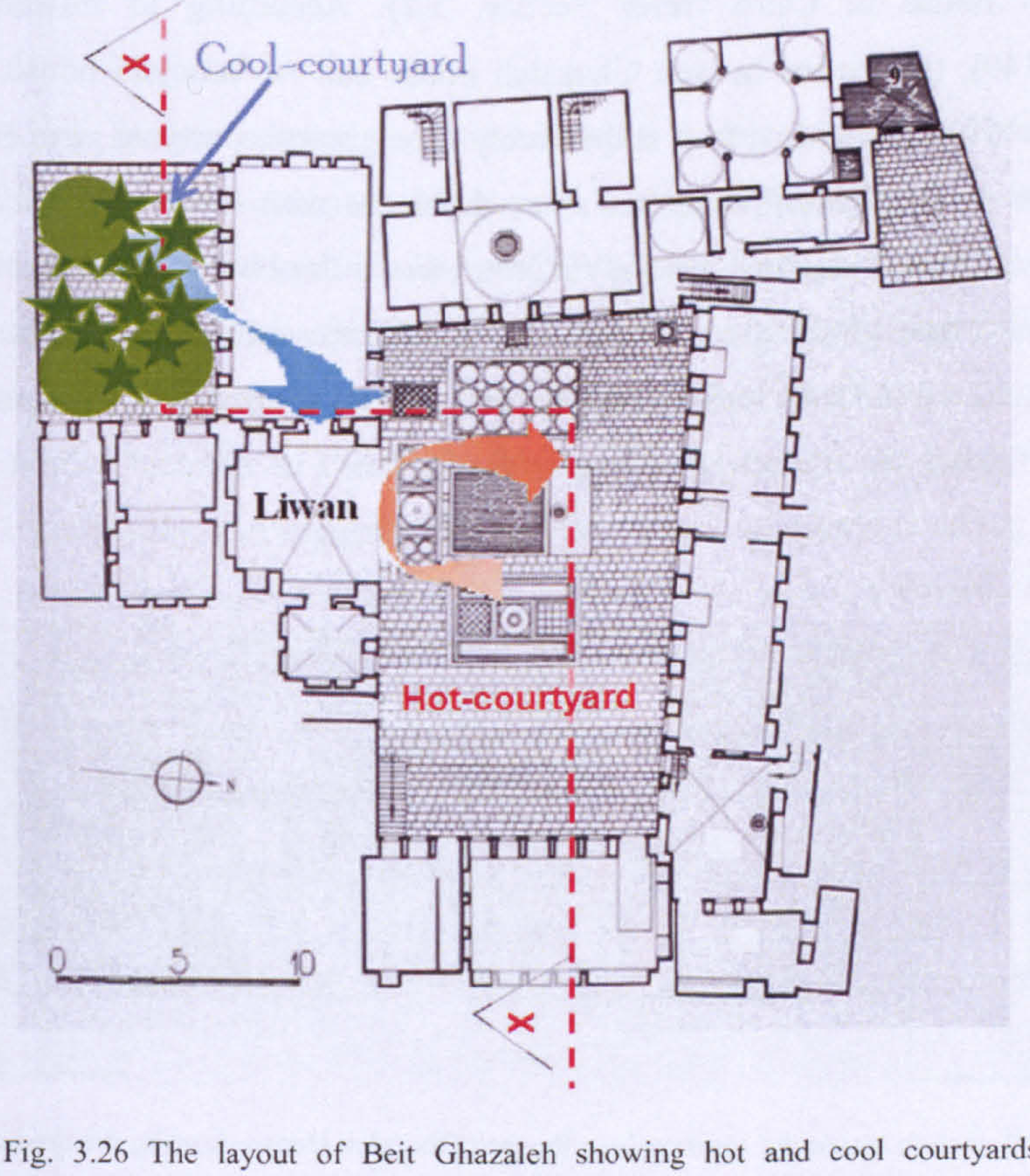


Fig. 3.26 The layout of Beit Ghazaleh showing hot and cool courtyards, Source: Modified from ArchNet.org

3.4.3 Garden-courtyard

The distinctive character of multiple-courtyard buildings in the Middle East is the existence of an open garden-courtyard to provide a cool environment whilst also meeting the needs of privacy and serenity (see fig.3.27). This courtyard provides environmental balance between indoor and outdoor spaces; and life within enclosed and restricted areas and life in the open air. It is the most widespread green form in traditional Arab cities (ibid pp147). The relatively smaller peristyle courtyard has a limited access to solar radiation while packed with vegetation.

There is a similarity between the garden-courtyard in Beit Ghazaleh house and Al-Suheymi house in Cairo (refer Section 3.2). According to Edwards et al (ed. 2006pp149), the garden in Beit Ghazaleh house and Al-Suheymi house occupies 31% and 35.5% of the building area respectively. The garden-courtyard with adjacent shaded verandah in Beit Ghazaleh is set away from the main courtyard which is near the entrance and more exposed to solar radiation. From the *Liwan*, the back of the house can be accessed through the garden-courtyard. Besides the cultural and religious roles, it can be conjectured that the characteristic cooler and private peristyle courtyard is purposely set to influence the climatic condition in the *Liwan*.

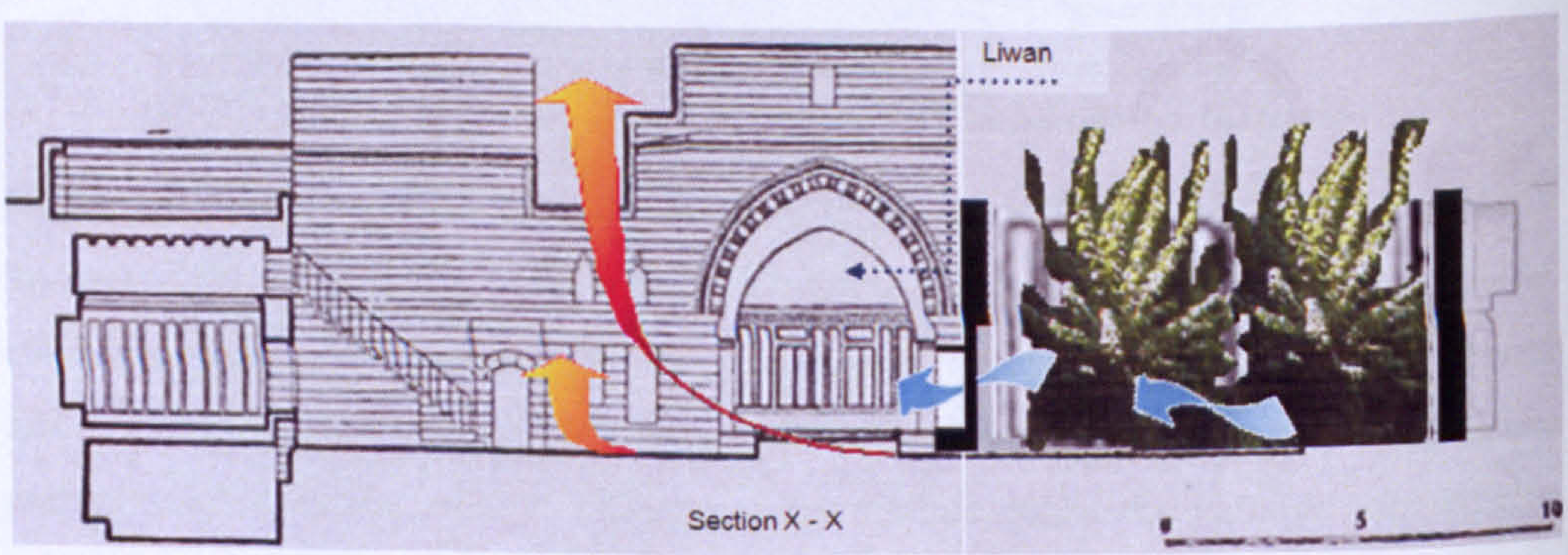


Fig. 3.27 A section across the courtyards in the Beit Ghazaleh House showing the predicted air movement (Source: modified from ArchNet.org)

3.4.4 The Liwan

Liwan is a ceremonial entrance hall accessible from the main courtyard in a traditional Arabic courtyard house. According to Khoueiry (2002), Mats and carpets are usually spread on the floor of the Liwan for inhabitants to sit. It is believed that the word Liwan originated from the word 'al-iwan' meaning 'the iwan'. It is a word used since ancient times to refer to a long narrow-fronted hall or vaulted portal found in Levantine homes that is often open to the outside (Abercrombie P. (1910 pp266). Islamic courtyards can have several iwans for various different purposes. It is a common practice to have one of the iwans used for religious purposed, hence facing Mecca 'Qubaa'. This study focuses on buildings which have employed a climatic strategy using Liwan as a transitional space between the main courtyard and garden-courtyard.

Liwan is faced directly as you enter the main courtyard in Beit Ghazaleh house. It is used as an open summer sitting room facing north (see fig. 2.4), hence practically shaded from solar radiation for most part of the day. Though flanked by a fountain in the front courtyard, the location of Liwan suggests a climatic connection with the peristyle-courtyard (garden). Its location between front courtyard and peristyle garden has a similar location as the Takhtabūsh and Tablinum in Al-Suheymi and Roman Domus respectively, and suggests that similar climatic principle is taking place. It is conjectured that an opening was available for cool air to flow from the peristyle-courtyard to provide summer-time cooling in the Liwan (see fig.3.27). This study suggests that the multiple-courtyards concept is used to promote the outflow of cool air from the peristyle courtyard to the main courtyard through the Liwan space.

3.5 Conclusion

This chapter has presented some historic precedents which have employed the multiple-courtyards concept. The precedents which have helped to appreciate the concept are identified from historical buildings in semi arid climates. The precedents which are discussed include; Al-Suhaymi House, Cairo, Egypt; Roman Domus, Pompeii, Italy; and the Beit Ghazaleh house, Syria. The layout in each precedent seems to nest different niches and experiences to building users. The layout and morphological characteristics of these buildings are discussed, whilst also drawing attention to the characteristic transitional spaces between courtyards. These precedents have suggested that interface between two courtyards with different thermal environments promotes convective cooling flows and present yard-to-yard transitional spaces with desirable microclimate.

This study asserts that the thermal condition in the transitional spaces (such as the Takhtabūsh in al-Suhaymi house and Tablinum in the Roman Domus) are influenced by temperature difference between the green cool-courtyard and grey (hot)-courtyard. While the heating in one courtyard space creates the air that is warm and less dense, vegetation and water in the other generates cooler and denser air. It is believed that the density of air is impacted by local thermal conditions. Sunshine affects the thermal properties of air in a reciprocated way. Solar radiation absorbed by the surfaces of the building produces some fluxes of heat. Since the density of air is inversely proportional to its absolute temperature, density fluctuation would create atmospheric turbulence and hence air motion by convection. Though conceptually simple, multiple-courtyard buildings suggest a self-regulating system of convective flow of air for cooling in the summer season. Detailed examination of a case study is carried out in the forthcoming chapters.

CHAPTER FOUR: THE HISTORY OF SOUTHERN SPAIN & CASA DE PILATOS

4.1 Introduction

This chapter discusses the context and building to be investigated. The discussion involves the history and climate of Seville as the city influenced by Moorish architecture. Moors are muslims who migrated from North Africa to conquer and influence the architecture in Southern Spain. The city of Seville was once the capital of Al-andalus later known as Andalucia is the name given to the peninsula by the Moors. It is believed that Moorish architecture provided cooling and maintained comfort by using techniques learnt from life in the Sahara desert. The Casa de Pilatos (Pilate's house) is used by this work as a typical axample of Moorish attempt to design with climate in Southern Spain (see fig.4.1).

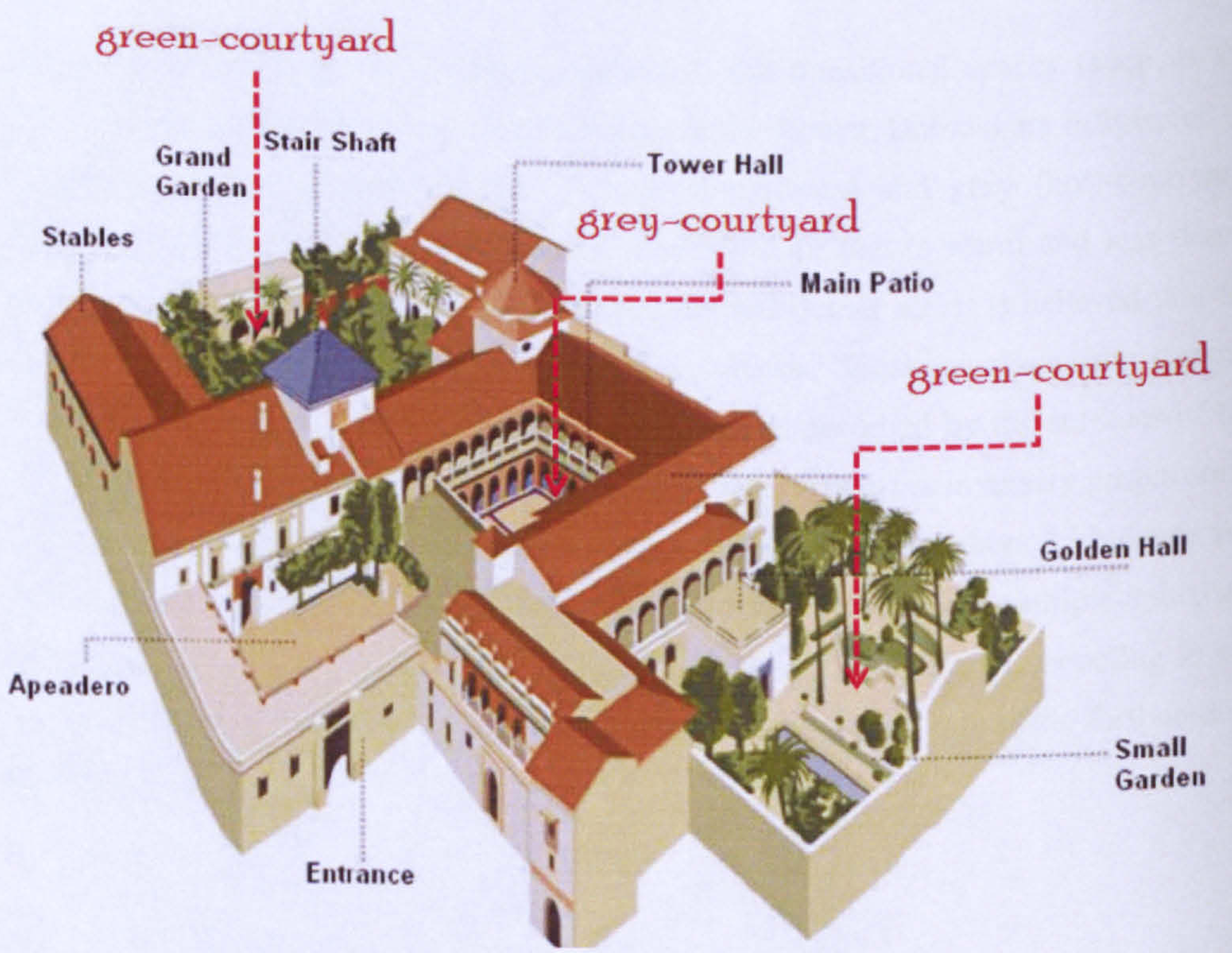


Fig. 4.1 3D image of the Casa de Pilatos in Seville, Spain, Source: agbeaver.com

The climatic strategies used in the Casa de Pilatos are used to show Moorish attempt to design with climate. Moorish affection with plant life, water, and garden are discussed. Courtyards were employed to moderate the extremes of climate for plants to survive and human comfort to be maintained. The thermal environment in the garden-courtyards is influenced by direct solar radiation and radiant cooling from vegetation, fountains, and building surfaces. It is suggested that latent heat of vaporisation from vegetation and water fountains play an important role on the conditions in the garden-courtyards. It is conjectured that temperature difference between the multiple-courtyards in the Casa de Pilatos is employed as an environmental strategy to promote convective flow of air through the transitional spaces.

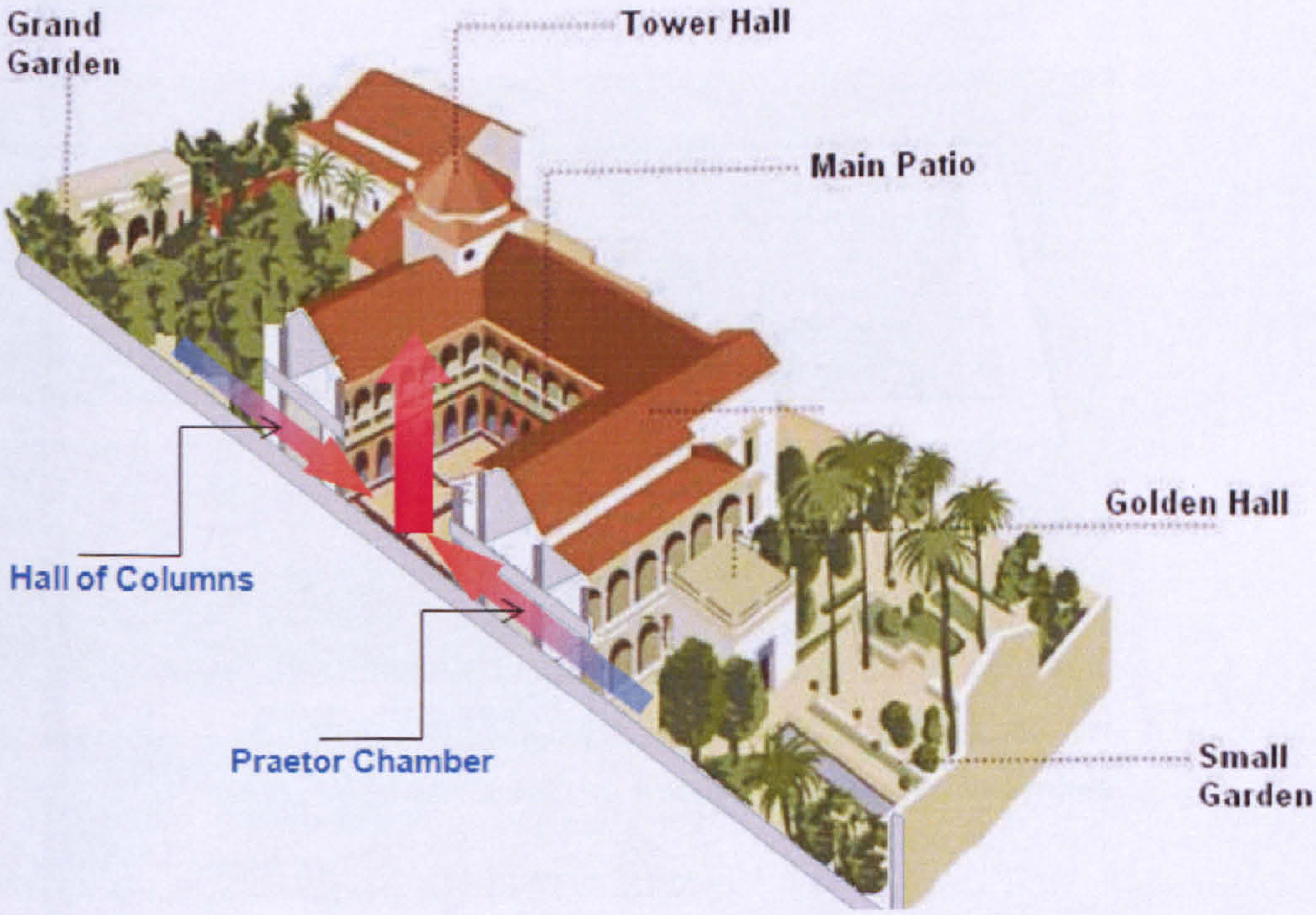


Fig. 4.2 Cross section of the Casa de Pilatos showing the transitional spaces; Source: modified from agbeaver.com

This work is based on a single-case study of Casa de Pilatos. This building is chosen because it dates back in the 16th century when thermal comfort was attained through passive means. The case is also a well maintained and identified to have minimun intervation and intact fabric and layout. This study involves physical investigation of environmental conditions in the courtyards and the transitional spaces between courtyards in the Casa de Pilatos (see fig.4.2). The Hall of Columns and Praetor Chamber are the transitional spaces to be investigated in this building (see fig.4.2 – 4.3). The impact of temperature difference on air movement through transitional spaces is investigated. Field work and theoretical studies will be used to confirm this strategy. This chapter has discussed the history, living patterns and environmental design features in this building.

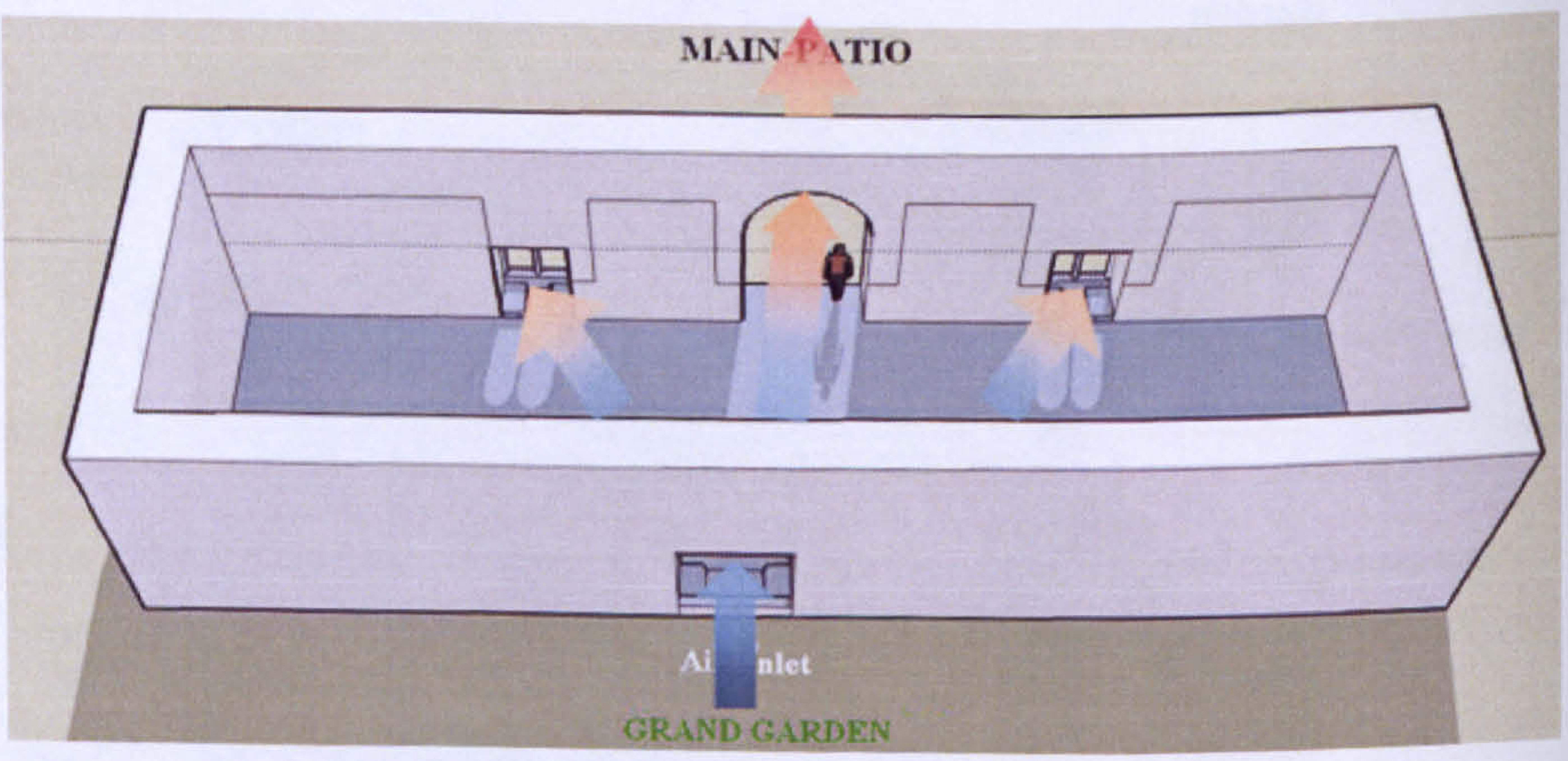


Fig. 4.3 The configuration of the transitional spaces (hall of columns and praetor chamber) between garden-courtyard and the main-patio in the Casa de Pilatos

4.2 The Moorish Architecture

Moorish conquered Spain from 711AD and exerted a very strong influence on its architecture. Irwin (2004) has shown that Moorish life started by living in tents, and later evolved to create a very sophisticated culture and architecture. Later on, the fall of Seville to Christians under Ferdinand III and his son Alfonso X in 1248 were followed by two centuries of preserving and utilizing Islamic forms and building styles. Mudéjar was the title given to the architectural style which employed Islamic features in Christian era. According to Villiers-Stuart (1994), Mudéjar styles were employed to an extent that Christian additions were difficult to make a distinction from the Islamic ones. Seville, being the richest and leading city in the South Spain (see fig.4.4), adopted the most elaborate courtyard houses. The Casa de Pilatos is taken as an example of courtyard house with elaborate garden courtyards and transitional spaces between its multiple-courtyards.

Fig. 4.4 Location of Seville in the map of Spain, Source: http://images.allrefer.com

Moorish design of courtyard houses has chambers for royal concert or halls for leisure activity located adjacent to garden-courtyards. Such chambers have taken the most strategic location in the courtyard architecture which dominated Moorish construction. Environmental features such as vegetation, fountains, and pools are installed in the courtyards. Moreover, additional features such as carved images, interiors with elaborate carved wood, horseshoe arch, minaret, (see fig.4.5 – fig.4.7), glazed ceramic tile-work. and very elaborate plaster molds (fig.4.7) were common. The building design is dominated by plain exterior and richly decorated interior. In most cases the building materials were the same. A mixture of rubbles and adobe is covered with stucco and widely used with considerably different results. Examples of prominent chambers are Hall of Columns and Praetor Chamber which are yard-to-yard transitional spaces between the garden-courtyards in the Casa de Pilatos in Seville.

Fig. 4.5 (left) Horse shoe arch in the Church of St. María la Blanca – Toledo, (right) the application of plaster molds in Moorish Architecture, Source (left) www.green-man-of-cercles.org; (right) Sevilla Mini-Guide (2005)

Gardens and courtyards became the most common features in the Moorish Spain. Arcala (2002) acknowledged a deep inter-penetration between architecture and gardens in Moorish Spain, citing the environmental qualities in the Palace of Generalife and the Alhambra of Southern Spain. According to Heschong (1979, pp67), the Koranic description of paradise was the guide to most earthly gardens in Islamic culture. Gardens were a paradise of the desert people.With this in mind, Moors hoped to create an anticipation of heaven in their gardens-courtyards. Heschong (1979 pp66) made a distinction between two Islamic gardens, namely palace gardens '*bagh*' and the gardens in the inner courtyard of a house '*bustan*'. The climatic aspect of the gardens in the inner courtyards of the house is the main focus of this work. The garden-courtyards are characteristic evidence of the Moorish ability to preserve coolness and moisture in the midst of hot and dry climates.

A courtyard was a tool for regulating the duration of exposure to high temperatures and solar radiation. The Muslim culture in the desert wilderness is an explanation for the wide spread of garden-courtyards in Southern Spain. A garden-courtyard with flowing fountains and water ponds created a cool atmosphere, similar to the 'oasis effect' in the midst of intense heat of hot and dry environment. Courtyards were important because, in extremely hot weather, damages on vegetation are usually irreversible and many organisms and plants would survive as long as duration of exposure to high temperatures is limited (Jones, 1992). It is believed that garden courtyards were primarily used to provide shade and cooling through evaporation of water from pools, fountains and vegetation.

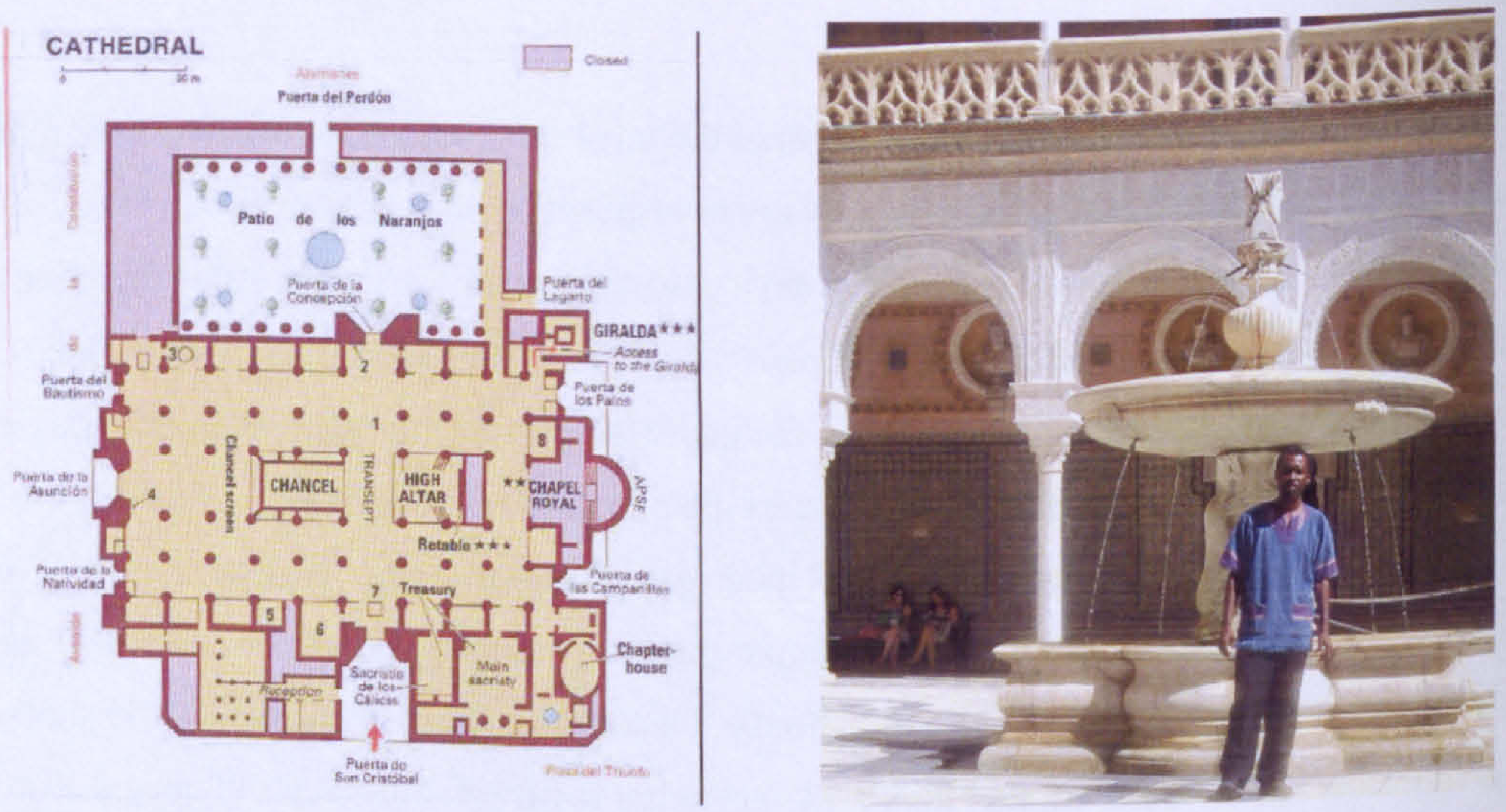


Fig. 4.6 The courtyards in the Cathedral (left) and Casa de Pilatos (right)
Source: (left) Seville Mini-Guide (2005)

Fig. 4.7 A typical fountain point and pool in the Moorish gardens in Seville

Fountains and formal pools decorated Moorish houses and gardens (fig.4.6). Costly and elaborate irrigation was the only means of obtaining the desired results (Villiers-Stuart, 1994 pp4). Hill and Grabar (1964) relate the Moorish affection to plant life with the absence of vegetation during their migration across deserts. Therefore, they showed their gratitude by adopting signs of life such as water and plants in their architectural practice. Particularly, those plants (i.e. lotus) they found during their migration across deserts in

Middle East and North Africa. However, the decorative water channels disappeared during the Christian conquest of Southern Spain (Ibid). Future alterations in the garden irrigation system caused most of Moorish garden-courtyards to go through significant transformations.

The design of Moorish courtyard houses was also influenced by maritime hot and dry currents from Sahara desert. These currents did lead into construction of dense towns with narrow and deep streets. Narrow streets avoided direct exposure to undesirable solar heat and created natural convective flows to cool the houses in the summer season (see fig.4.8). Buildings were white washed to reflect solar radiation/sun heat; and had flat roofs to provide a sleeping place in summer season as well as collecting rain water into cisterns. The layout of the old city of Seville was influenced by semi arid climate in the Southern Spain.

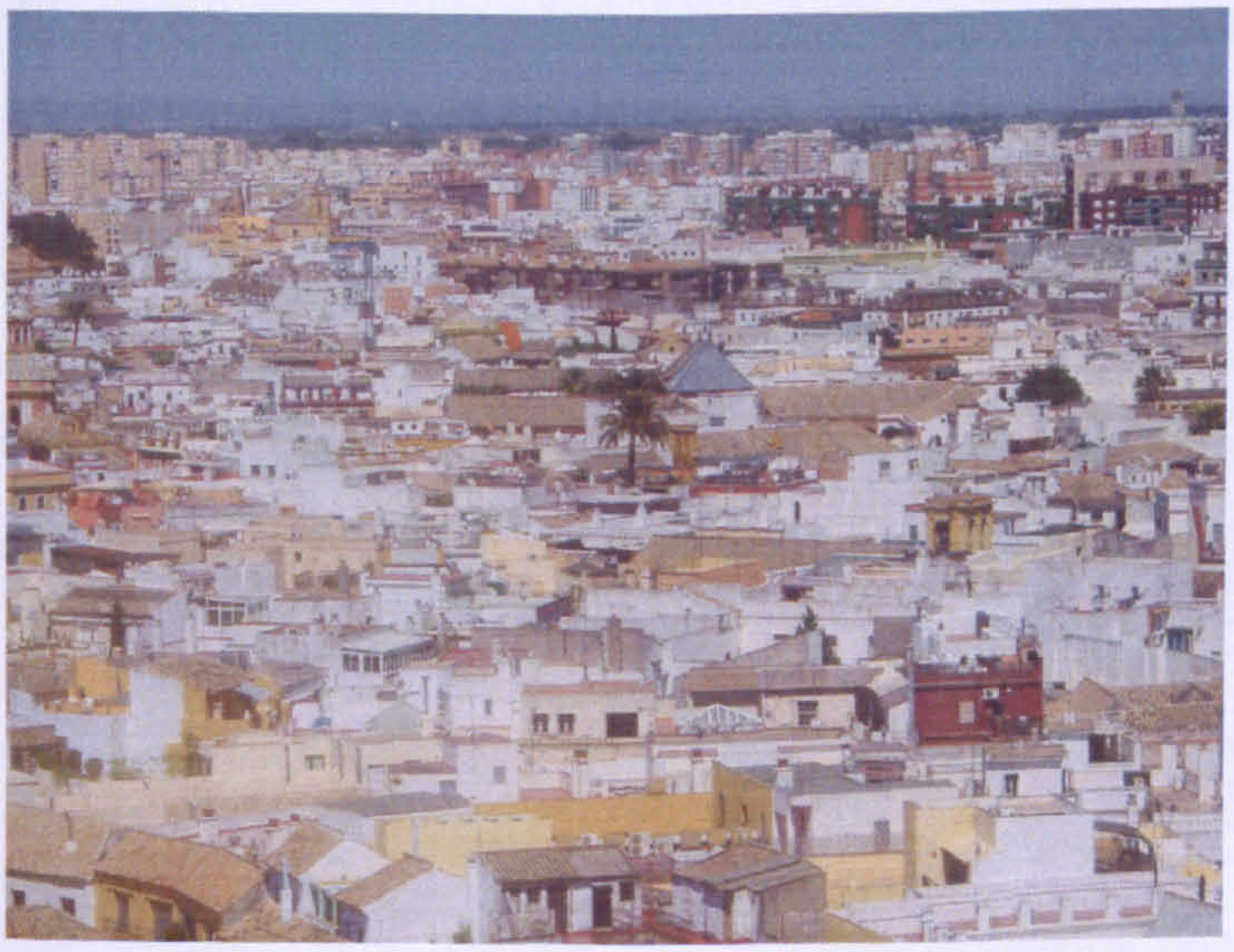


Fig. 4.8 (left) The compact historical city of Seville, and (right) a typical narrow street

Source: (right) Sevilla guide

4.3 The climate of Seville

The city of Seville is located at 37°23'N, 5°58'W in the Southern Spain. Seville location is typically Mediterranean with the influence of tropical streams from Sahara desert and polar streams from continental Europe. Seville is located between the warm waters of Mediterranean Sea and the cool waters of Atlantic Ocean. However, the city of Seville is screened from humid streams of Mediterranean Sea by the south-east Penibetic Mountains. The city is also on the river basin, screened from cool Atlantic streams. Compact historic city of Seville provides shades and helps to protect streets and houses from hot and dry tropical streams from the Sahara desert flowing through the valley of river Gualdalquivir.

Summer seasons in the Southern of Spain are typically hot and dry. Temperatures may go well beyond 40^0C and relative humidity (RH) would easily fall below 25%. According to Arcala (2002), three climatic zones are found in this part of Iberian Peninsula: The first is 'Penibetic zone' where city of Granada is located. The second is 'Basin of the river Gualdalquivir' where the city of Seville is located. And the last one is the 'Mediterranean coast' where city of Malaga is located. Seville averaged wind speed of 1.7m/s for June and July and 1.4m/s for August and September is prevailing from southwest (Alvarez ed. 1992 pp156). A summary of monthly variation of dry bulb temperatures is shown in fig.4.9. The meteorological data for Seville are summarized in figure 4.10 and figure 4.11.

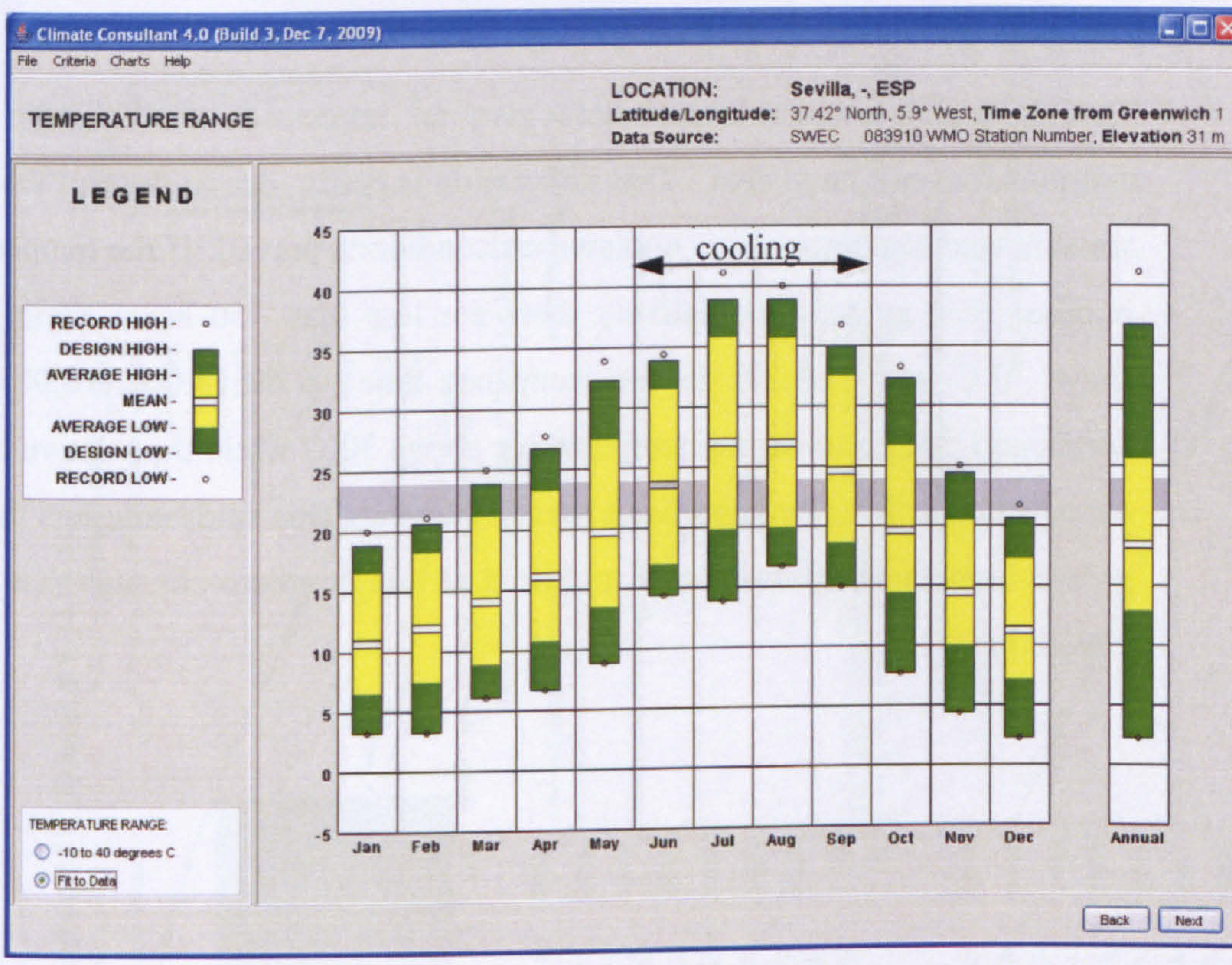


Fig. 4.9 A summary of Seville's monthly variation of dry bulb temperatures, Source: Climate Consultant 4.0 software

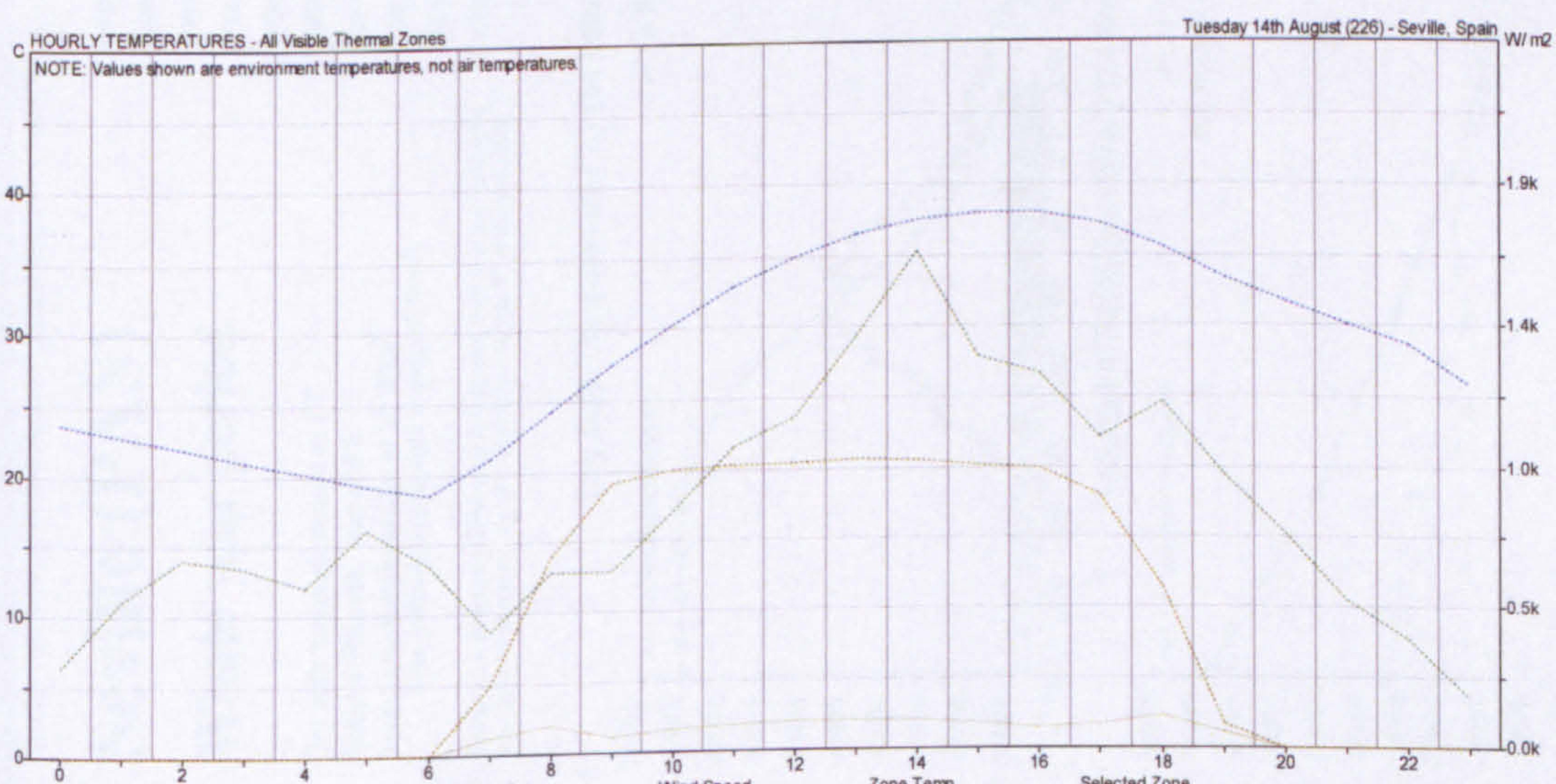


Fig. 4.10 A summary of hourly variation in Seville's DBT, Solar radiation and wind speed

Source: Ecotect software

Though useful, meteorological data give an impression that climate is uniformly distributed over a large area. This impression is partly due to the fact that weather data are collected at points where undisturbed conditions prevail. If the temperature of 30^0C is taken as a guide. Cumulatively there are less than 750 hours facing temperatures above 30^0C (see fig.4.10). In the occupancy time (09:00-14:00h, 16:00-19:00h), there are around 500 hours facing temperatures above 30^0C while the relative humidity (RH) remains below 50% for significant part of the year. This study suggests that this general picture is not a representative of multifold of minute micro-climates that would exist at ground level.

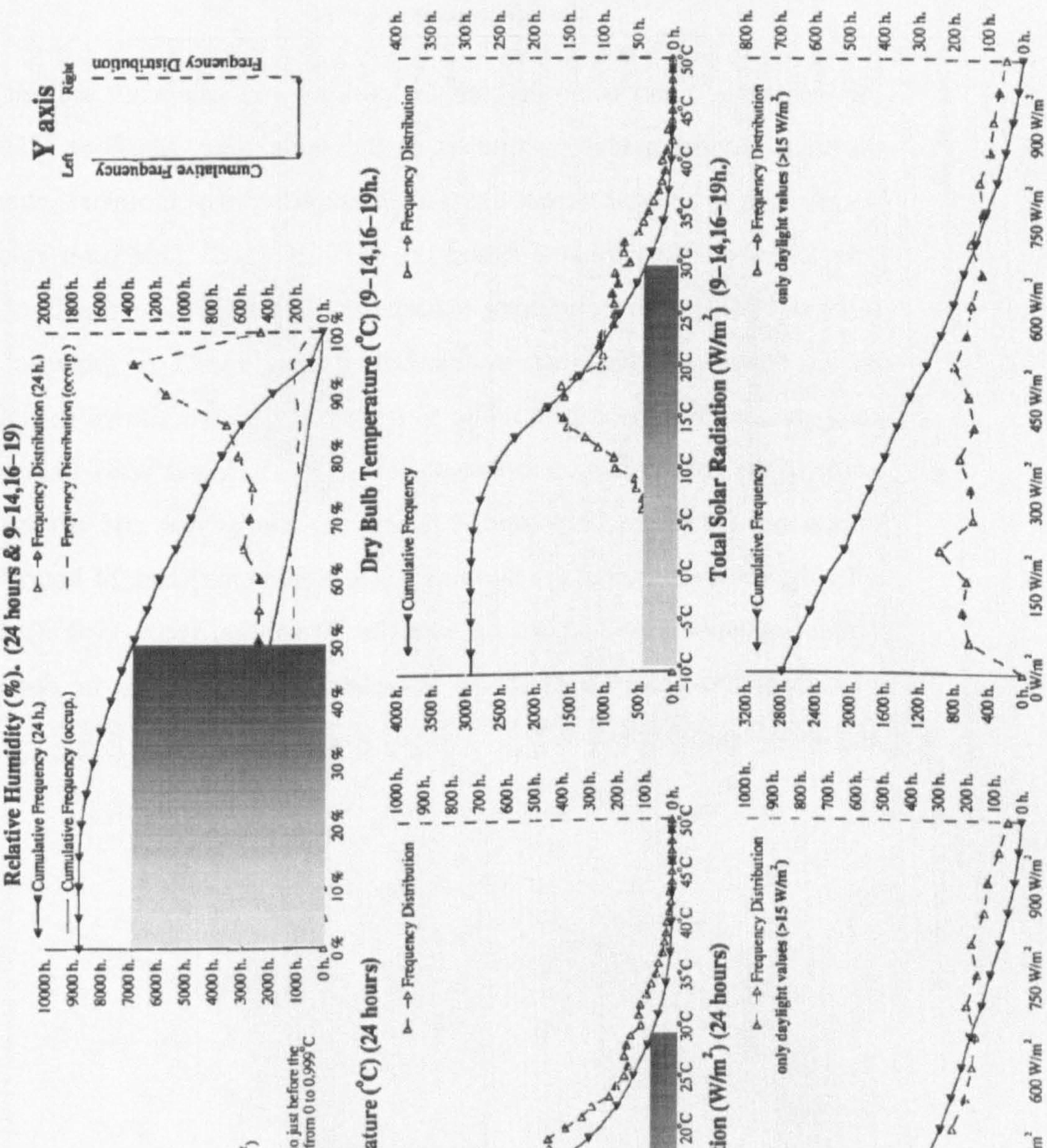


Fig. 4.11 Frequency distribution and cumulative frequency for Seville (PAS), Source: adopted from Martinez (2000)

Psychrometric chart is useful tool for plotting and analyzing the relationship between different environmental parameters at the same time. Martinez (2000) used climatic hourly data to show different formats of simplified psychrometric charts (see Fig.4.12). The lower comfort limit is based on DBT of 25°C. This limit is extended to 28°C (Givoni, 1992) after combining natural ventilation (NV) or night cooling (NC). These charts have indicated that mechanical cooling (MC) is required above wet bulb temperature (WBT) of 23°C. The psychrometric charts shown in figure 4.12 combine some of the environmental factors such as DBT, RH, and WBT to present four different situations: (i) whole year and 24 hours, (ii) whole year and occupancy time (09:00-14:00h, 16:00-19:00h), (iii) Summer (June-September) and 24 hours, and (iv) Summer (June-September) and occupancy time (09:00-14:00h, 16:00-19:00h). The zones in these psychrometric charts suggest the boundaries of ventilation or cooling technique for maintain thermal comfort.

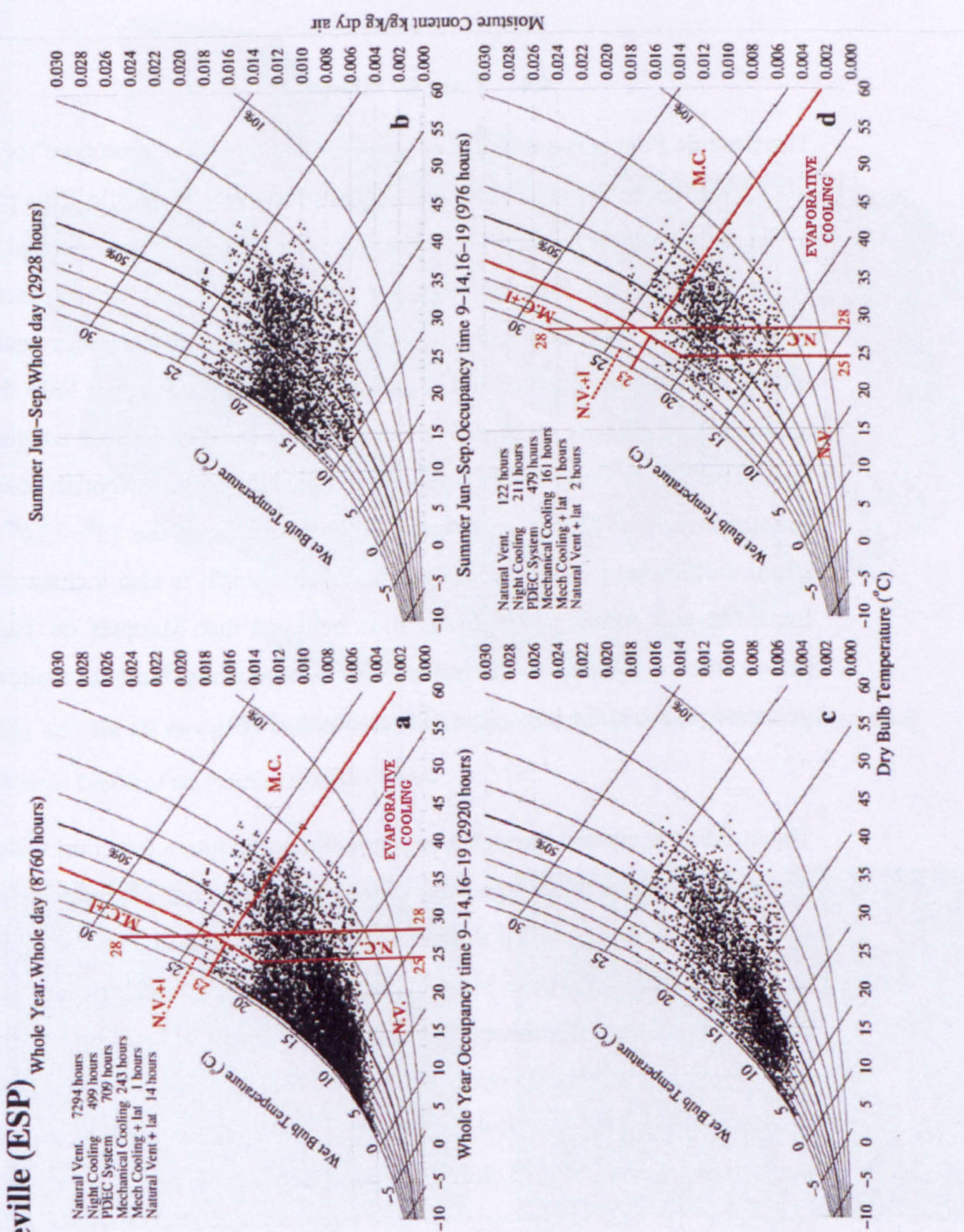


Fig. 4.12 Psychrometric charts showing limitations of various cooling options

Source: Martinez (2000)

4.4 Casa de Pilatos

The Casa de Pilatos is a multiple-courtyard building and a "prototype" of an Andalusian palace located on the narrow streets in the historic part of Seville. This palace was built in the 16th century for a family of a wealthy aristocrat and now converted into a museum by the government. The building is a mixture of Italian Renaissance and Spanish *Mudějar* style. The architectural styles of Baroque, Renaissance and Mudějar are seamlessly blended together in this palace. The historical account links the architectural approach and climatic strategies in this building with the Islamic conquest and culture that arrived from North Africa to Southern Spain during the Moorish conquest. Mudějar denotes a style of Iberian architecture and decoration of the 12th – 16th centuries with strong influence of Moorish taste and workmanship. It is also a characteristic blend of European and Arabic inspirations. It is believed that Marqués de Tarifa named the palace after a journey to Jerusalem, and subsequently built to replicate the Roman governor palace in the holy city (Villiers-Stuart, 1994).

The building is entered through a large marble portal into a forecourt with a side passage or arcaded Apeadero (carriage way) which leading into a tiled central-court (Main-Patio) decorated with sculptures of Roman emperors and statues of the Greek mythology (see fig.4.13 and fig.4.14). The Main-Patio with a water fountain leads on one side to a Praetor-Chamber with enchanting glimpses of Small-Garden which is seen through on opening with Spanish iron *rejas*. Equally, on the opposite side of the Main-Patio is the Hall of Columns with a similar opening to the Grand-Garden planted with palms and orange trees among at least thirty species which are present in the Casa de Pilatos (see Appendix 1). The Main Patio is also linked to an elegant staircase leading to the apartments on the upper floor.

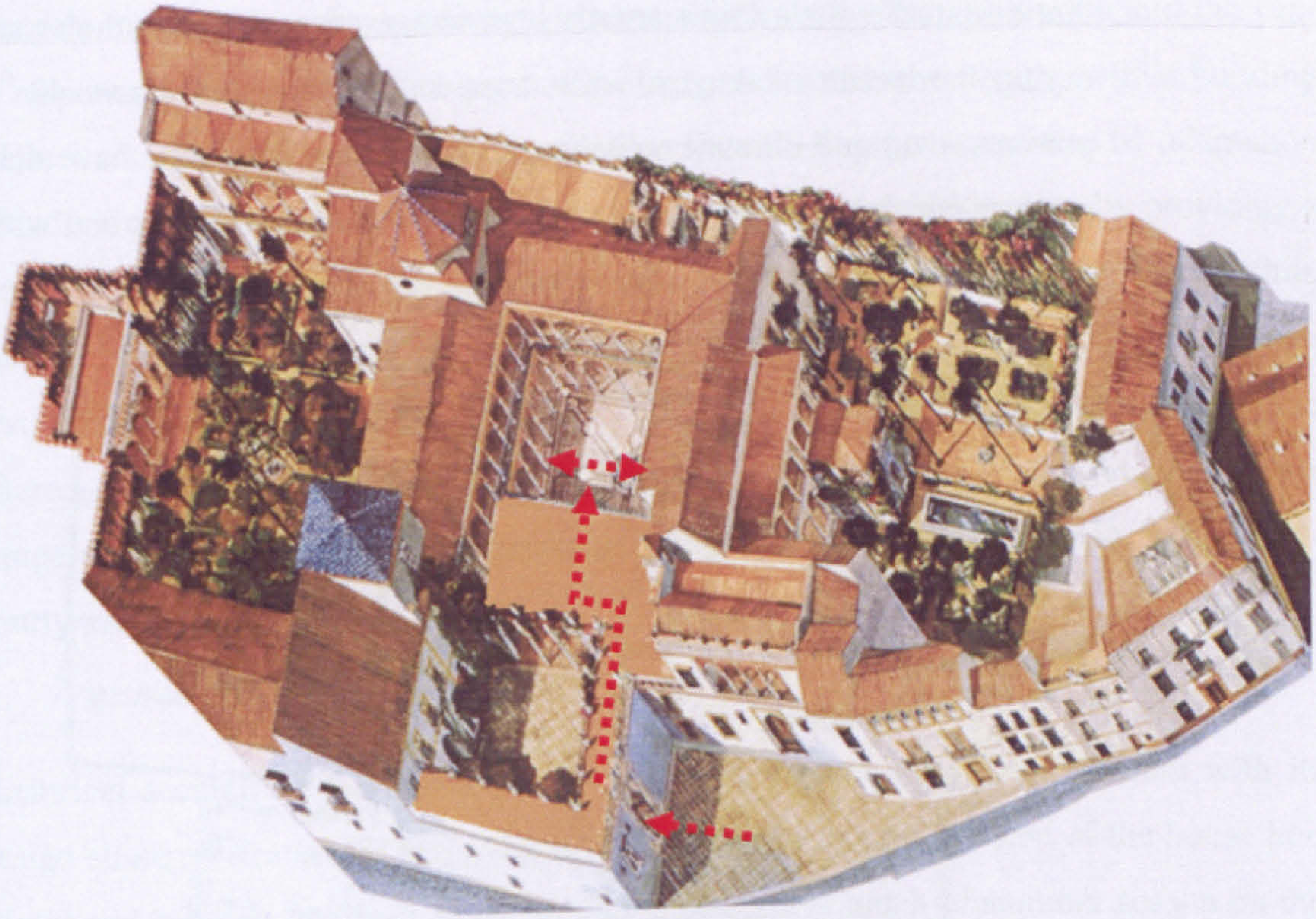


Fig. 4.13 The 3D view of the Casa de Pilatos showing path to the main patio from the main entrance

Source: Leaflet of the Fundación de Medinaceli

Fig. 4.14 the main entrance to the Casa de Pilatos

Fig. 4.15 the Main Patio in the Casa de Pilatos

Source of figures: http://images.allrefer.com

The building form has integrated one, two, and three storey structures (see fig.4.15). It is believed that the building form is mainly influenced by climate. Ford B. (2006) suggests that despite Seville's characteristic high temperatures in the summer season, especially during the month of August when temperatures are well above 40 ^{0}C, this building presents a unique climatic experience. The house does also have a history of living patterns which have adapted to building climate in both summer and winter seasons.

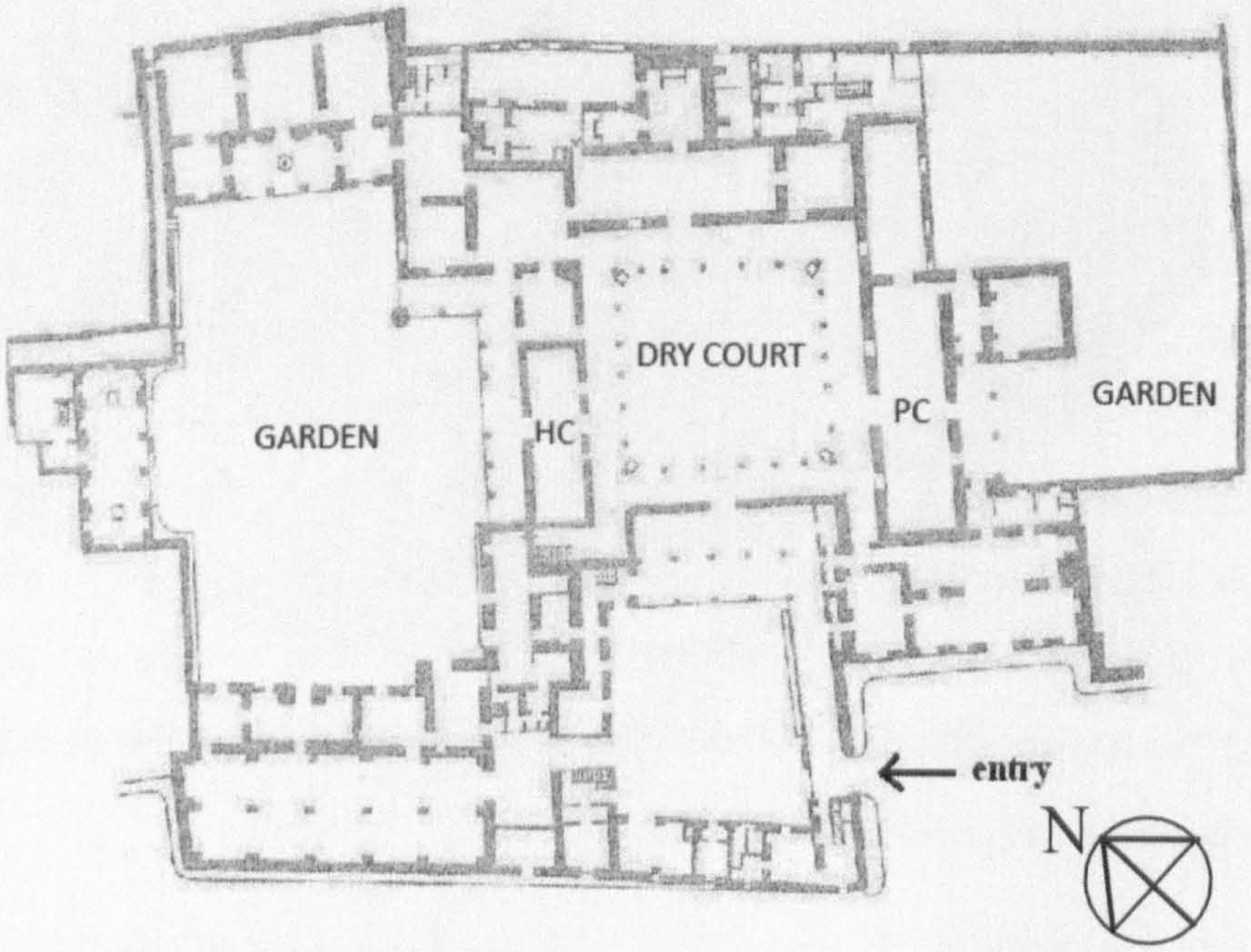


Fig. 4.16 The layout of the Casa de Pilatos showing the dry courtyard, garden, and transitional spaces (Hall of Columns – HC and Praetor Chamber – PC)

4.4.1 Living patterns

The living patterns in the Casa de Pilatos are a result of various impacts. The earth rotation gives the heartbeat of day and night which regulates activities and life style. On the other hand, the revolution of the earth around the sun sets the rhythm for different seasons, hence hot and dry summers on the southern-part of Spain. Furthermore, whether each locale in Casa de Pilatos is cool or warm is largely determined by its relative distance from fountains, vegetation-courtyards, and Main-Patio among other features (see fig.4.16 and fig.4.17).

Casa de Pilatos adopted some living patterns which were changing throughout the year in response to microclimatic changes. Residents choose whether to stay within building walls, under the roof or in the courtyard. Comfortable living was assisted by adaptation of individual life-style which the designers have taken into consideration by providing a range of microclimates. In the summer season, people would start working earlier while the day is cool and stop shortly after midday when a break is taken so that people can rest 'siesta' during the hottest part of the afternoon. Activity would restart later in the afternoon when outside temperature has fallen from their peak. As indoor air temperatures continue to rise, inhabitants had opportunity to relocate to the garden-courtyards.

Historical account of the building shows a living pattern which is consistent with its design strategy. Feature of particular interest is the horizontal division of the house into winter and summer quarters. Household members spent much of summer season on the lower floors and winter season on upper floors. Ground floor is an open plan with direct access to the courtyards, while the upper floor is closed with shutters and partition walls. Apartments and balconies in upper floors benefit from warm and less dense air rising from the lower floor while the ground floor would benefit from a flux of cool and denser air from the building mass and vegetation.

Additionally, the position of window-seat suggests that occupants were taking advantage of the microclimate in intermediate courtyards. The window-seats are located in the spaces which are adjacent to the courtyards, including the staircase. There are balconies running around the upper floor to receive every ray of the winter sun into a winter living space. Residents had exposure to winter evening sun through huge balconies on the North West part of the compound. Leading off these balconies are winter dining rooms and living spaces. Since winter nights are extremely cold, upper floor windows have shutters, and people slept in closed spaces. Transitional spaces on the ground floor are open to the courtyards where fountains and vegetation were used to relieve the building from summer heat. Occupants have opportunity to spend time in gardens or next to the fountain and benefit from wide range of microclimates.

Fig. 4.17 Balconies to access winter sun on the Western courtyard of Casa de Pilatos

Source: adopted from the leaflet of the Foundacion de Medicenali

Fig. 4.18 Variation in microclimates across the spaces in the Casa de Pilatos

4.4.2 Environmental design features

A range of environmental design features are responsible for the anticipated range of microclimates in the Casa de Pilatos. These features include courtyards, vegetation, water fountains, pools, building mass, and arcades. Most vegetation is in the garden-courtyards, with water fountains located in multiple locations in the building. It is believed that evaporative cooling processes have significant influence on environmental conditions in the garden-courtyard. Arcades exist between courtyards and between transitional spaces, and most of upper floor living rooms have balconies. The entire building envelope is also encompasses thick walls. The building mass of around 900mm thick walls is used to provide thermal lag and stabilise against temperature swings in the transitional 'intermediate' spaces.

Although these environmental design features have various roles in the creation of desirable microclimates, solar time does also influence the design criteria and features used for passive control of extreme summer temperatures. Thermal environments are influenced by the sun's position as a day progress from morning to evening. Fathy (1986) and Konya (1980) has shown that yard to yard convective cooling is the likely to be influenced by temperature difference caused by exposure to solar radiation. This study suggests that solar radiation has a significant influence on the organisation of thermal environment in Casa de Pilatos.

4.4.3 The building orientation

The thermal environment in the Casa de Pilatos is significantly influenced by sun path and building orientation. The orientation of the building is set to either accentuate or attenuate the impact of solar heat in one courtyard relative to another, particularly, in the summer season, when air temperatures are high. The axis across the three courtyards (grand garden, main patio, and small garden) extends from northwest to southeast (fig.4.18). As the earth moves on its orbit around the sun and spins on its own axis, various microclimates are formed in the garden-courtyards and dry-courtyards. These microclimates are a result of unique pattern of shaded and shadows shaped by solar path. It is believed that most significant microclimatic variations in the Casa de Pilatos are created by differences in sun and shade patterns.

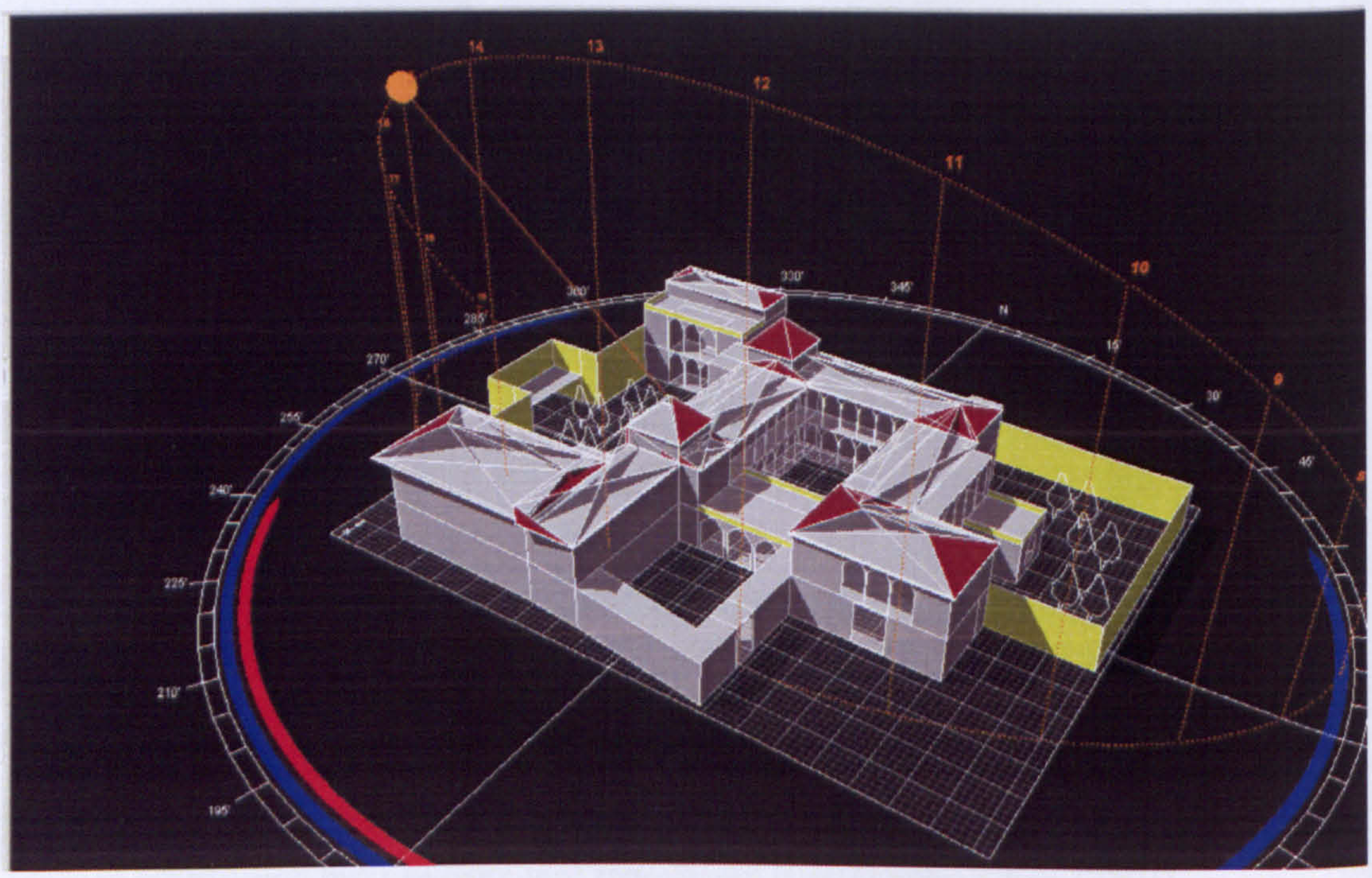


Fig. 4.19 the solar altitude at 15:00 hours on the Casa de Pilatos (model with Ecotect software)

Southeast façade of the Small Garden is covered with terraces, galleries, and vegetation to shade against morning sun, while the Main-Patio exposed to direct solar radiation. According to Yannas et al, (2003), a marked differences of as high as 20 – 40 degrees centigrade is common when building surfaces are exposed to solar radiation. The impact of solar radiation does also depend on the nature and orientation of the receiving surfaces. It is believed that the choice of orientation is greatly influenced by microclimates that are required in particular locations around the building.

The variation in building heights are worked out so that the higher parts would cast shadow on specific areas and at specific time to cut down on direct solar gain in the garden-courtyards. The higher the exposure the surface has to sunshine, the more marked are the temperature differences. The strategy produces a unique pattern of shades and shadows in the building. For example, solar radiation covers significant part of the Main Patio after 11:00h in the morning (see fig.4:19 and fig.4:20c). It is conjectured that after this time, high dry bulb temperatures in the Main Patio have promoted convective flow of cool air through the transitional spaces.

shade in the main-patio at 10:00h	(b) main-patio at 11:00h	(c) main-patio at 12:00h

Fig. 4.20 The position of the shadow in the main-patio at 10:00, 11:00, and 12:00hrs

4.4.4 Multiple-courtyards

The multiple-courtyards in the Casa de Pilatos are part of compact urban settlement where a group of buildings help to provide mutual shading and shady narrow streets between buildings help to minimize exposure to solar radiation. The tendency in these climates is to make use of arcades, colonnades, and courtyards (Konya, 1980 pp49). The Casa de Pilatos has four courtyards, namely, the entry-patio and Main-Patio which are paved with clay tiles, and the Grand Garden and Small Garden which are garden-courtyards. The gardens-courtyards use water fountains and pools to create a cool atmosphere, similar to 'oasis effect' in the midst of intense heat of hot and dry summers. It is believed that the enclosed and inward looking spaces in this building uses multiple-courtyards to control the amount of heat that is gained and lost during the day.

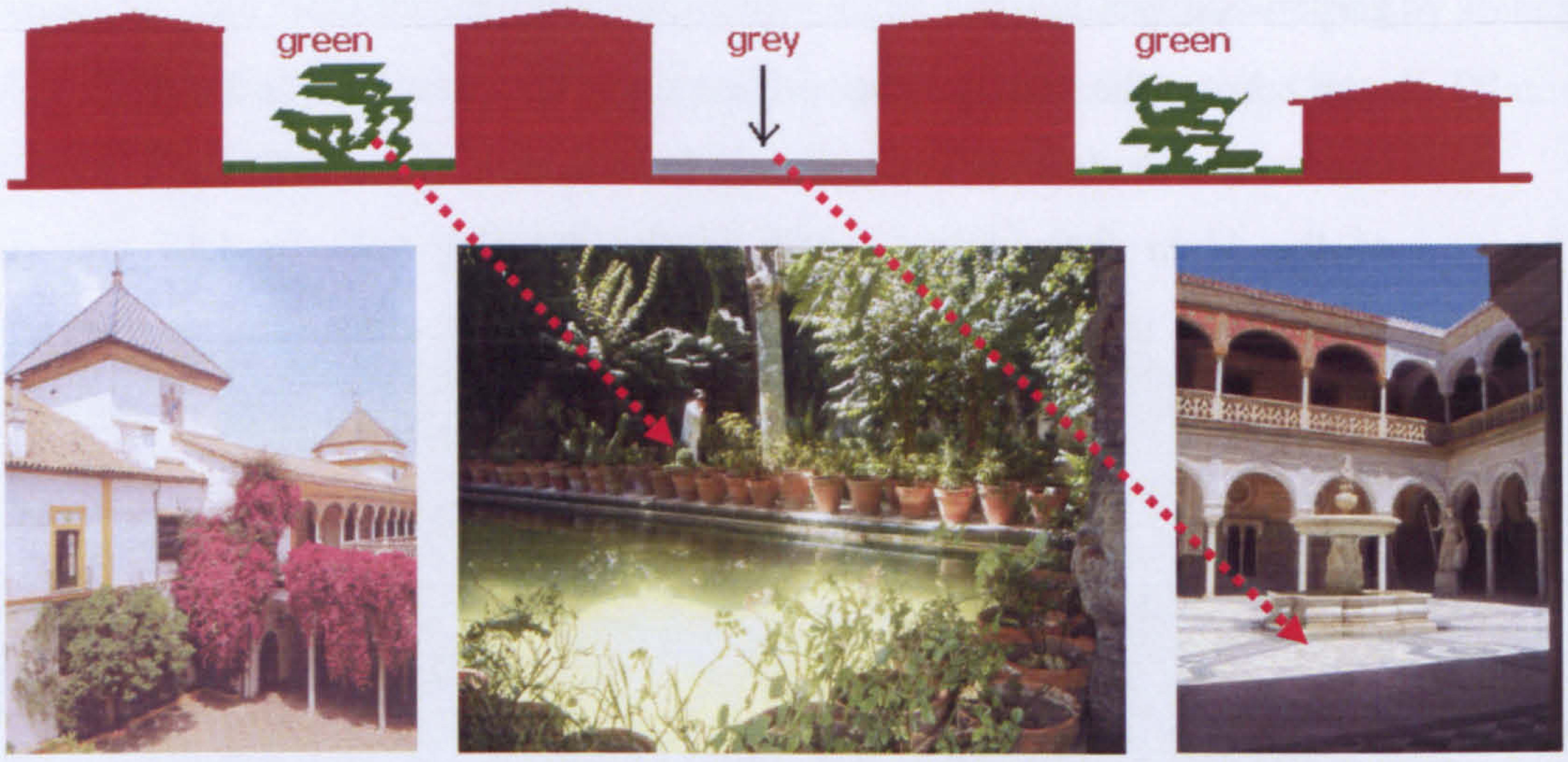


Fig. 4.21 (left) entry-patio, (middle) Small Garden, and (right) Main Patio in the Casa de Pilatos; Source: (left) Leaflet of Medinaceli Foundation

The Main-Patio is exposed to a significant amount of solar radiation (fig.4.19 – fig.4.22). This includes direct component 'sunshine' that falls directly on all un-shaded surfaces with a direct view of the sun, as well as the diffuse component from visible sky (skylight). Exposure to intense solar radiation creates a significant reflected component among surfaces of the main-patio in Casa de Pilatos. The flux of heat from its surfaces causes air to rise as it becomes less dense due to rising temperatures. It is predicted that in this process buoyant air leaves the main-patio and air from garden-courtyards is driven across transitional spaces replacing a vacuum created by escaped hot air. This process is likely going to intensify in the summer season. (see fig.4.22 and fig.4.23).

Fig. 4.22 Solar radiation and flow of air in the Main-Patio

Moreover, it is also predicted that the environmental conditions in the spaces between courtyards are influenced by the thermal environments in the garden-courtyards and Main-Patio. A conjectural summary of airflows is shown in figure 4.21 – 4.22 consider the pattern of shades and shadows in the building. Thermal dynamics in the garden-courtyards are less strong due to shading and lower temperatures. In the hypothetical patterns shown in fig.4.24, Flow-A suggests that airflow is induced by temperature difference, while Flow-B is influenced by strong re-circulating vortex in the Main Patio compared to garden-courtyard. It is conjectured that, convective flows in this building would arise from temperature differences.

Fig. 4.23 A sketch section illustrating the flow of air due to temperature differences in courtyards of Casa de Pilatos

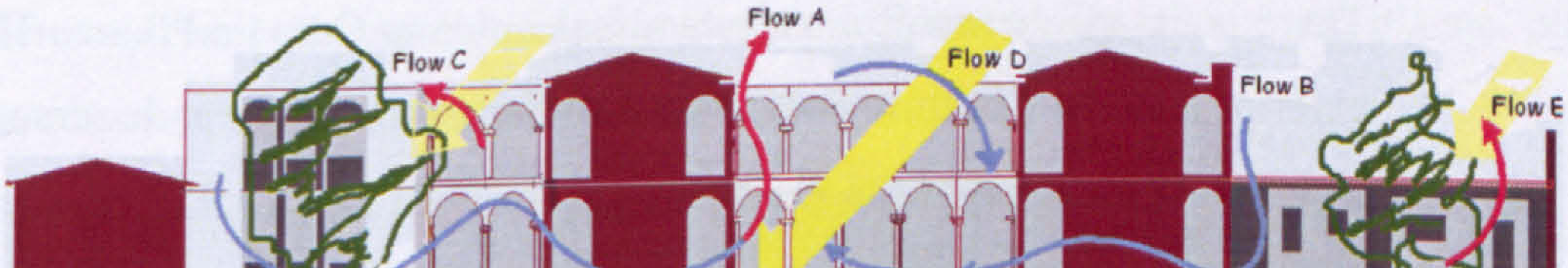


Fig. 4.24 A summary of the thermodynamics of buoyancy flows due to sun heat

4.4.5 Transitional spaces

The Hall of Columns and Praetor Chamber are the main transitional spaces existing on the ground floor between the courtyards in Casa de Pilatos. These spaces are accessed directly from the Main Patio and have openings giving access to the garden-courtyards. As the climate of Southern Spain is typically characterized by extreme summer heat, the opening between these transitional spaces and the garden-courtyards with vegetation and water give access to pleasant cool atmosphere when fountains are flowing and trees cast shades and shadows. Social function of these spaces is also emphasized by interior designs, especially their impressive ceramic tile-work on walls and broad elaborate carved wood on their ceilings. These spaces make a visual declaration of owner's wealth and status. Their location and choice of decoration makes suggests that through them the host did intend to convey a message of social significance.

Seats are strategically built-in all window openings in the Hall of Columns and Praetor Chamber. In an environmental with large diurnal temperature variations, the thermal conditions in these spaces would also benefit from the 'time lag' introduced by 900mm thick walls. As a result, the air in these transitional spaces would warm up much slower than outside air, providing occupants with pleasant indoor spaces in the midst of extremes summer season. It is anticipated that the micro-climate in the window spaces is influenced by a breeze of cool air from garden-courtyards due to temperature differences between garden-courtyards and the Main-Patio.

4.4.6 Arcades & balconies

There is extensive use of arcades and balconies in Casa de Pilatos. They are among the exterior features that form part of the building character. Arcades are semi-outdoor space and thus shade most of the functional spaces from direct solar radiation. The Main-Patio is wholly surrounded by arcade, with Hall of Columns and Praetor Chamber having arcades in their front and rear facades facing the Main-Patio and garden-courtyards respectively. It is likely that presence of arcade on the ground floor of the Casa de Pilatos has impacted temperature as well as thermal convection of air. It is anticipated that transitional spaces use arcades as a buffer against the conditions in the courtyards (fig.4.25).

Fig. 4.25 View of arcades, towers, and balconies in the Casa de Pilatos, Source: www.exploreseville.com

4.4.7 The garden-courtyards

Garden courtyards are outstanding feature in the Casa de Pilatos (see fig.4.26). It is where fruit trees and fragrant plants were planted in the Moorish period. Plants have variable cooling effects depending on evapotranspiration process, shading and local wind regime. Refreshing coolness and humidity in the garden-courtyards is compatible with Spanish hot and dry summer season. Large parts of garden-courtyards in Casa de Pilatos were devoted to fruit trees mostly being orange trees. However, historical account has shown that these gardens are not currently in a state they used to be. Villers-Stuart (1994) has shown that a lot of replanting has taken place to gardens in post-Moorish period, citing example of the Alcazar. Irrigation systems in the garden-courtyards were also significantly altered in the Christian Spain. The performance of garden-courtyards in semi arid climates is influenced by choice of plants, plants' irrigation system and airflow characteristics.

Fig. 4.26 (Left) the grand-garden, (right) the verandah connecting the Hall of Columns to the grand-garden in the Casa de Pilatos, Source: (left) the leaflet of Medinaceli Foundation

In general, it is unlikely for summer temperature in the Southern Spain to remain within favourable range for most plants. In Casa de Pilatos, the plant life is sustained by irrigation system hidden under pathways, with water is turned on between 09:00h in the morning and 17:00h in the evening. According to Scudo (2002) the choice of plants is critical for a balanced climatic influence. Although general effectiveness of vegetation, especially trees in providing coolness is well known, there are very few quantified studies (Sandifer et al 2004). According to Larcher (2003), favourable temperature range for vital functioning of most plants is approximately 5 – 25 ^{0}C. The garden-courtyards provide a space for plants' life and performance to benefit from low temperature due to the amount of solar radiation being intercepted.

The presence of vegetation creates an environment with low temperatures due to evapotranspiration process. As living machine, plants create cooling effect by turning large amount of energy into latent heat. Cooling potential of vegetation is evident in a study of vines by Sandifer et al (2004), whereas DBT in and below foliage are reduced by 7 – 10^{0}C.The difference in the mean radiant temperature (MRT) in shaded and none shaded surfaces in built spaces can be significant (up to 30^{0}C), as compared to difference in air temperatures which is as low as 1^{0}C. The multiple-courtyards strategy suggests that garden-courtyard is a place where building microclimate is used to promote human comfort.

The garden-courtyards are used to limit the exposure to solar radiation. According to Roaf et al, (2007) a well shaded and properly contained garden with walls around it can lower air temperature by 2–5 ^{0}C in hot dry climates. The Moorish architecture inherited the strong Arabic tradition of enclosing nature as a private interior garden full of trees, shrubs, flowers and fountains. Moreover, they designed white towns with narrow streets to shade from solar radiation and avoid direct exposure to maritime hot and dry air currents. Despite the requirement for shading from intense solar radiation in the summer, garden-courtyards have also responded to local wind regime.

The garden-courtyard is a feature that has also considered the local wind regime. Jones (1992 pp123) observed that as air moisture decreases, vegetation becomes more sensitive to increased wind speed. This explains the significance of courtyard's envelope in Casa de Pilatos. Exposure to air movement increases sensible heat exchange between plants foliage and atmosphere, hence increasing leaf surface temperature and reduce impact of evaporative cooling. Courtyards are used to reduce air movement as vapour transport is further reduced within plant foliage. The garden-courtyard in the Casa de Pilatos presents an environment in which air movement is attenuated and radiant cooling is accentuated through dense plant foliage. This study suggests that the garden-courtyards are part of the strategy to isolate hot and dry summer winds prevailing from southwest.

4.5 Conclusion

This chapter presented the environment and context to be investigated in this study. The climate and history of the Southern Spain and the city of Seville is analysed together with the architectural heritage entitled Moorish architecture. The discussion of the relationship between building and climate has used the Casa de Pilatos as a building which represents Moorish attempt to design with climate. Casa de Pilatos was conceived in the period when buildings heavily relied on passive heating and cooling. It is shown that Moorish architecture in hot and dry climates relied on microclimates which were created in multiple-courtyards buildings.

The features of interest within the Casa de Pilatos were also discussed in detail, particularly are the living patterns and environmental design features in this building. Of more significance were the impact of direct solar radiation and radiant cooling from vegetation, fountains, and surfaces on thermal environment in Casa de Pilatos. It has been suggested that latent heat of vaporisation from vegetations and water fountains has an important part on the conditions to be experienced in garden-courtyards. It is also conjectured that solar penetration, shading, and evaporative cooling are among the criteria which have informed the choice of vegetation. Furthermore, it is also suggested that thermal environments in multiple-courtyards of Casa de Pilatos produced the desirable micro-climates.

Yard-to-yard concept is presented together with some aspects of thermal environment which have influenced the dynamics in the convective movement of air through transitional spaces. The temperature difference between courtyards is the key feature in multiple-courtyard strategy. It is conjectured that the convective flow of air between courtyards of this building is a result of temperature differences. It is also suggested that hot air rising from Main-Patio has a significant role of driving airflow through intermediate spaces. These hypotheses will be tested through fieldwork and theoretical modelling in the succeeding chapters. The results from field investigation of Casa de Pilatos are presented in the next chapter.

CHAPTER FIVE: FIELDWORK

5.1 Introduction

This chapter presents the fieldwork data recorded at the Casa de Pilatos, Seville, Spain between 11th and 19th August 2008. The aim of the fieldwork was to collect climatic and physical data from the building's courtyards and transitional spaces. The primary data recorded during field studies are air temperatures, relative humidity, and air velocity. The collected data are used to determine the drivers for yard-to-yard airflows, convective cooling, and thermal comfort in chapter six. A record of DBTs was important because it is conjectured that yard-to-yard temperature differences are the driver for air convection through transitional spaces. A record of air moisture (humidity) and velocity will be used to estimate the amount of convective cooling attributed to yard-to-yard airflows. The period of measurement is limited by resources and accessibility to a very popular tourist site. Surface temperatures are also taken to help to assess the impact of the thermal properties of vegetation and building surfaces.

The chapter starts by explaining the set up and location of recording instruments. Then the results and description of field data is presented. Lastly, the data are correlated with meteorological data.

5.2 Set-up and Location of Instruments

The data which is primarily produced from fieldwork includes air temperature (DBT), relative humidity (RH), and air speeds. These data are collected around 24 hours of the day for one week. Experimental set up (shown in fig.5.1 – 5.9) is conducted by using various data recording instruments. The choice of field instrument focused on their ability to provide a continuous record of data. The data loggers (tiny-tags and tiny-talks) are used to record temperatures and relative humidity, and air velocity transducers 'anemometers' for air velocity. These anemometers are connected to a data logging instrument 'data taker dt500' and laptop computer. The 'delogger' software is used for continuously record of data from dt500. All the collected data are summarized into hourly data.

The collected data is limited by the number of available data loggers (see Appendix II). Two anemometers were shared between the Roof-Top, the Hall of Columns and the Praetor Chamber. 'Gemini' data loggers 'tiny-tags' were used to provide a continuous record of air temperatures (DBT) and relative humidity (RH) from six locations. The accuracy of all instruments ranged between 1–3%. The monitoring process is stopped for up to one hour at times in order to download the recorded data. This was necessary to limit the loss of data.

The instrument set up considered a number of issues. In order to avoid excessive moisture from the fountain in the middle of the Main Patio, the data logger are stationed about six metres from the water fountain and four metres from the arcade boundary (see fig.5.1). The instruments in the garden-courtyards (Grand Garden and Small Garden) are also set up to avoid fountains.

Data loggers for air temperature (DBT) and relative humidity (RH) are suspended on a mast at the height of at least 1.5 meters from the ground. Moreover, the sensors are oriented to avoid direct radiation from ground or floor surfaces. The data loggers 'tiny-tags' are protected by using cardboard sheets to avoid direct solar radiation (fig.5.9).

It is also important to note that the recording instruments in the Hall of Columns and Praetor Chamber are not stationed in the middle of the spaces. It was agreed with the building administrators that the instruments are stationed near the inlet windows for safety of visitors (see fig.5.4 and fig.5.5). This was also necessary step for the security of the instruments since the building is open to tourists and public.

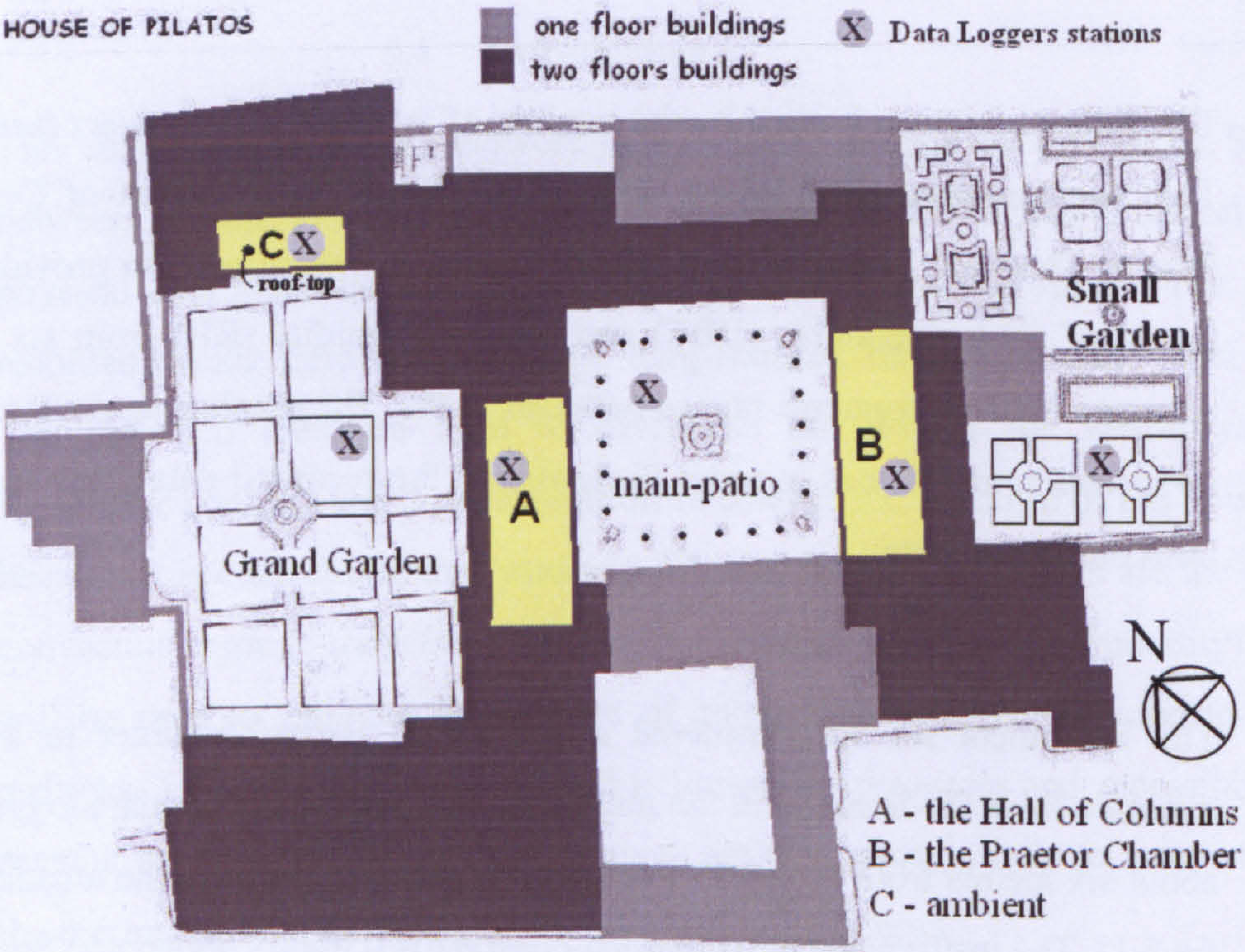


Fig. 5.1 Location of set up data recording instruments 'X' and air velocity anemometers 'A, B, and C'

Fig. 5.2 The entrance to the Hall of Columns with the openings facing the main-patio and

Fig. 5.3 the façade of the Hall of Columns showing the only window overlooking the Grand Garden

Fig. 5.4 Data recording equipment located at the window within the Hall of Columns

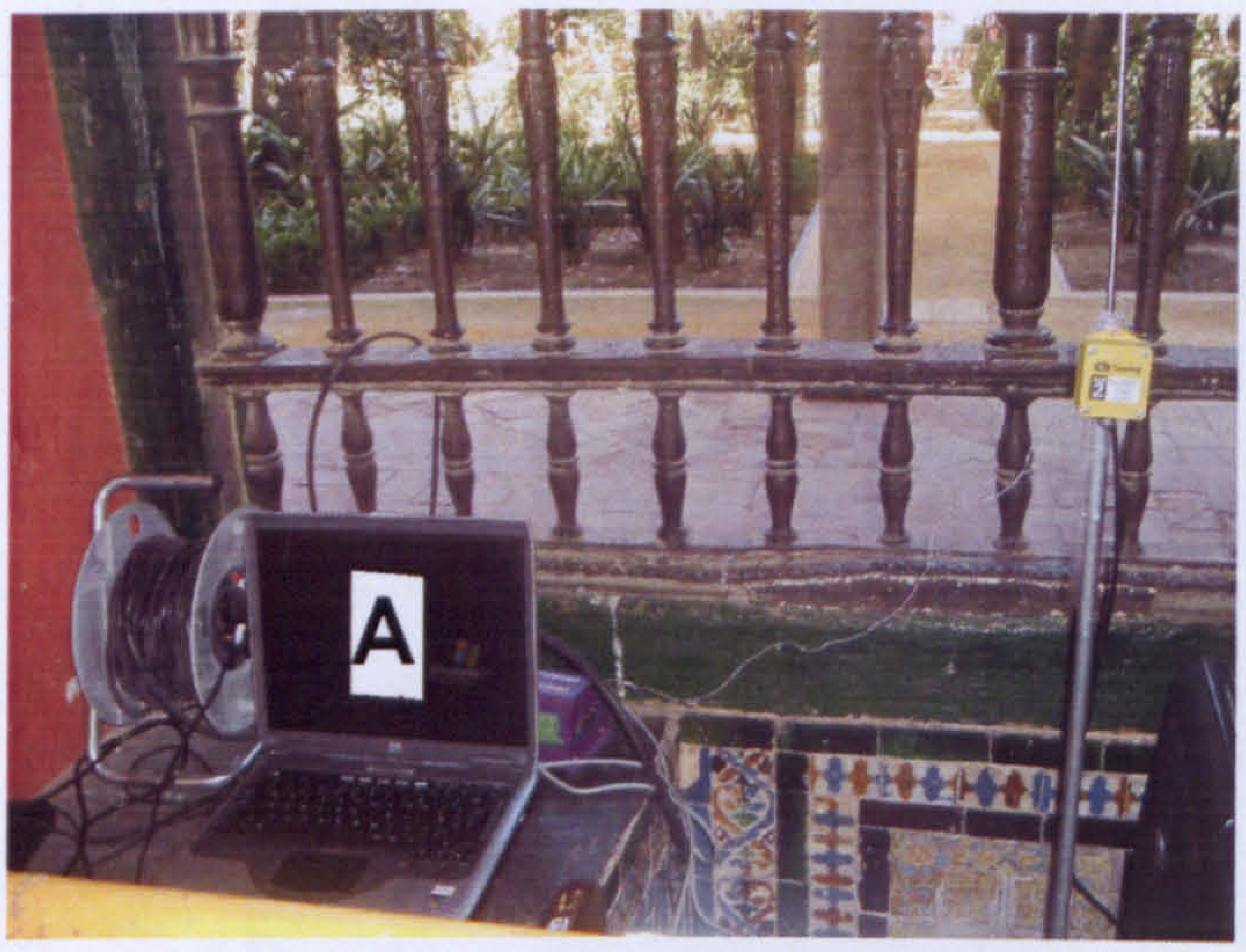


Fig. 5.5 equipment set-up at the inlet to the Hall of Columns

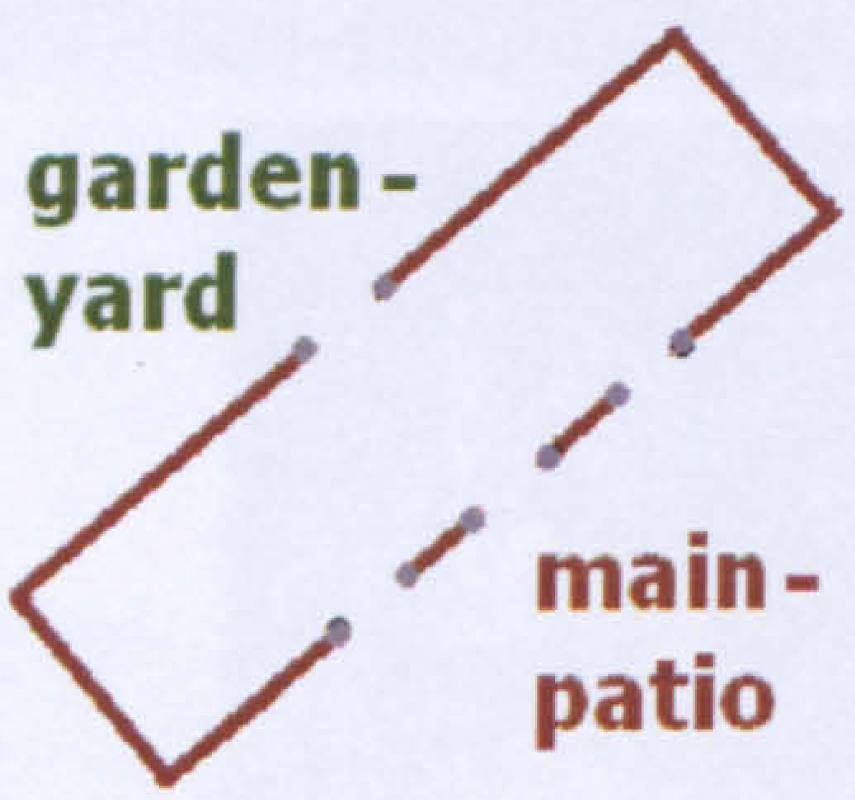


Fig. 5.6 The sketch drawing showing the location of openings in the Hall of Columns and Praetor Chamber

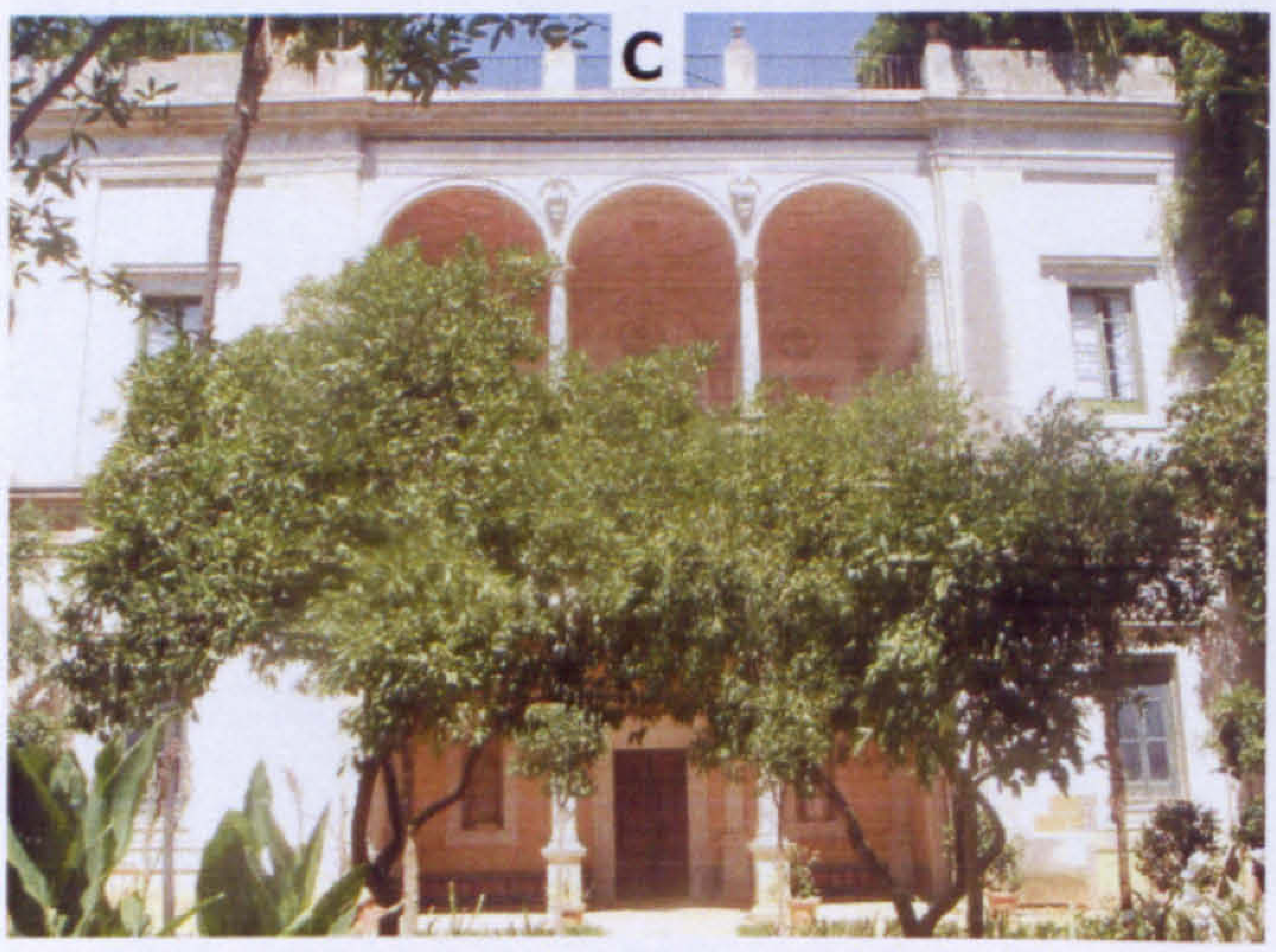


Fig. 5.7 the view from the Grand Garden showing the location 'C' where Roof Top data were recorded

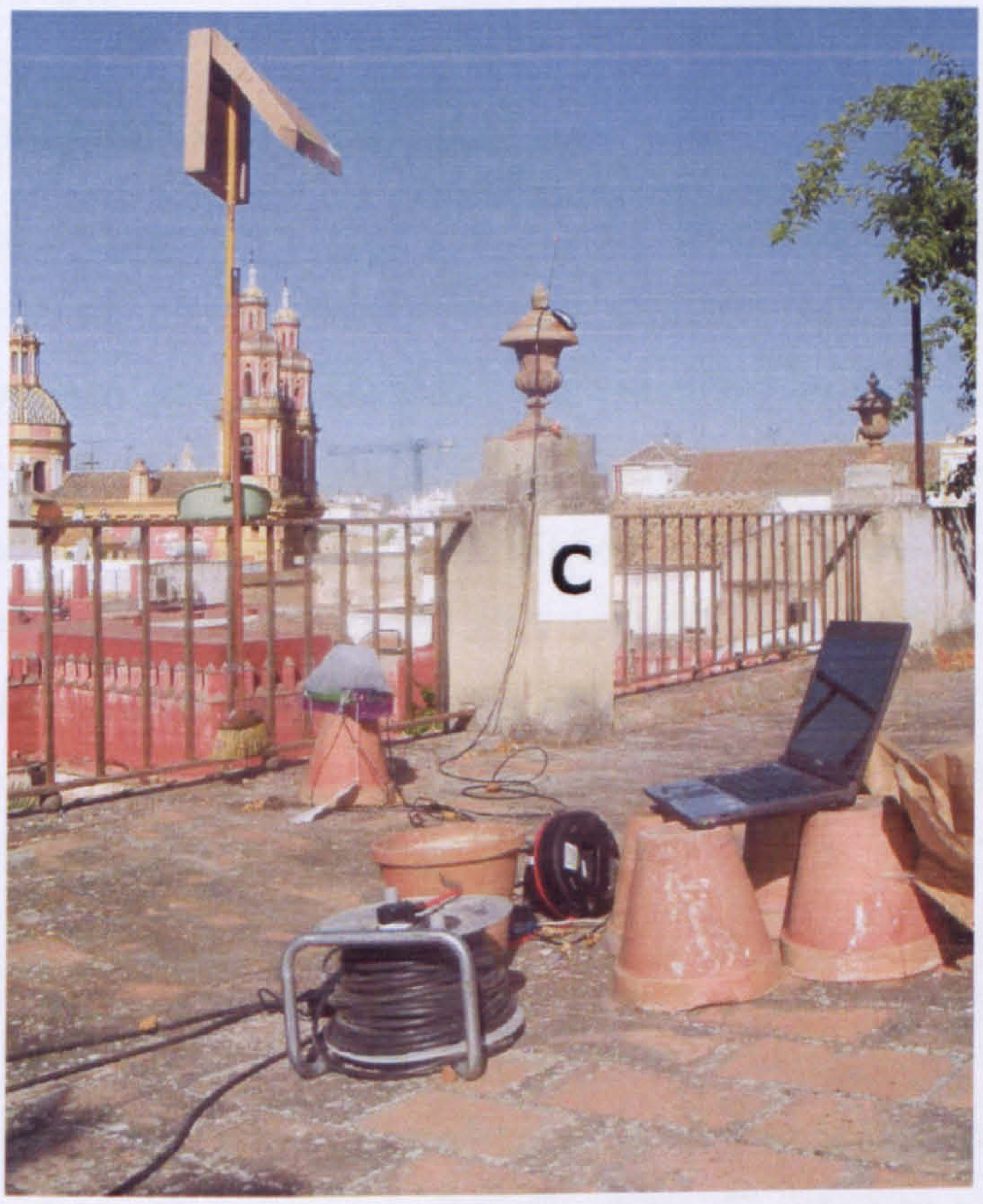


Fig. 5.8 equipment set-up at the Roof Top

Fig. 5.9 Set-up of data loggers and cardboard cover against direct and indirect solar radiation

5.3 Results and description of field data

5.3.1 Air temperature & Relative humidity

The primarily collected data are air temperature (DBT) and relative humidity (RH). These data are taken in six locations namely; Grand Garden, Main Patio, Praetor Chamber, Roof Top, Hall of Columns, and Small Garden. The range of temperature recorded in these spaces varies between 19^{0}C and 48^{0}C. The lowest temperatures are recorded at the Roof-Top at 06:00h (see fig.5.13), while the highest temperatures are recorded in the Main-Patio at 13:00h (see fig.5.12). On the other hand, the range of air moisture (humidity) varies between 9% RH and 77% RH. The lowest is recorded in the Main Patio at 15:00h in the afternoon (see fig.5.12), while the highest is recorded at the Small Garden at 05:00h in the morning (see fig.5.15). An outline of the results is presented in figures (fig.5.10 – fig.5.15).

Unlike the temperature fluctuations recorded in outdoor spaces, stable conditions are observed in the Hall of Columns and Praetor Chamber (fig.5.10 and fig.5.14). There is comparatively less fluctuation of DBT within data collected in these spaces. Unlike the DBT which has maintained the same pattern throughout the week, the RH varies significantly. While RH reaches the maximum of 40% for the days in the beginning of the field period, it increases to as high as 70% in the last two days.

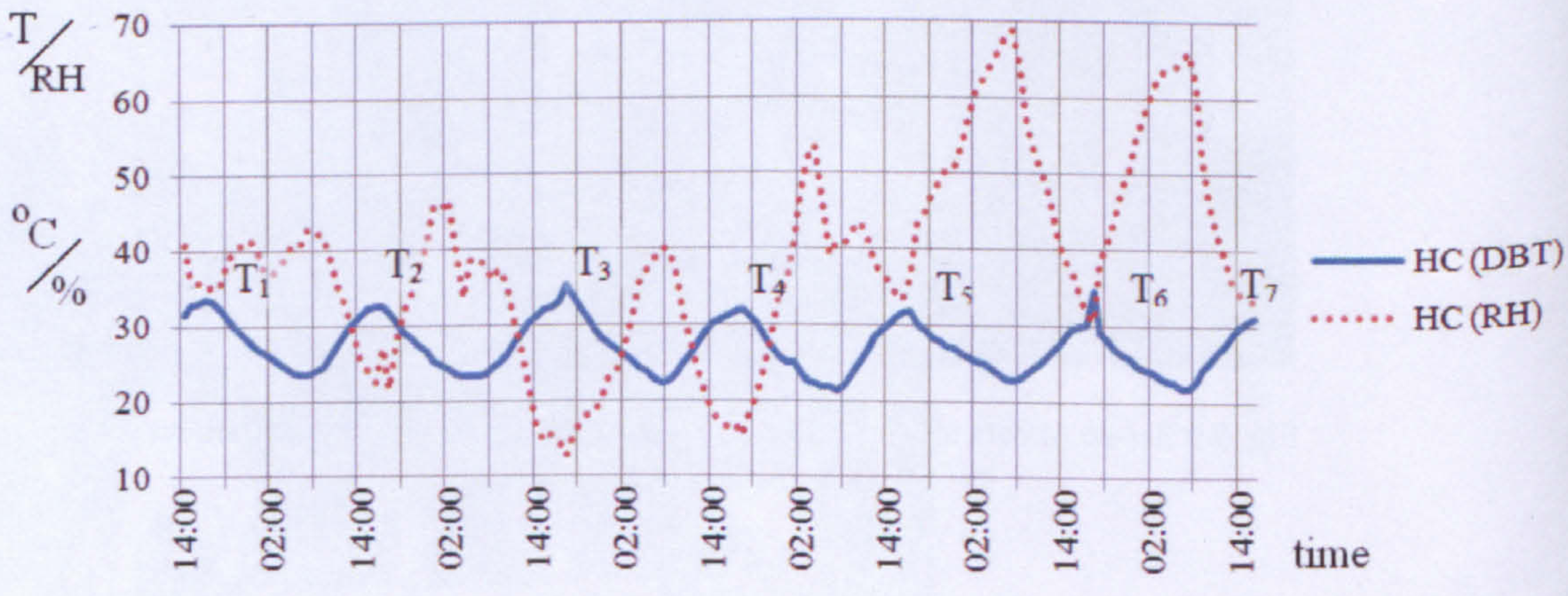


Fig. 5.10 Field data recorded in the Hall of Columns (HC)

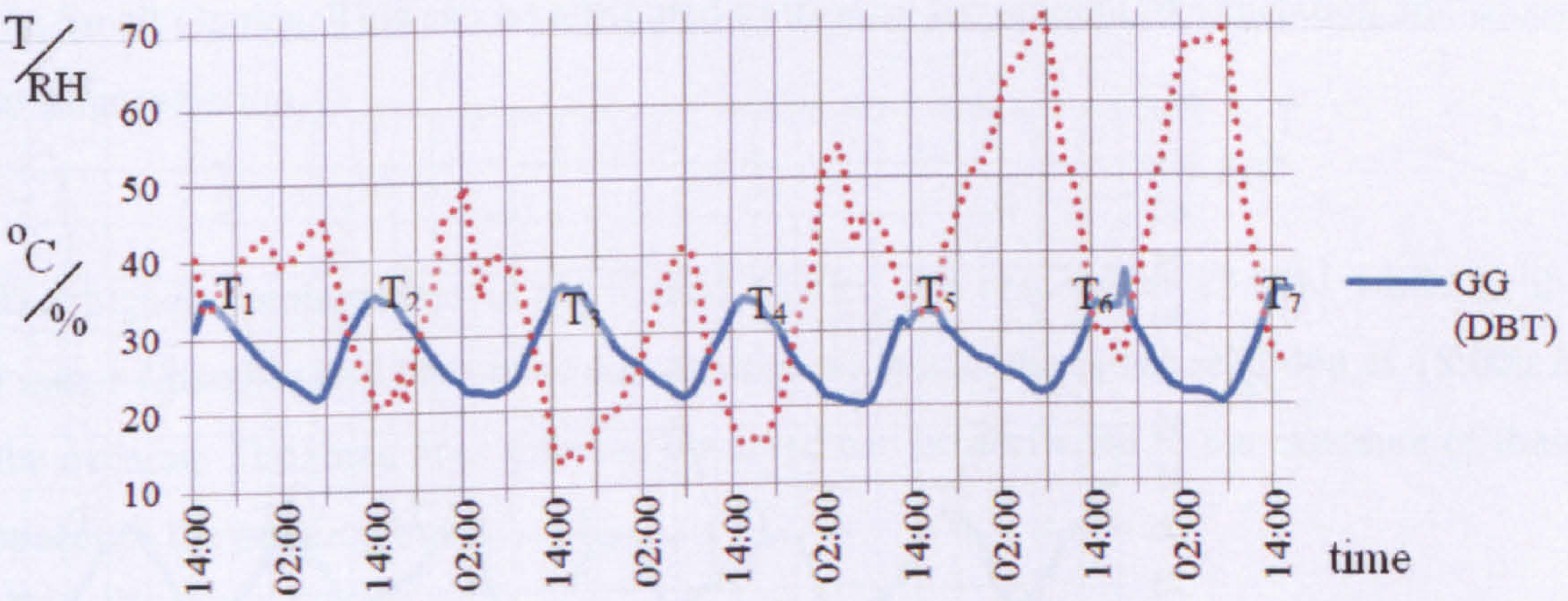


Fig. 5.11 Field data recorded in the Grand Garden (GG)

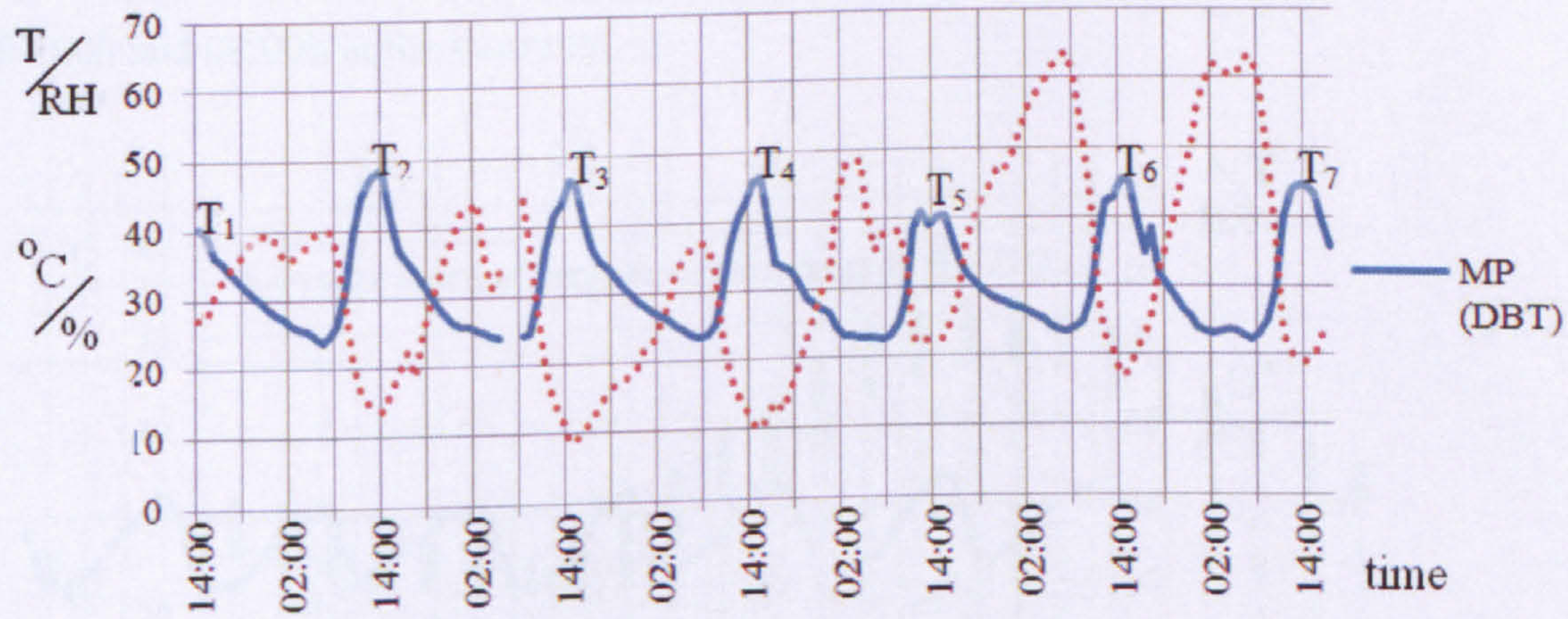


Fig. 5.12 Field data recorded in the Main Patio (MP)

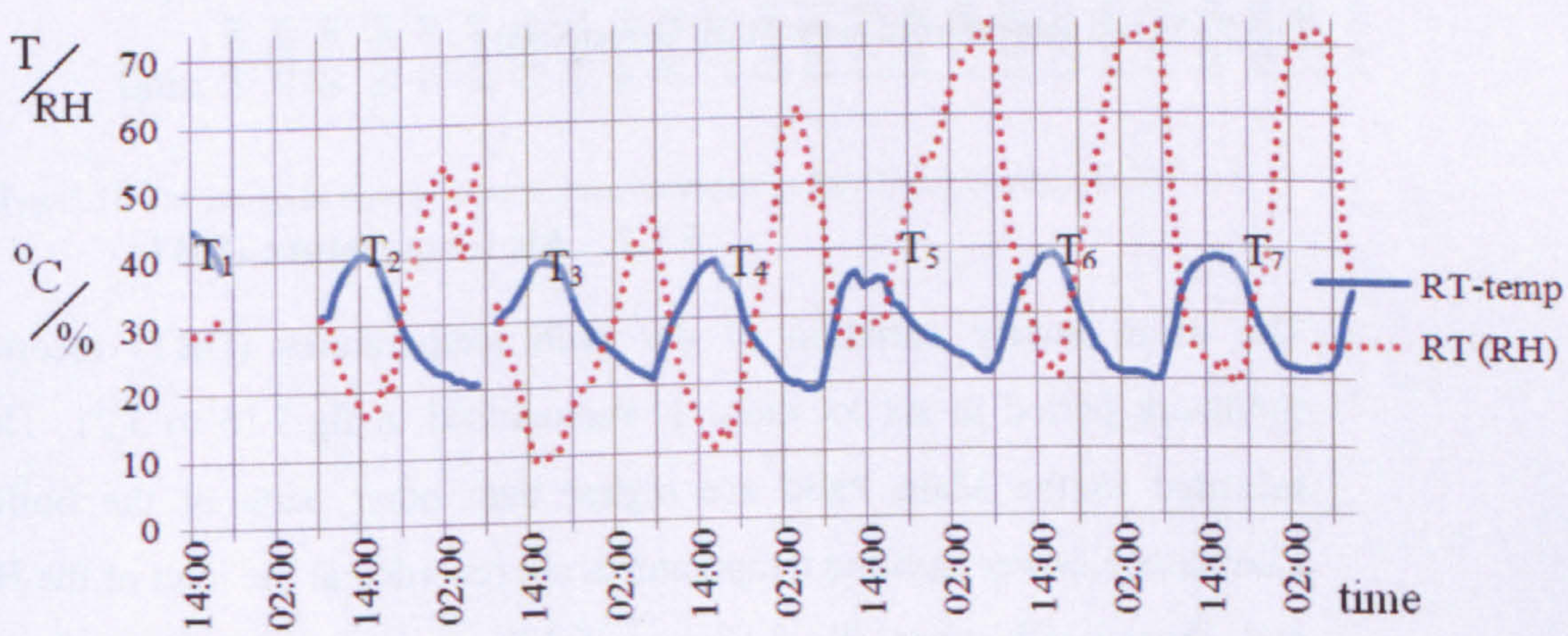


Fig. 5.13 Field data recorded in the Roof Top (RT)

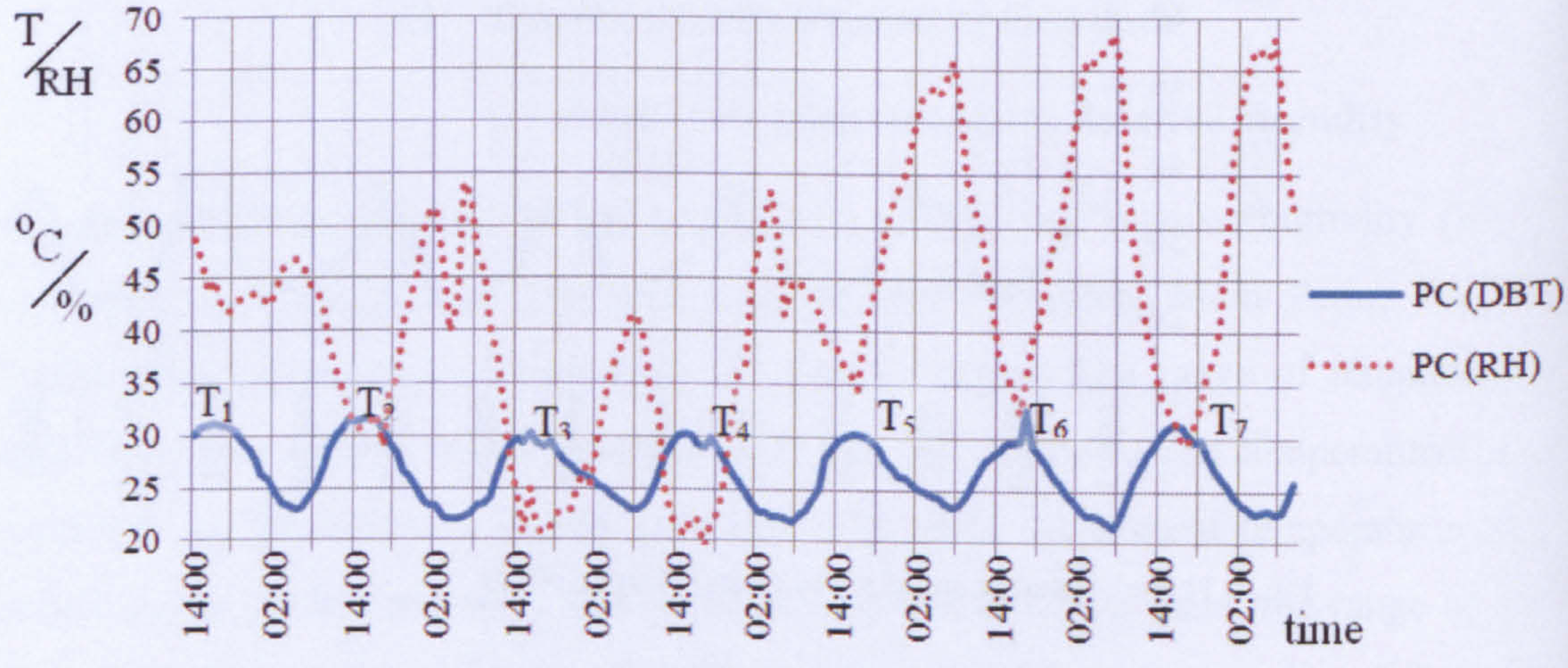


Fig. 5.14 Field data recorded in the Praetor Chamber (PC)

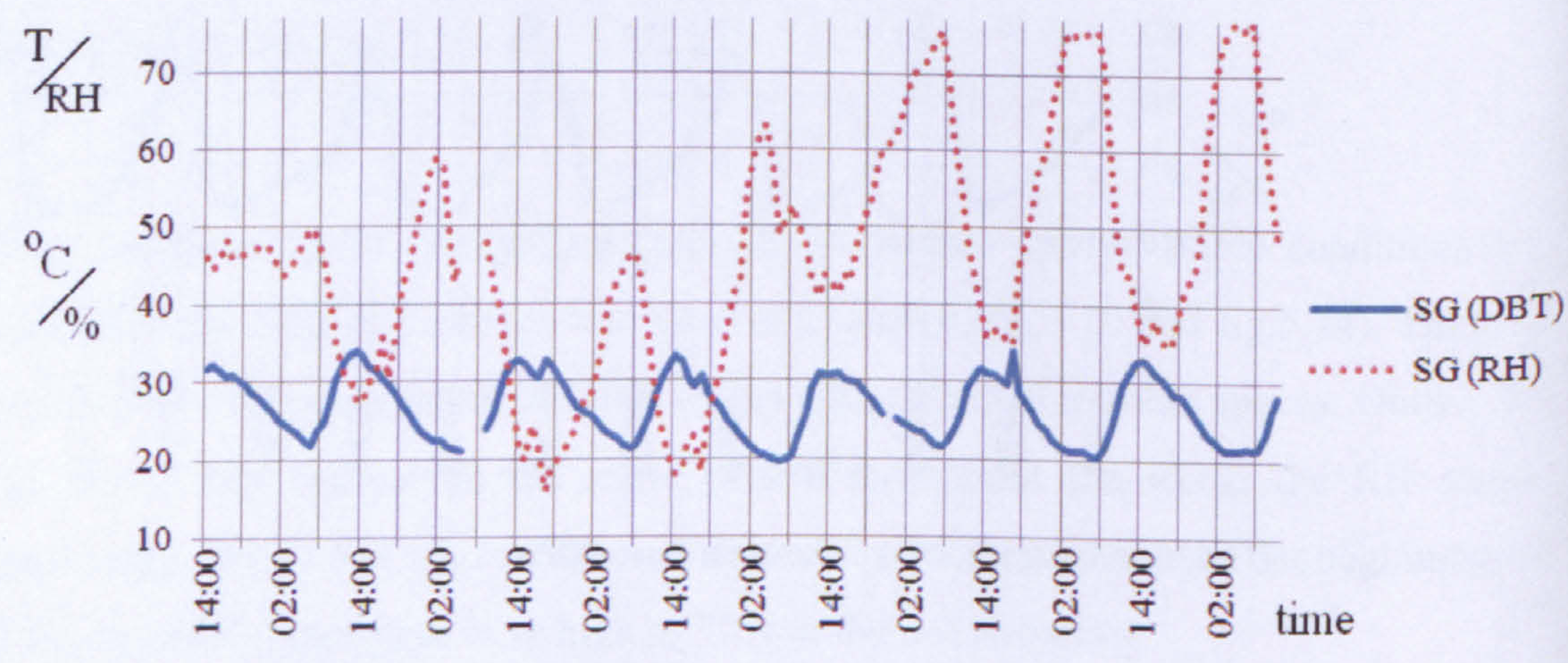


Fig. 5.15 Field data recorded in the Small Garden (SG)

5.3.2 Air temperature (DBT)

The mean hourly variation of dry bulb temperatures (DBT) recorded during the fieldwork period in six locations is summarised in fig.5.16 to 5.21. The temperatures recorded in the Main Patio are higher than other parts of the building (fig.5.18). Conversely, lower daytime temperatures are recorded at the inlet of the Hall of Columns and Praetor Chamber (fig.5.17 and 5.19). It is important to also note that, the temperatures recorded in the middle of the Grand Garden are higher temperatures than the Small Garden. This can be attributed to its size, the amount of vegetation and access to solar radiation.

The highest temperatures in the Grand Garden are reached at 15:00h, while in the Praetor Chamber and Hall of Columns; highest temperatures are recorded at 18:00h in the evening. The three hour time lag observed can be attributed to the exposure of these spaces to the building mass.

The significant hourly variation in the Main Patio is observed between 09:00h and 10:00h, while at the Roof Top, a temperature swing of nearly 10k is observed between 07:00h and 08:00h in the morning.

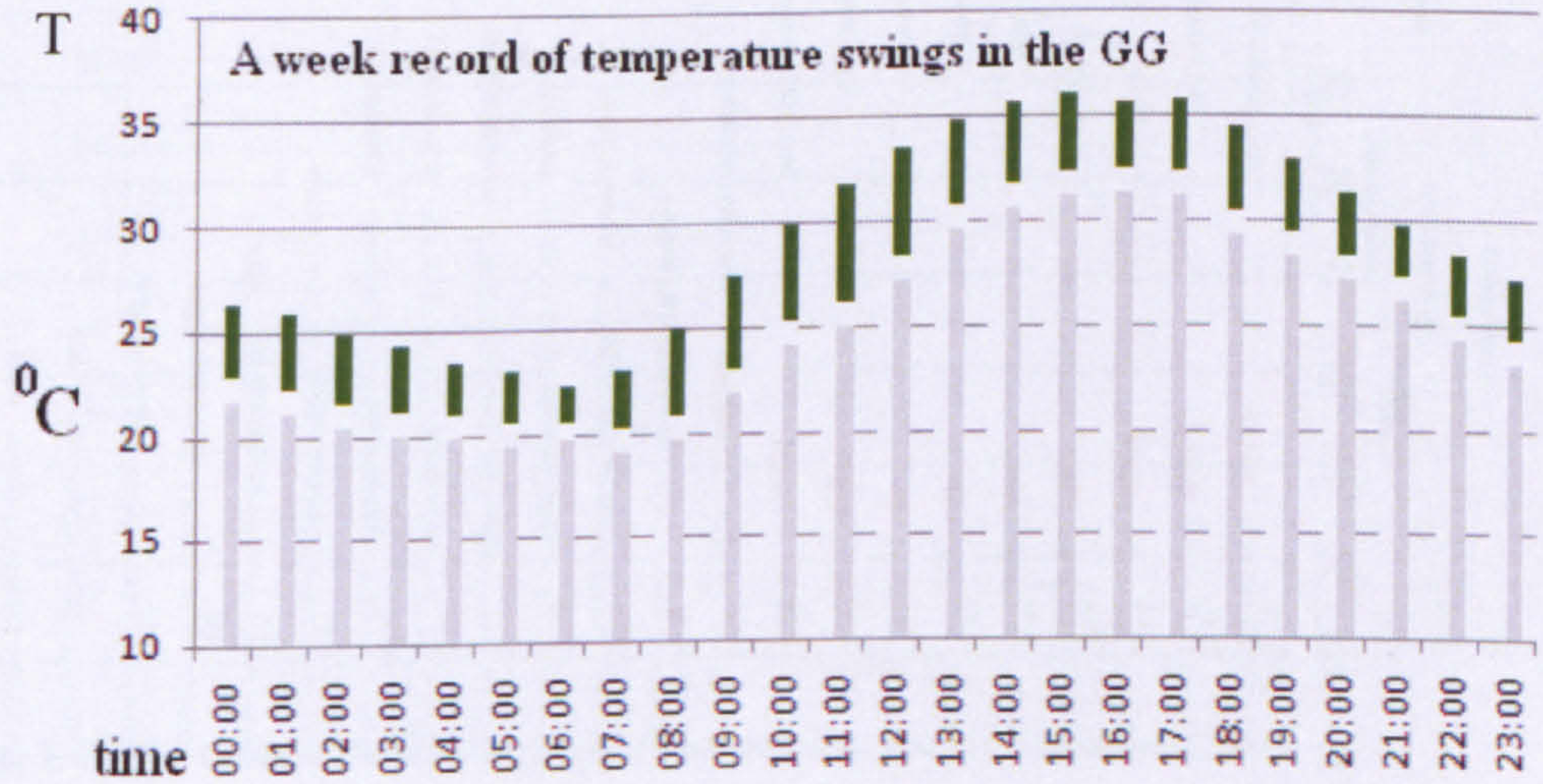


Fig. 5.16 The range of hourly temperature recorded in the Grand Garden (GG)

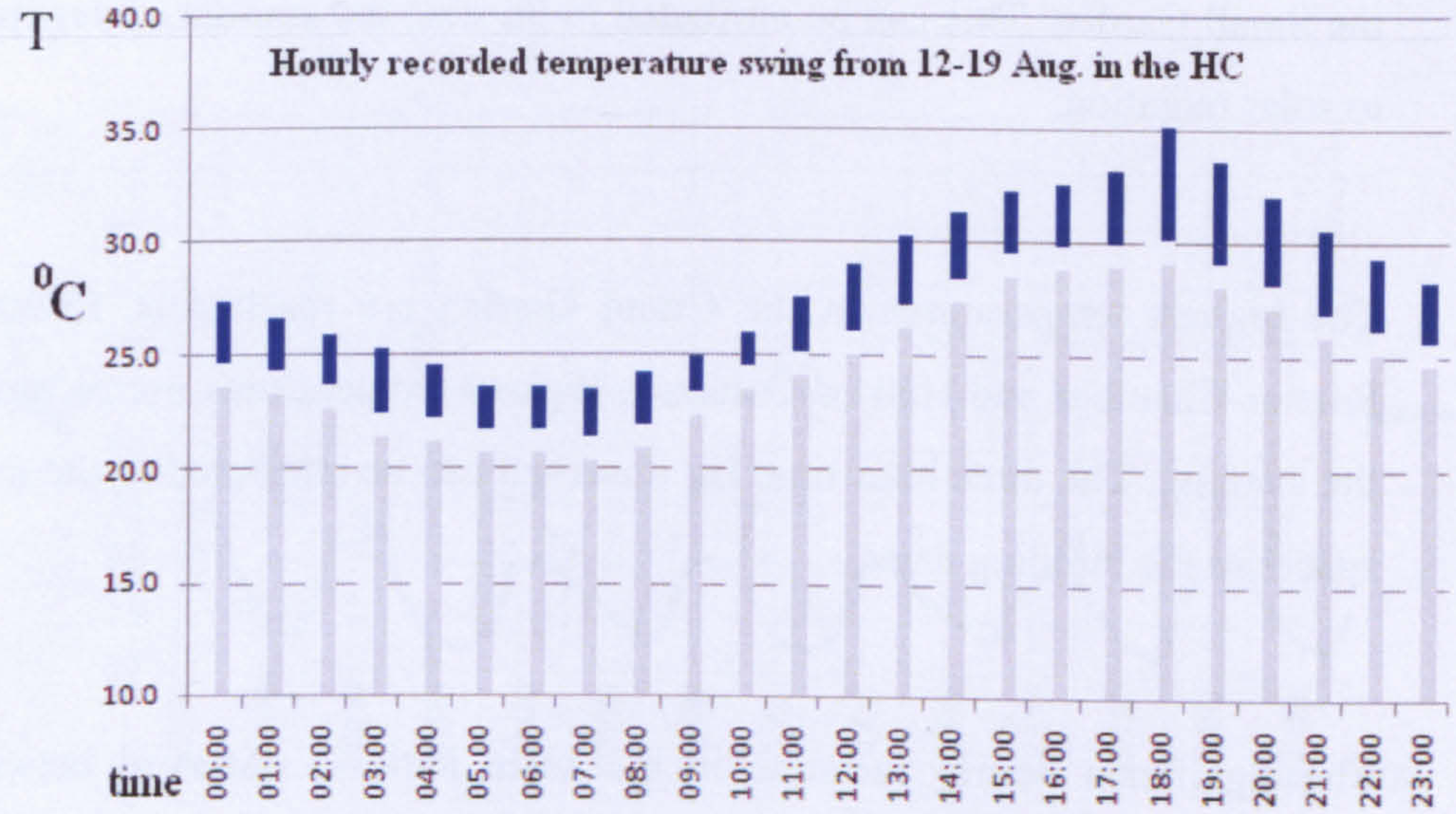


Fig. 5.17 The range of hourly temperature recorded in the Hall of Columns (HC)

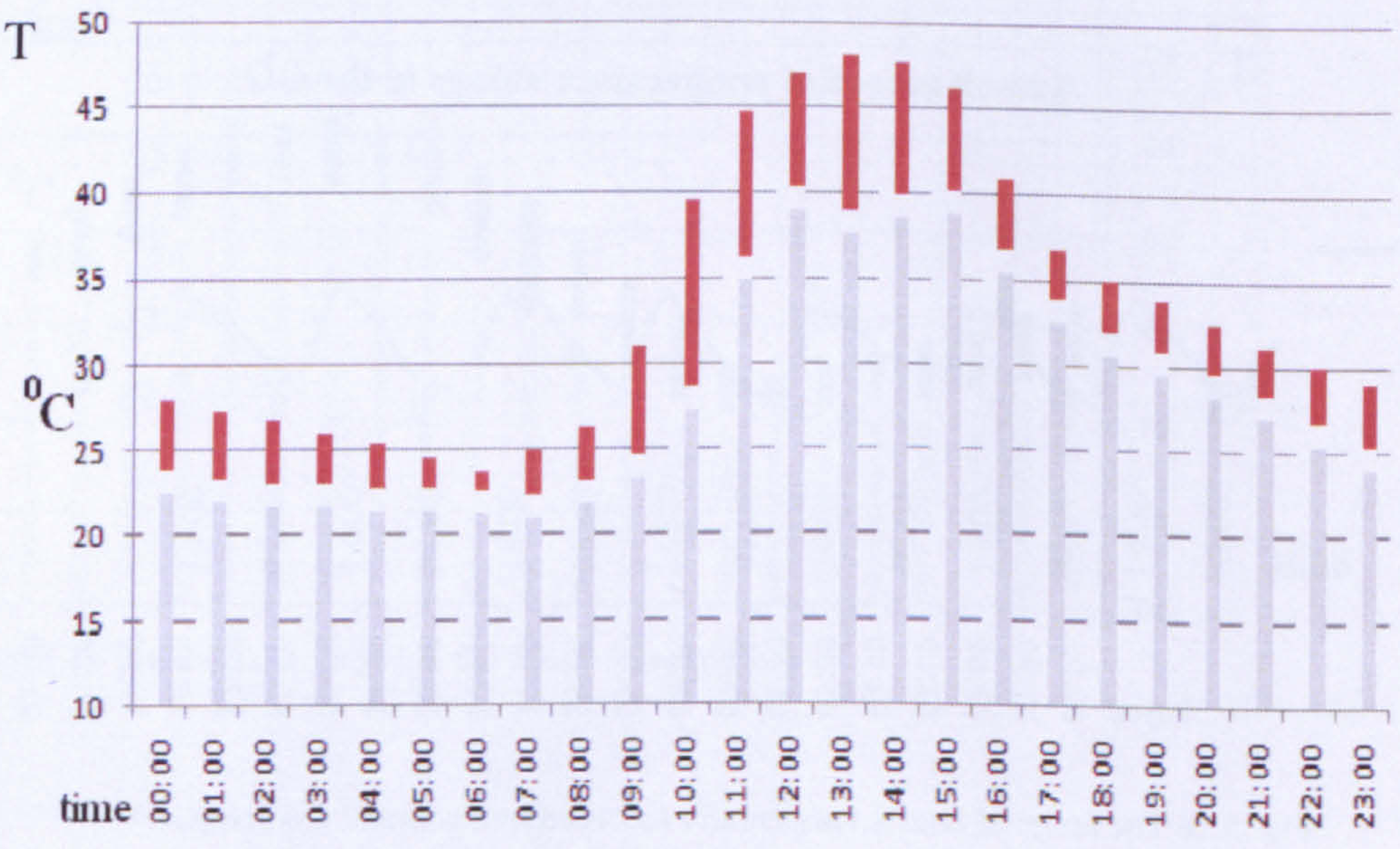


Fig. 5.18 The range of hourly temperature recorded in the Main Patio (MP)

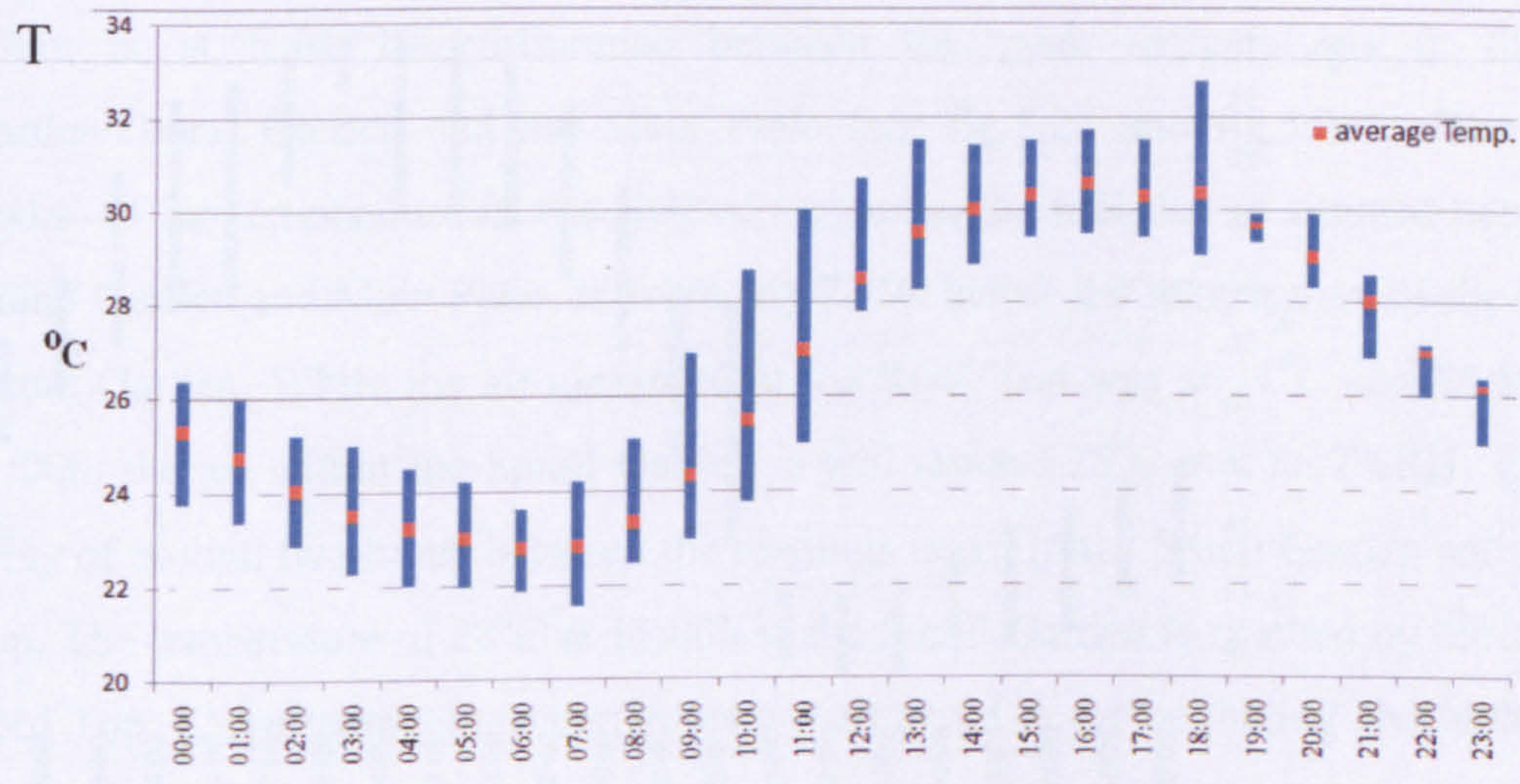


Fig. 5.19 The range of hourly temperature recorded in the Praetor Chamber (PC)

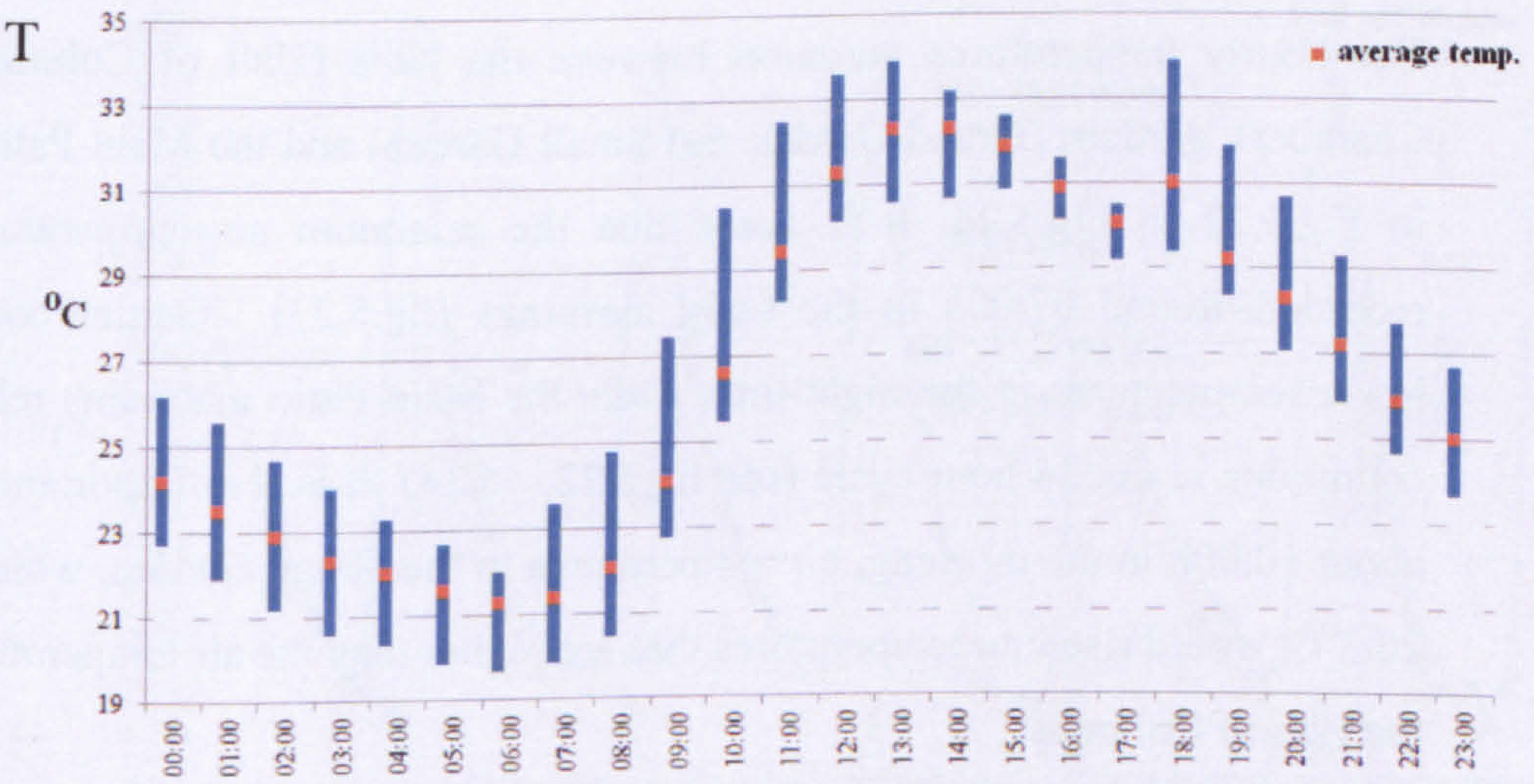


Fig. 5.20 The range of hourly temperature recorded in the Small Garden (SG)

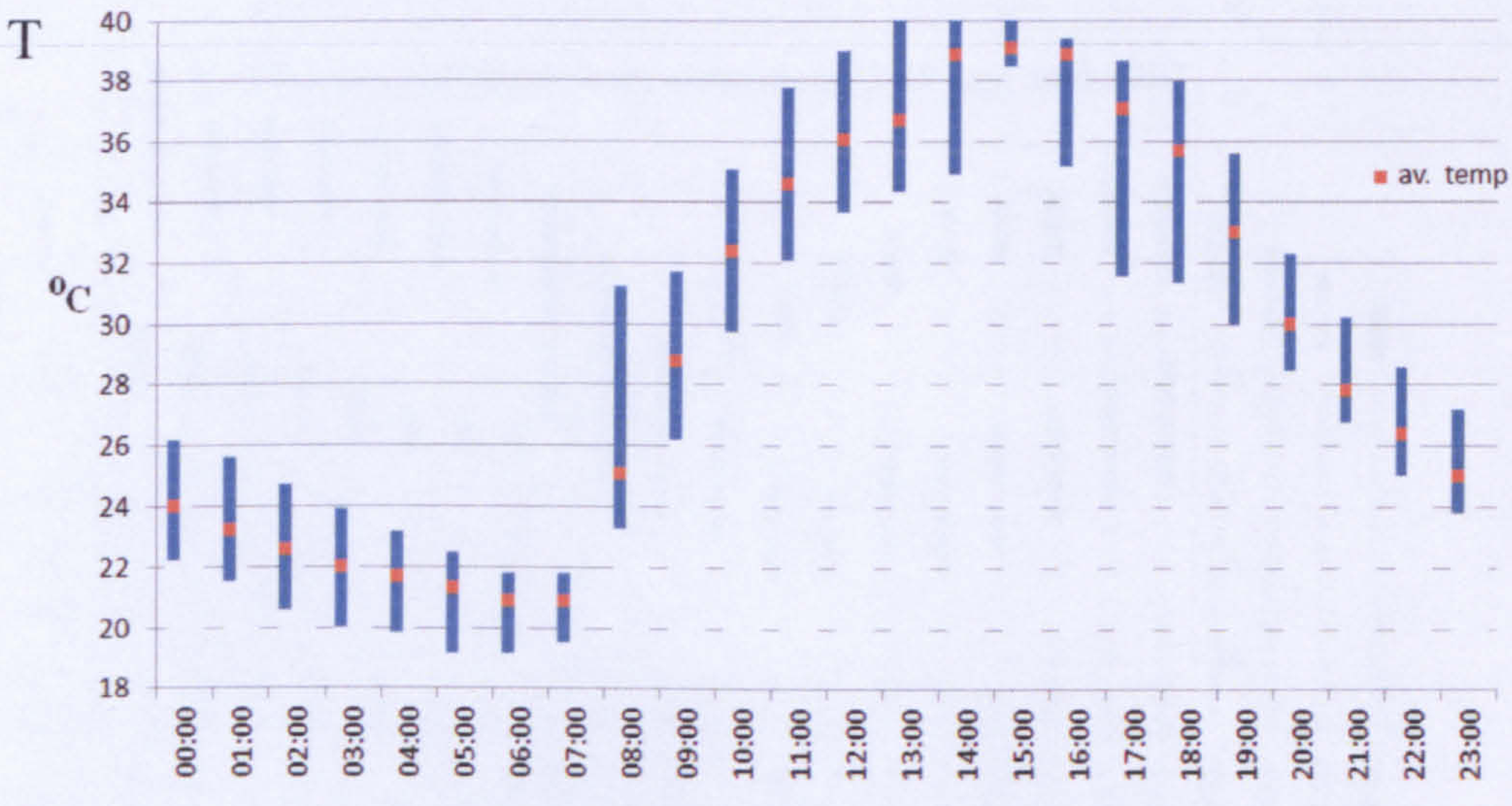


Fig. 5.21 The range of hourly temperature recorded at the Roof Top (RT)

The hourly temperatures variation between the halls (Hall of Columns and Praetor Chamber), gardens (Grand Garden and Small Garden) and the Main-Patio are presented in Fig.5.22 to Fig.5.24. It is noted that the minimum air temperatures (DBT) are recorded around 07:00h in the early mornings (fig.5.23). Garden-courtyards record lower temperatures in the night-time while the Main Patio maintains relatively warmer conditions in the 24 hour cycle (see fig.5.22 – 5.24). It is also important to note that, at about 10:00h in the morning, air temperatures in the Grand Garden, which are as low as 20.3^{0}C, would rise into temperatures that are higher than the air temperatures recorded in the Hall of Columns.

The Main Patio records an average minimum temperature of 23.4^{0}C at night and average peak temperature of 44.6^{0}C during the day (see fig. 5.21 & 5.22). The DBT in the Main Patio remains at least 8K higher than the DBT in the Hall of Columns for at least 5 hours (11:00h – 16:00h). The difference is quickly widening after 11:30h, as the temperature difference widens from 2K to 7K by 12:00h (noon).

There is at least 10k difference between the peak temperatures in the Small Garden/Grand Garden and the Main Patio (see fig.5.22 and fig.5.24). The daytime peaks' of air temperature in the Hall of Columns, the hall that is situated between the Grand Garden and Main Patio, is averagely 2.19k below the temperature of the air in the Grand Garden. While the air measured at the Roof Top was at 31^0C and 38.5%RH by 11:00h, the air within the Small Garden is still around 25^0C and 56.7%RH. There is a delay of around two hours between the readings taken in the Small Garden and the Roof Top. The temperature of 28^0C at 11:00h in the Small Garden is reached by 09:00h at the Roof Top. Large temperature variations are observed in the beginning and at the end of the observation week (see Table 5.1 – 5.3).

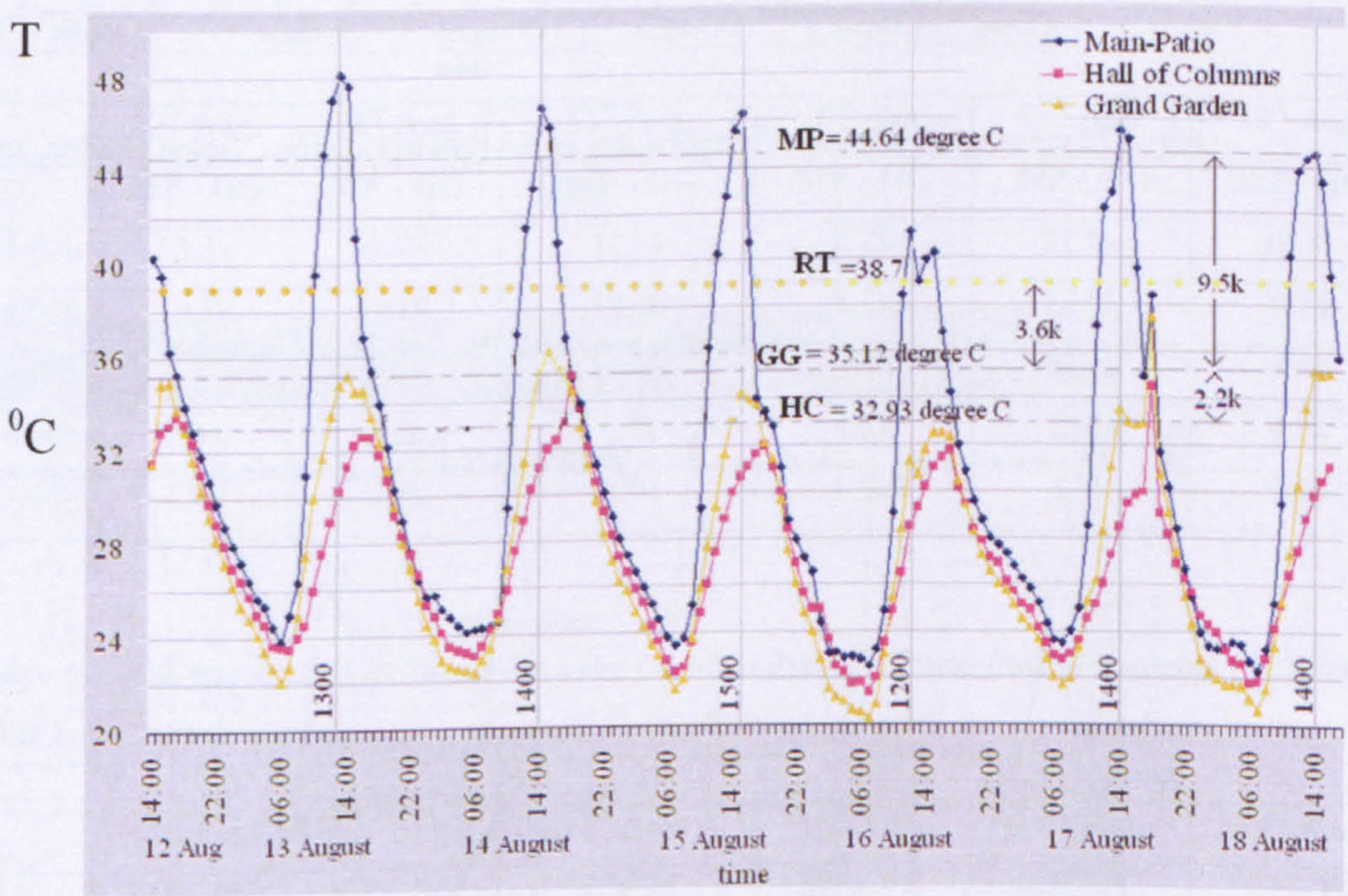


Fig. 5.22 The average of peak temperatures in the cross section of the Grand Garden (GG), Hall of Columns (HC), Main Patio (MP) and Roof Top (RT)

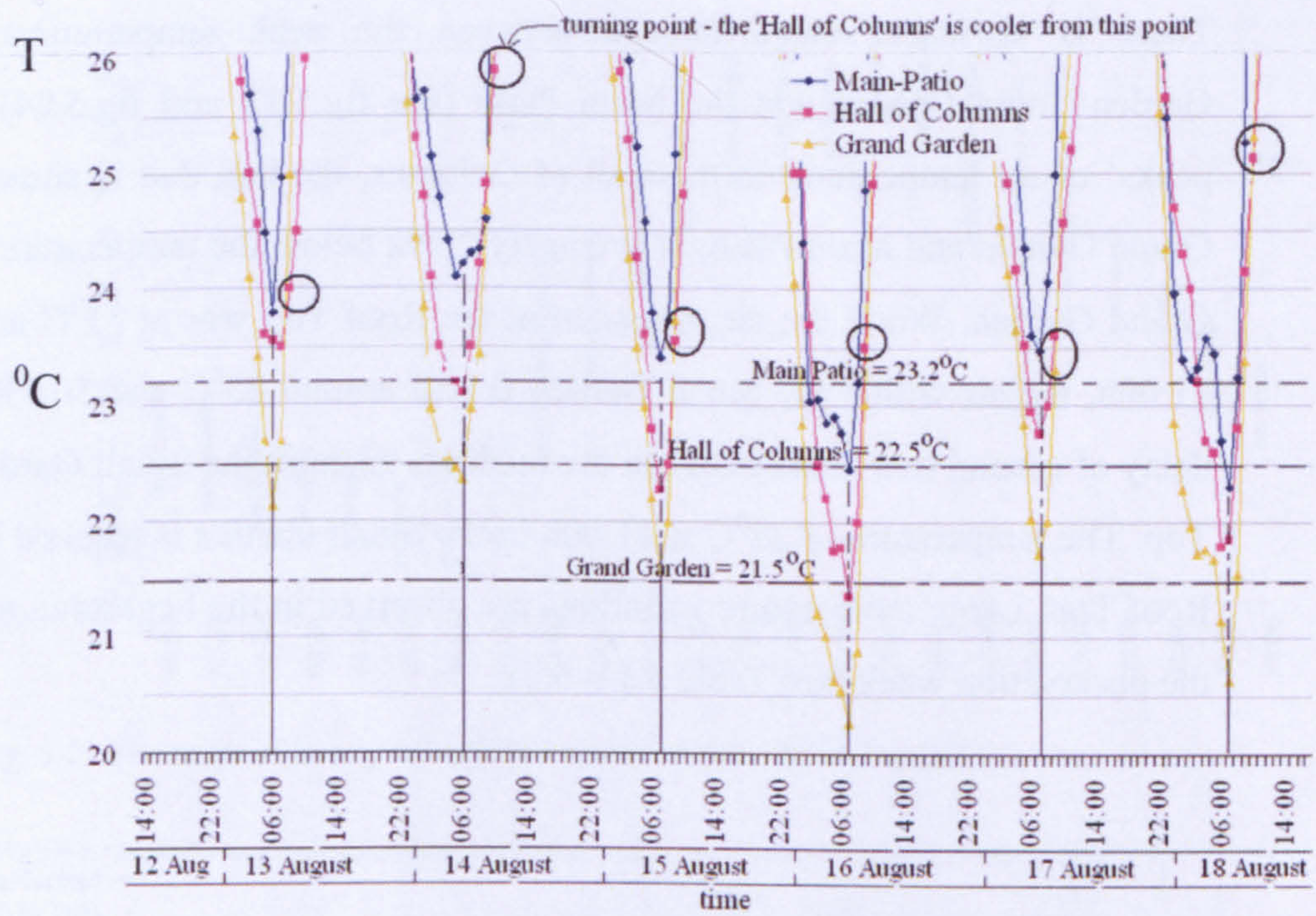


Fig. 5.23 the average minimum temperatures in the Hall of Columns, Grand Garden, and Main Patio

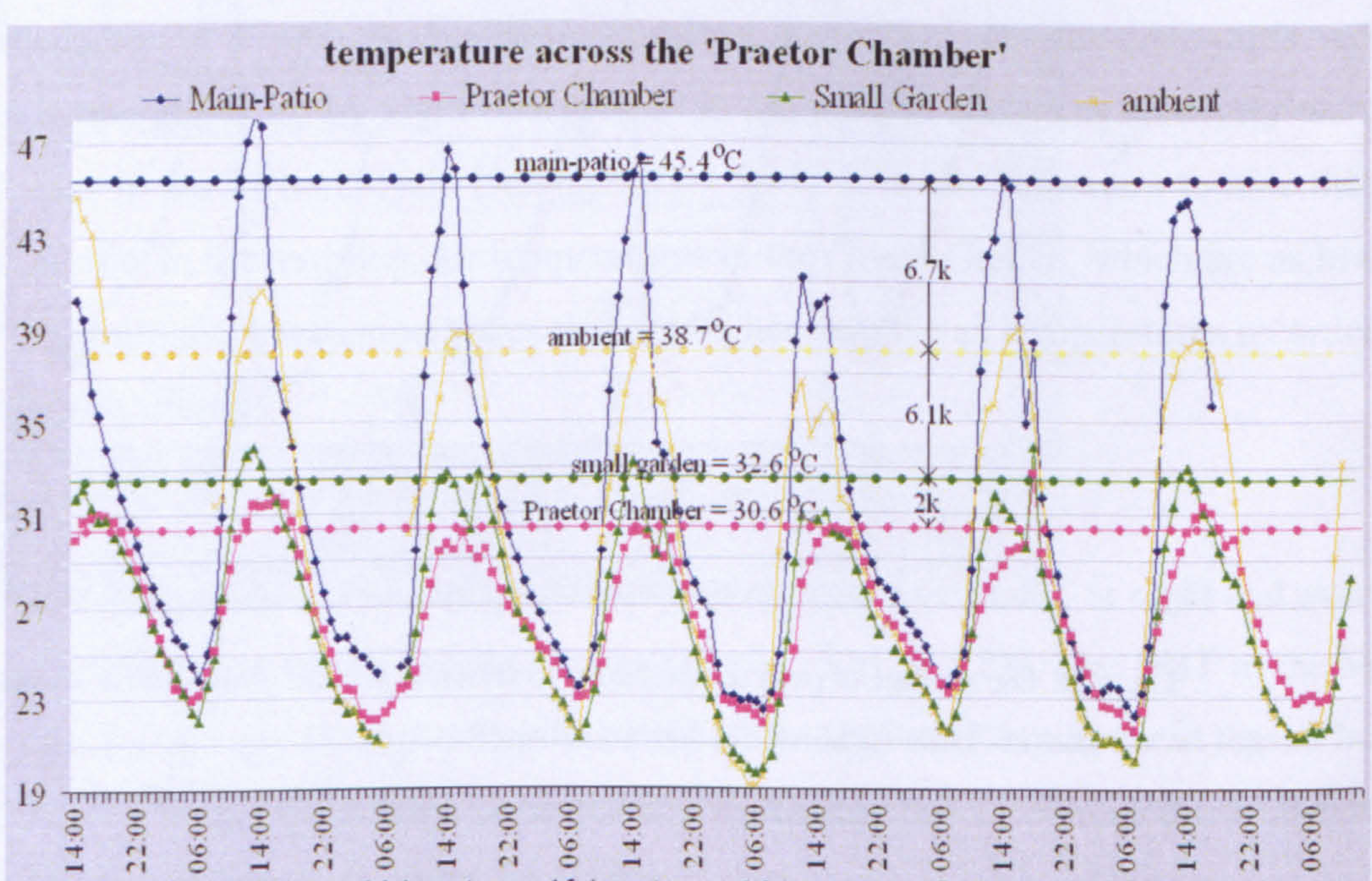


Fig. 5.24 The average of peak temperatures in the cross section of the Small Garden, Praetor Chamber, and main Patio

Table 5.1: The temperature difference between the Main Patio and Hall of Columns (MP – HC) from 13:00h to 17:00h

	13th Aug.	14th Aug.	15th Aug.	16th Aug.	17th Aug.	18th Aug.
	MP - HC	MP - HC	MP - HC	MP - HC	MP - HC	MP - HC
13:00h	17.8k	12.9k	13.9k	9.6k	15.6k	15.5k
14:00h	16.3k	15.5k	15.5k	9.8k	17.0k	14.6k
15:00h	8.9k	13.8k	15.6k	9.2k	15.6k	12.8k
16:00h	4.3k	8.5k	9.6k	5.3k	9.6k	8.2k
17:00h	2.8k	3.6k	2.4k	2.4k	4.9k	

Table 5.2: The temperature difference between the Main Patio (MP) and Grand Garden (GG) from 13:00h to 17:00h

	13th Aug.	14th Aug.	15th Aug.	16th Aug.	17th Aug.	18th Aug.
	MP - GG	MP - GG	MP - GG	MP - GG	MP - GG	MP - GG
13:00h	13.3k	9.7k	11.1k	8.2k	11.8k	10.8k
14:00h	12.3k	11.0k	12.3k	8.2k	12.0k	9.3k
15:00h	6.5k	9.7k	12.0k	7.7k	12.1k	8.3k
16:00h	2.4k	5.2k	6.7k	4.2k	6.6k	4.2k
17:00h	1.9k	0.9k	0.3k	1.9k	1.9k	1.0k

Table 5.3: The temperature difference between the Main Patio (MP) and Praetor Chamber (PC) from 13:00h to 17:00h

	13th Aug.	14th Aug.	15th Aug.	16th Aug.	17th Aug.	18th Aug.
	MP - PC	MP - PC	MP - PC	MP - PC	MP - PC	MP - PC
13:00h	16.7k	13.8k	13.3k	10.1k	14.5k	15.0k
14:00h	16.3k	17.0k	15.4k	10.3k	16.7k	14.3k
15:00h	9.6k	16.4k	16.1k	10.1k	15.7k	12.4k
16:00h	5.2k	10.7k	10.7k	6.5k	10.0k	8.0k
17:00h	3.9k	7.4k	4.6k	3.9k	5.3k	4.6k

5.3.3 Relative Humidity (RH)

The Casa de Pilatos is characterized by a wide variation in RH (see fig.5.25). For example, at 15:00h, when the average temperature in the Grand Garden is around 34°C, RH varies between 13.2% and 33.5%. In the early part of the day (before 12:00h noon), the garden-courtyards have recorded 15 – 20% more RH than the Roof Top. Across spaces, there is a variation of at least 25%RH in most instances and a difference of as much as 40%RH in 24 hours cycle. A difference of up to 20%RH is observed between the Main Patio and the Praetor Chamber in the period between 12:00h and 17:30h. These adjacent spaces are only separated by an arcade. Generally, the RH has varied to as much as 40% between 07:00h and 15:00h, with temperature difference of up to 20k.

During the day, RH had sometimes fallen as low as 8.8% when the DBT is 45.8^{0}C (refer fig.5.26). Unlike in the Main Patio where RH does fall sharply after 09:00h in the morning, the RH has risen and fallen steadily in the garden-courtyards, (see fig.5.26 and fig.5.27).

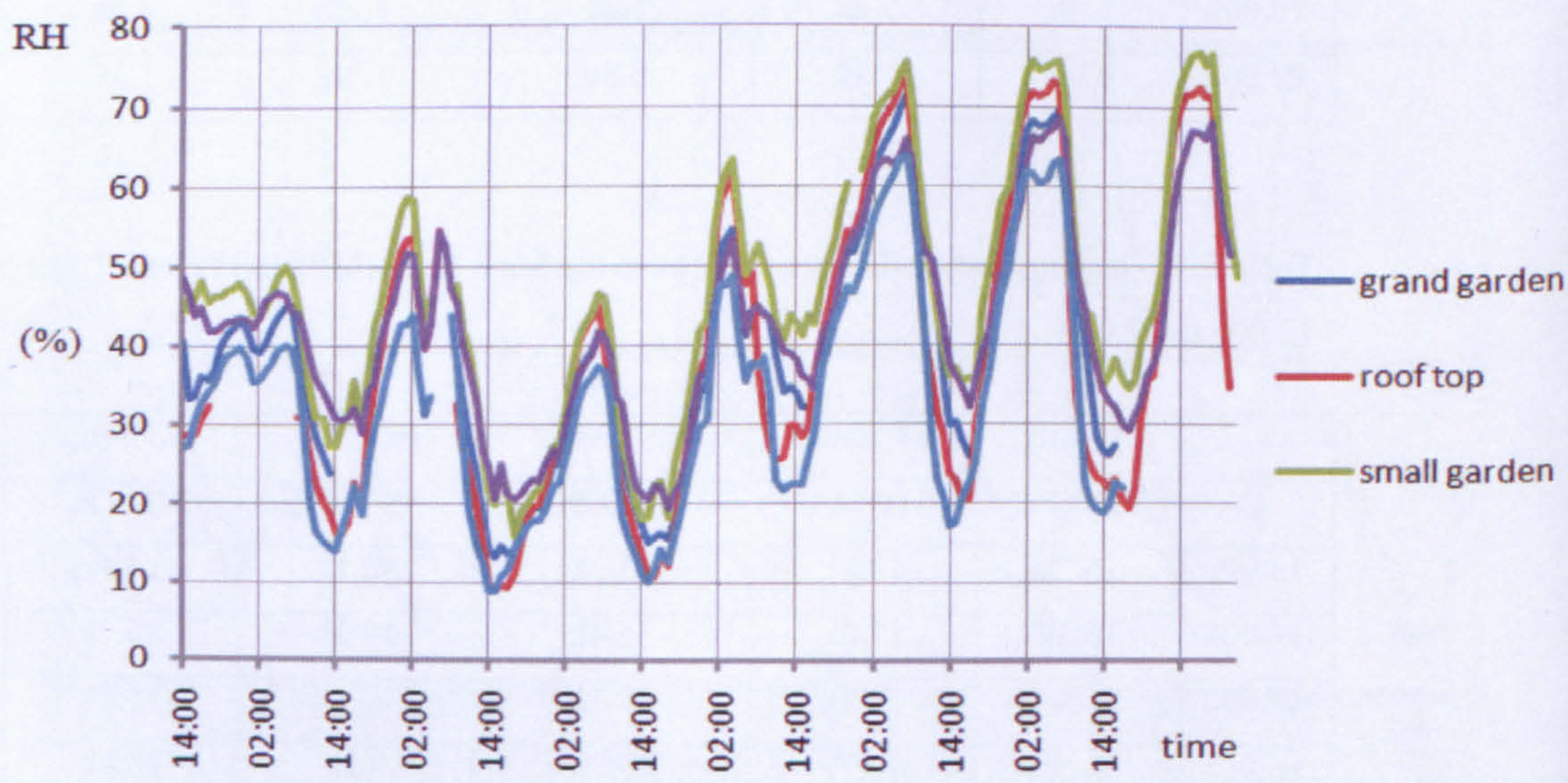


Fig. 5.25 The variation of RH with time over the fieldwork period

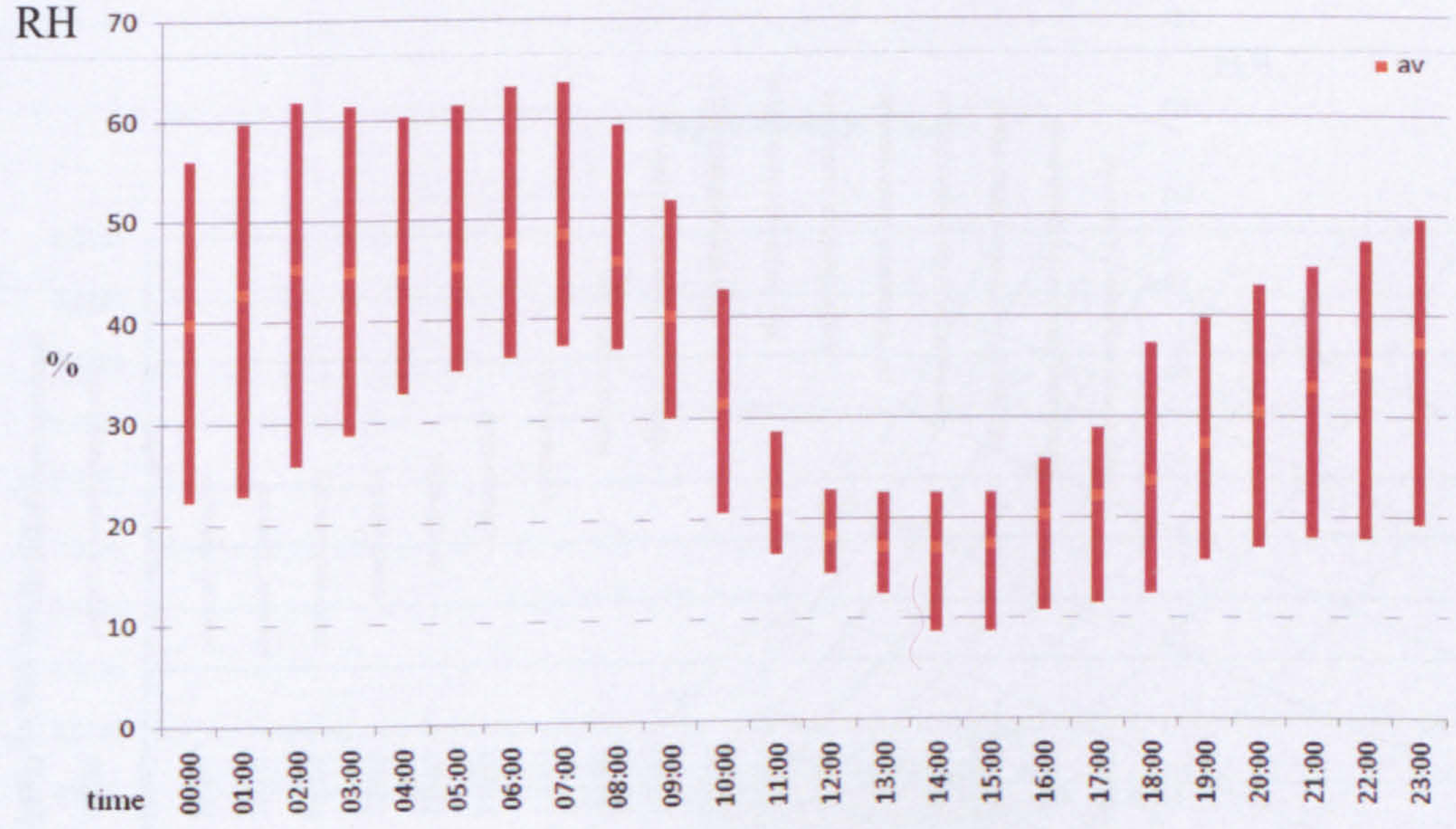


Fig. 5.26 the recorded hourly range of RH in the Main Patio for the fieldwork period

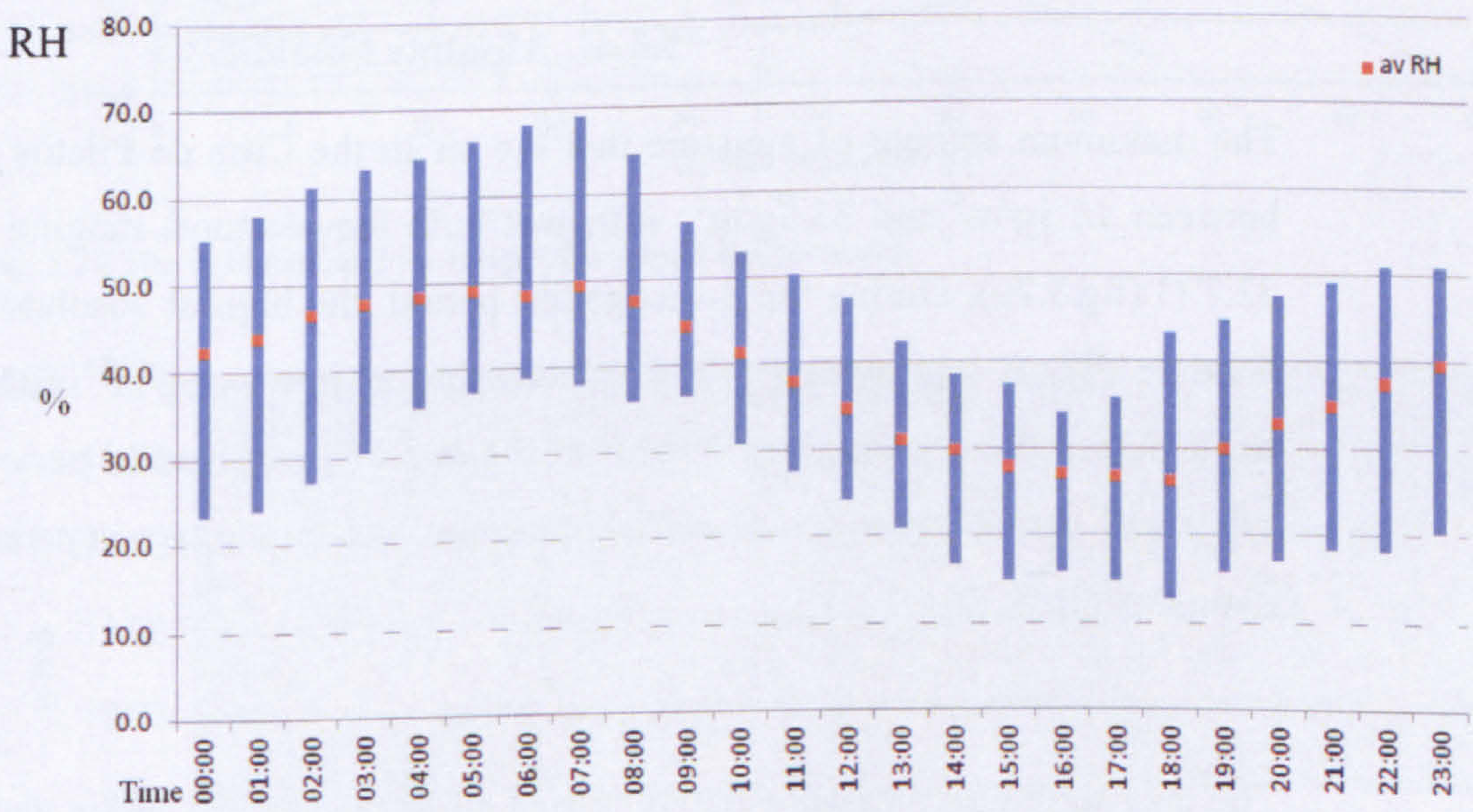


Fig. 5.27 the recorded hourly range of RH in the Hall of Columns for the fieldwork period

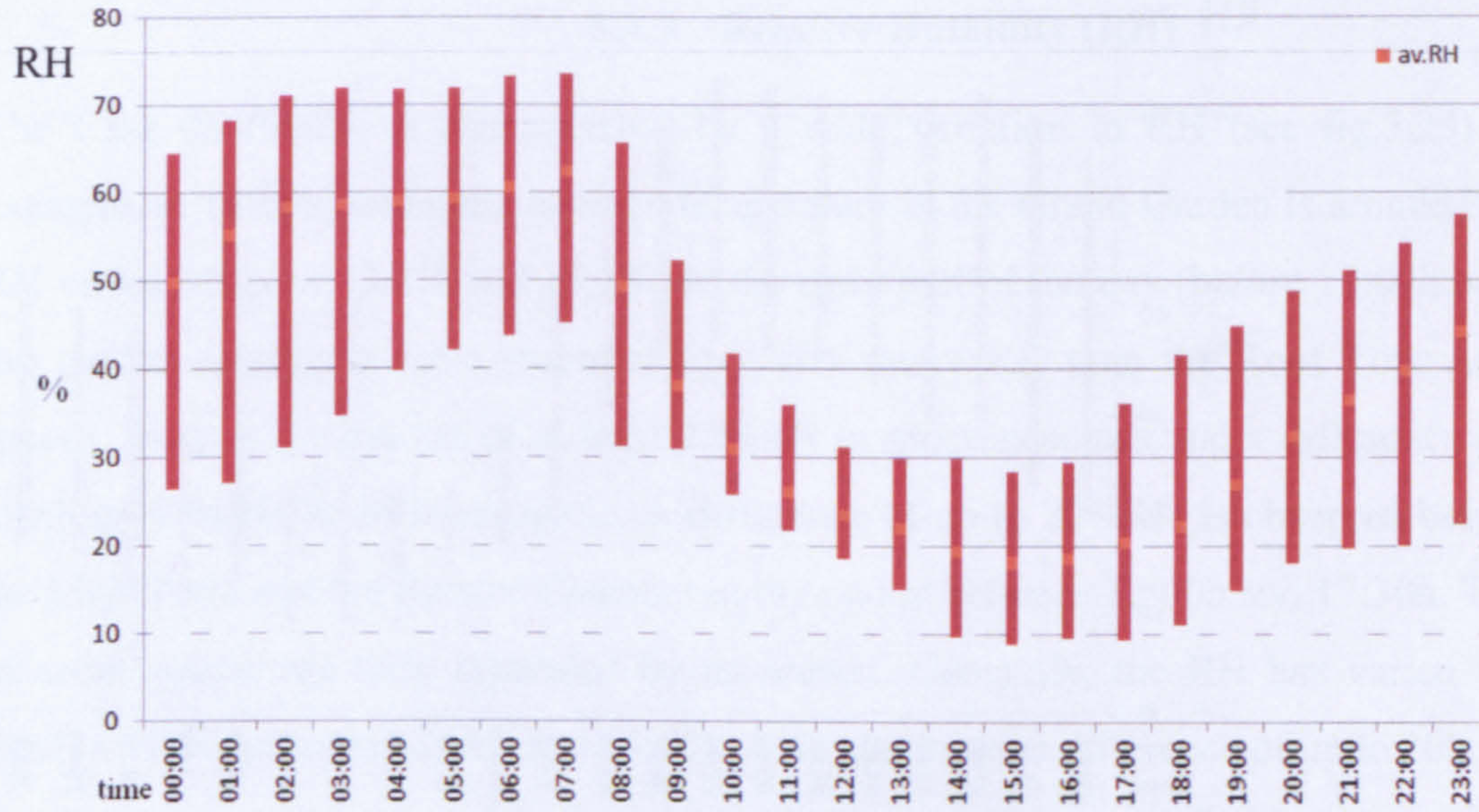


Fig. 5.28 The hourly range of RH at the Roof Top for the fieldwork period

5.3.4 Absolute humidity

The maximum amount of moisture that the air in the Casa de Pilatos can hold ranges between 16.5g/m^3 and 33.5g/m^3, with wet bulb temperatures ranging from 12.8^{0}C to 22.7^{0}C (fig.5.29). During the investigation period, the highest absolute humidity in the Casa de Pilatos was around 15g/m^3, decreasing as low as 6g/m^3 in the middle of the week before rising as high as 15g/m^3 at the end of investigation period (see fig.5:30). The small garden has a consistently higher absolute humidity compared with the Main Patio (see fig.5.30).

The data shows that the specific volume of air in the Grand Garden and Main Patio has increased with time as temperature rises after 06:00h in the morning. Generally, the specific volume of air has varied between 0.86 and 0.92 m^3/kg. The specific volume of the air in the Grand Garden has varied between 0.86 and 0.88 m^3/kg at 11:00h to (0.88 – 0.89) m^3/kg at 15:00h. The specific volume of the air in the Main Patio has varied from 0.89 to 0.92m^3/kg at 11:00h and 15:00h respectively. The increased specific volume means density of air decreases as temperature rises with solar radiation.

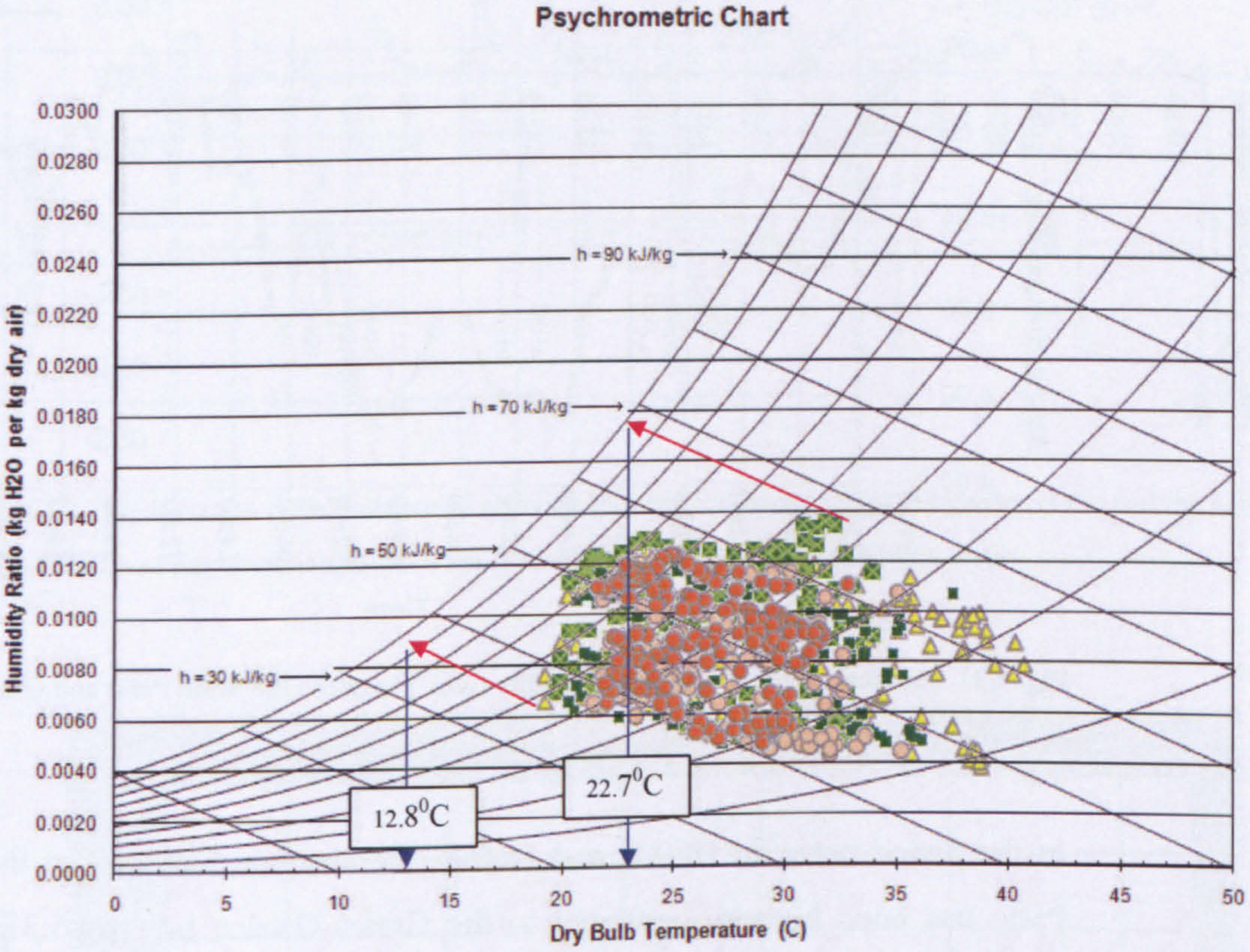


Fig. 5.29 The field data and the range of wet bulb temperatures

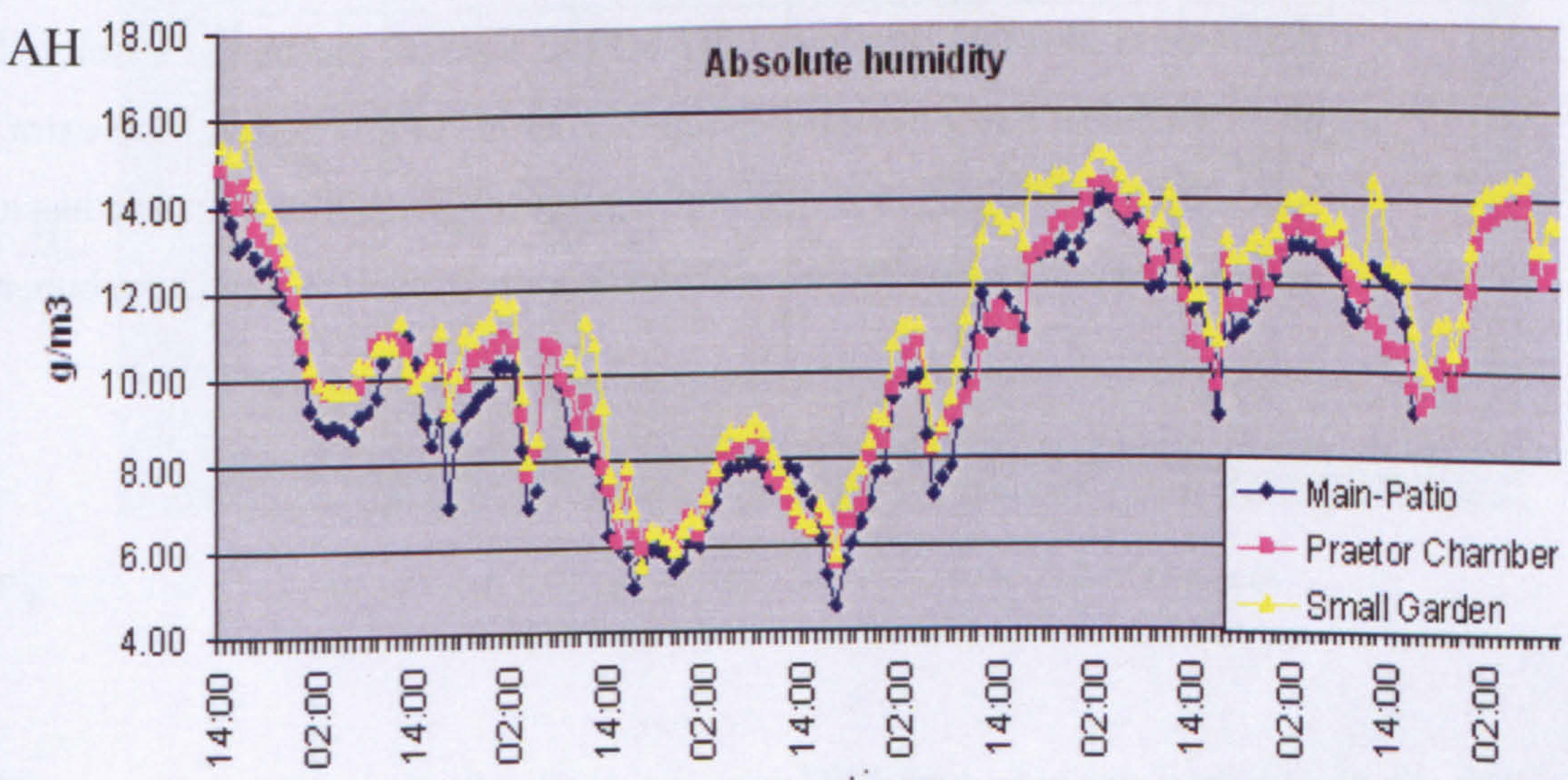


Fig. 5.30 The fluctuation of absolute humidity (g/m^3) between the Main Patio, Praetor Chamber, and Small Garden

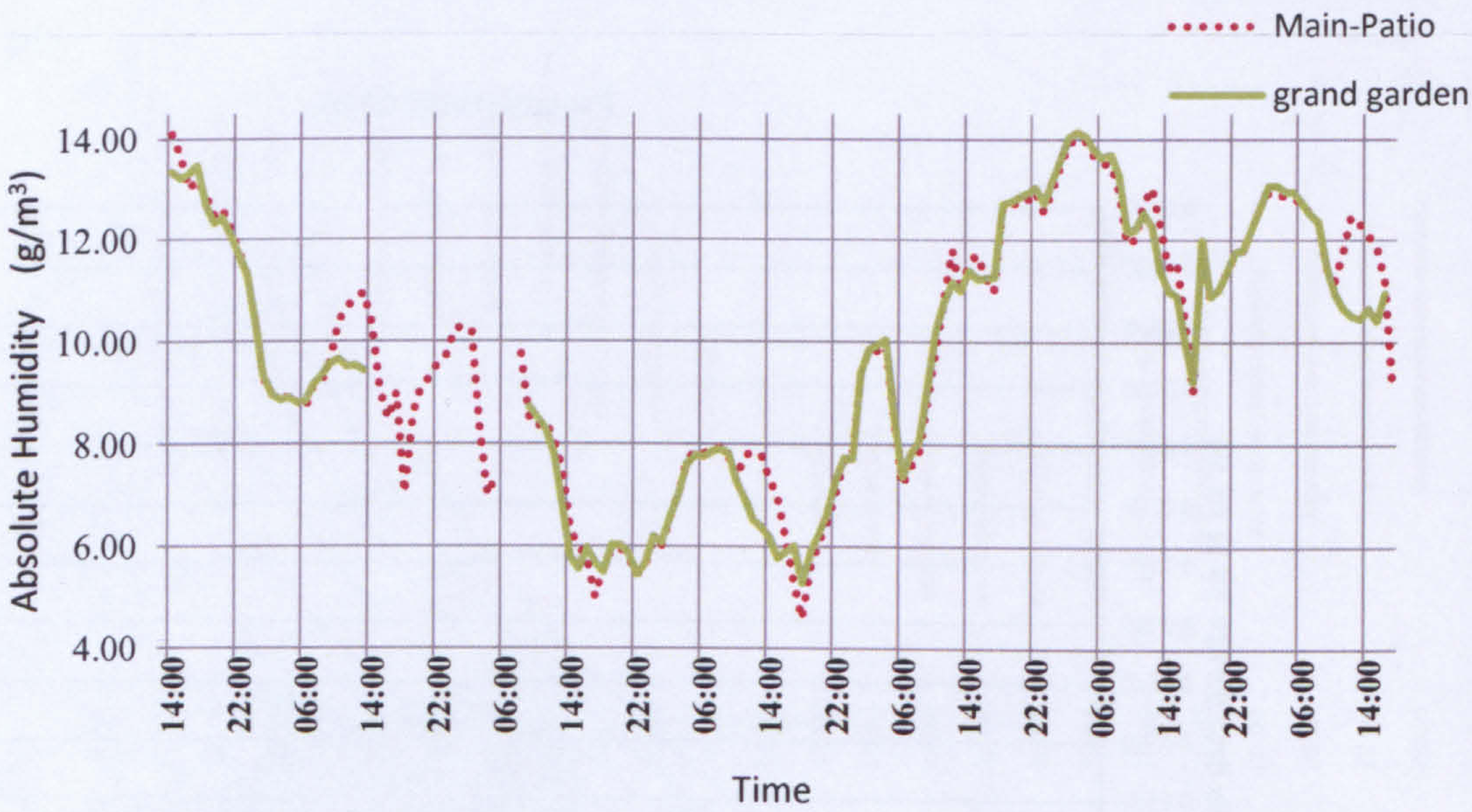


Fig. 5.31 The fluctuation of absolute humidity (g/m^3) between the Main Patio and Grand Garden

In the period between 10:00h and 16:00h, the absolute humidity of the air in the Main Patio has been highest compared to the Grand Garden (see fig.5:31 and fig.5.32). It exceeds the moisture in the Grand Garden by an average of 0.5g/m^3. This difference can be attributed to the fountain in the middle of the Main Patio. The repeated downward deflation of absolute humidity (GG-MP) in fig.5.32 means the absolute humidity of the air in the Main Patio is higher by up to 2.3g/m^3 in this period. The extra moisture in the Main Patio in this period is intentional since air with extra moisture has lower density. A combination of moisture and higher temperature result to a positive buoyancy force.

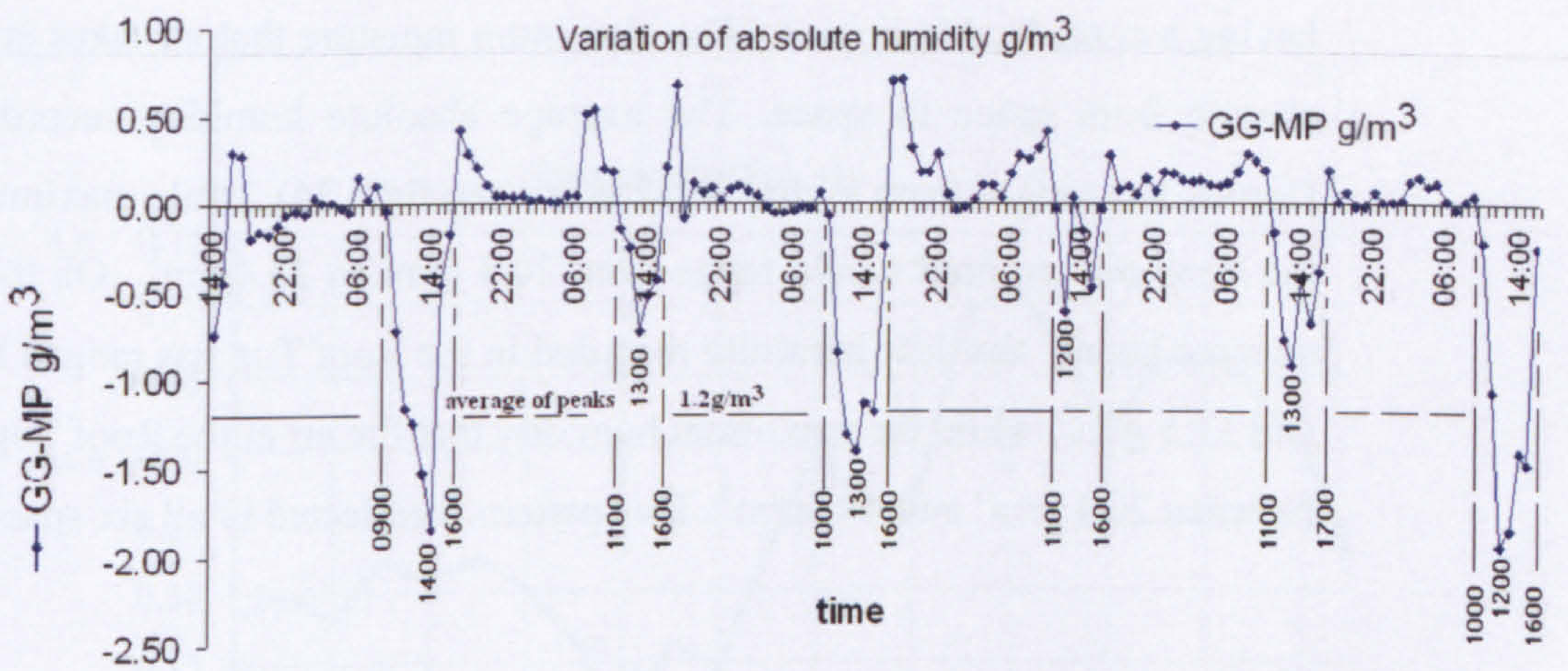


Fig. 5.32 The deviation in the balance of absolute humidity between the grand garden (GG) and the Main-Patio (MP), –ve deviation is shown in the period of more moisture in the Main-Patio

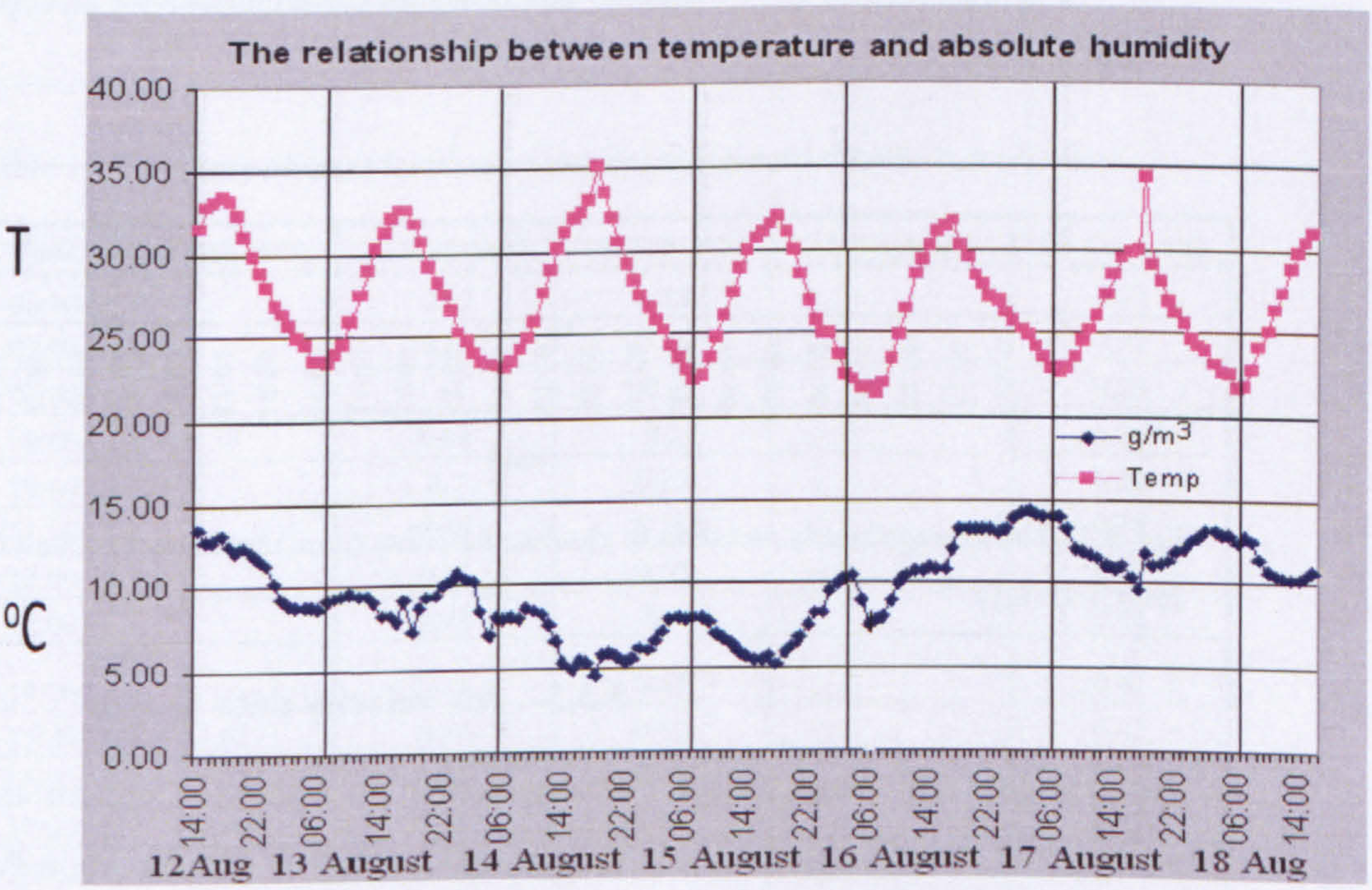


Fig. 5.33 The correlation between DBT and absolute humidity in the Hall of Columns

The correlation between the fluctuation in DBT and absolute humidity in the Hall of Columns has indicated a link between the periods of lower temperatures with increased absolute humidity (see fig.5.33). Meaning the inflow of air from the Grand Garden is having a considerable impact. The maximum moisture that air takes is also observed to change from space to space. The average absolute humidity recorded in the Small Garden has ranges from 9 g/m^3 to 12 g/m^3 (see fig.5.34), while maximum humidity that the same air can hold would range from 20.5 g/m^3 to 33.4g/m^3. On the other hand, the average hourly absolute humidity recorded in the Roof Top has ranged between 8.5 g/m^3 and 11.5 g/m^3, while the maximum humidity that the air at the Roof Top can hold ranges between 20.1 g/m^3 and 48.9g/m^3. This pattern is reflected in all six spaces.

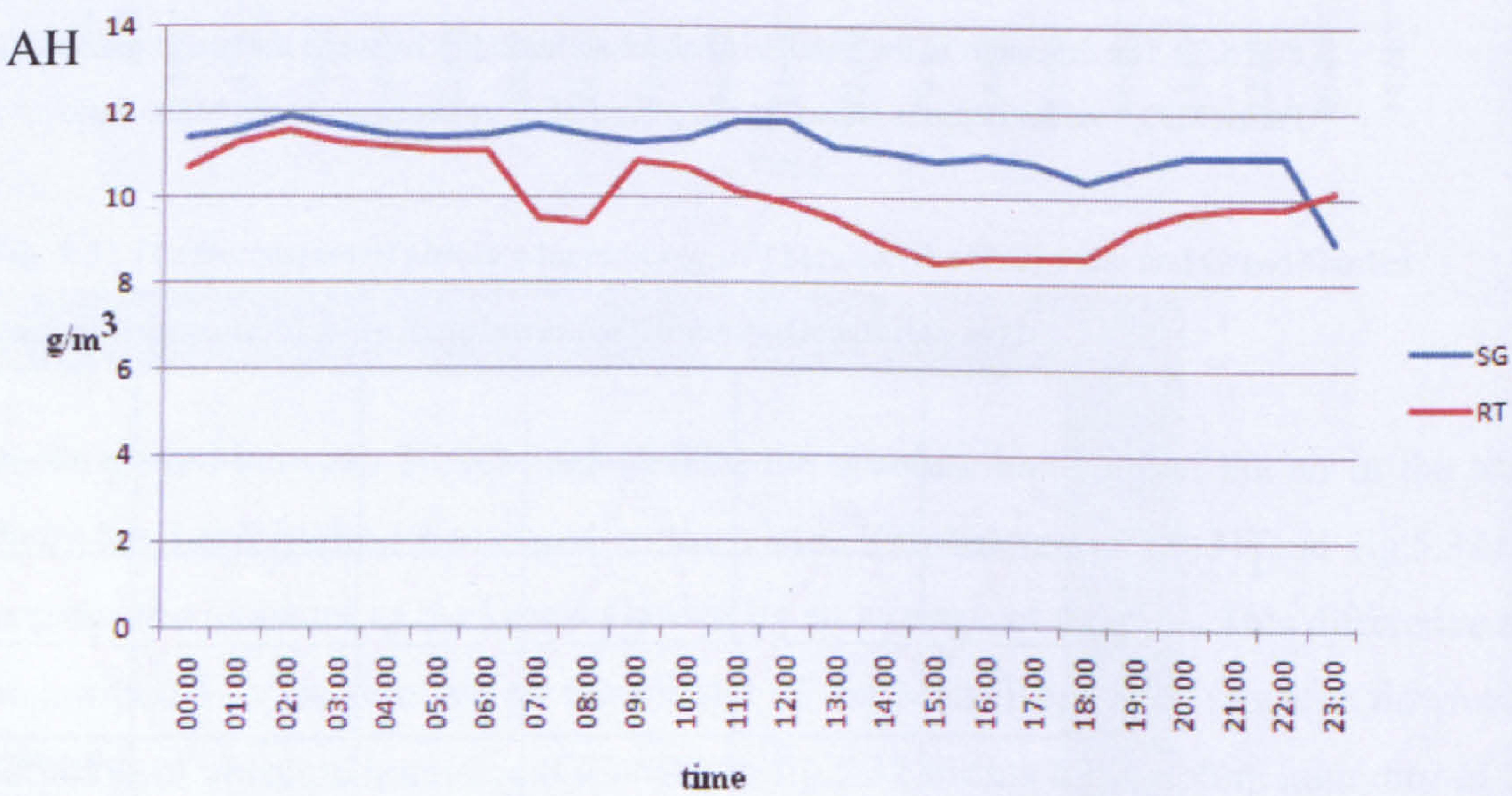


Fig. 5.34 The average hourly variation in absolute humidity (g/m^3) between the Small Garden (SG) and Roof Top (RT)

5.3.5 Air velocity data

Air velocity and wind speeds were measured in order to confirm the impact of the variation in temperature between the garden-courtyards and the Main Patio (see fig.5.35 and Table 5.4 – 5.5). Air velocity was measured at the inlet to the transitional spaces (Hall of Columns and Praetor Chamber). The wind speeds were measured at the Roof Top. The equipments were set to collect data every minute. The plot of volume flow rates against time for daytime data collected in the praetor chamber (08:00h – 18:00h) is shown in fig.5.36. All the data recorded in the Praetor Chamber are presented in fig.5.37. This data will be analyzed in the next chapter.

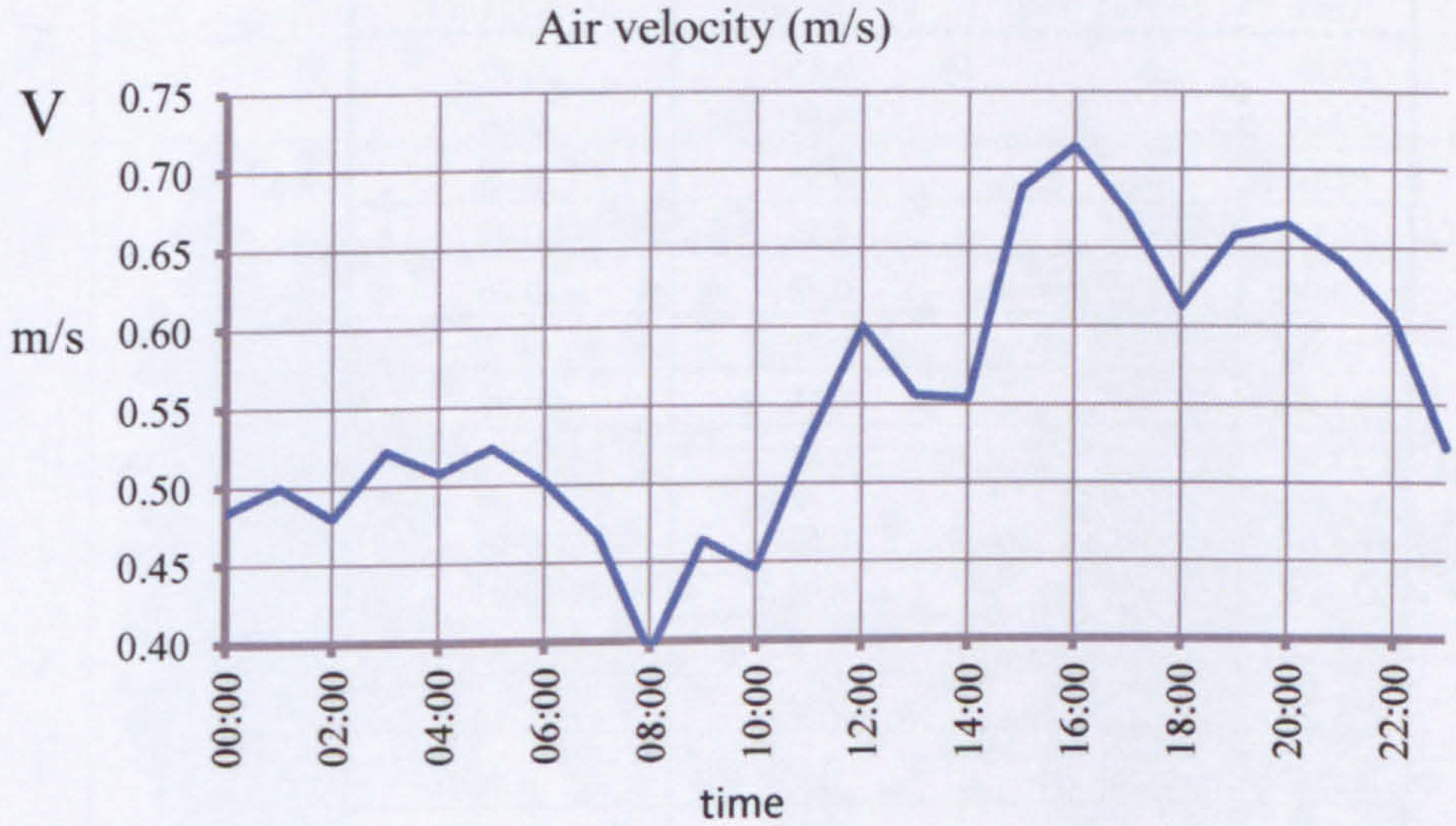


Fig. 5.35 Field recorded data for average air velocity

Table 5.4: Summary of mean hourly air velocity (m/s) recorded in the Hall of Columns

Time	12-Aug (m/s)	13-Aug (m/s)	14-Aug (m/s)	15-Aug (m/s)	16-Aug (m/s)
06:00		0.92	0.23		0.22
07:00		0.83	0.22		0.22
08:00			0.2		0.23
09:00		0.88	0.2		0.22
10:00		0.7	0.17		0.22
11:00		0.69	0.18		0.35
12:00		0.45	0.42		0.41
13:00		0.43	0.4		0.42
14:00		0.41	0.42		0.42
15:00	1.03	0.48	0.42		0.42
16:00	1.02	0.47	0.42		0.42
17:00	0.96	0.45	0.42		0.42
18:00	0.85	0.31			
19:00	0.96	0.22		0.79	
20:00	0.96	0.21		0.9	

Table 5.5: Summary of mean hourly air velocity (m/s) recorded in the Praetor Chamber

Time	16-Aug (m/s)	17-Aug (m/s)	18-Aug (m/s)
06:00		0.45	0.69
07:00		0.41	0.66
08:00		0.55	0.59
09:00		0.53	0.49
10:00		0.48	0.66
11:00		0.72	0.7
12:00		0.88	0.84
13:00		0.81	0.72
14:00		0.68	0.84
15:00		0.91	0.87
16:00		1.1	0.86
17:00		0.85	0.93
18:00		0.6	0.69
19:00	0.54	0.71	0.73
20:00	0.67	0.67	0.58

Two sets of equipment had to be shared between the Hall of Columns, Praetor Chamber, and Roof Top. The equipment in the Hall of Columns and Praetor Chamber was set near the inlet window (refer fig.5.1) to avoid interruption from visitors because the building is open to the public. Influx of cool air was experienced when monitoring the single-inlet façade-window that links each of these rooms with the respective garden-courtyard (Grand Garden & Small Garden). The recorded airspeeds have ranged between 0.2m/s to 1.6m/s. The relatively higher velocity at the inlet to the Hall of Columns ($2.4m^2$) can be attributed to larger outlet ($9.5m^2$ total) as the pressure within air decreases ('Bernoulli's Principle').

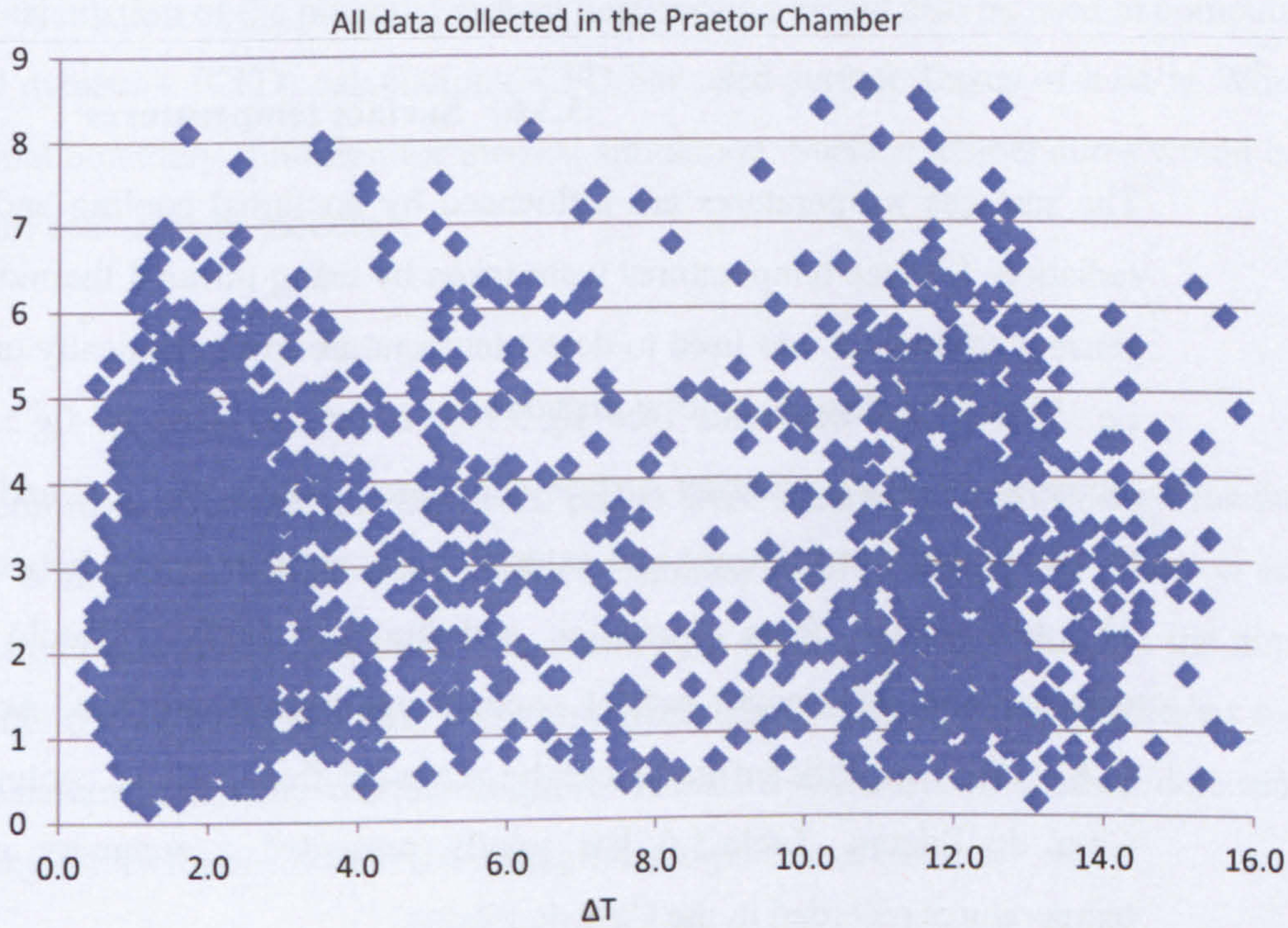


Fig. 5.36 A plot of volume flow rates versus temperature differences of all data collected in the Praetor Chamber

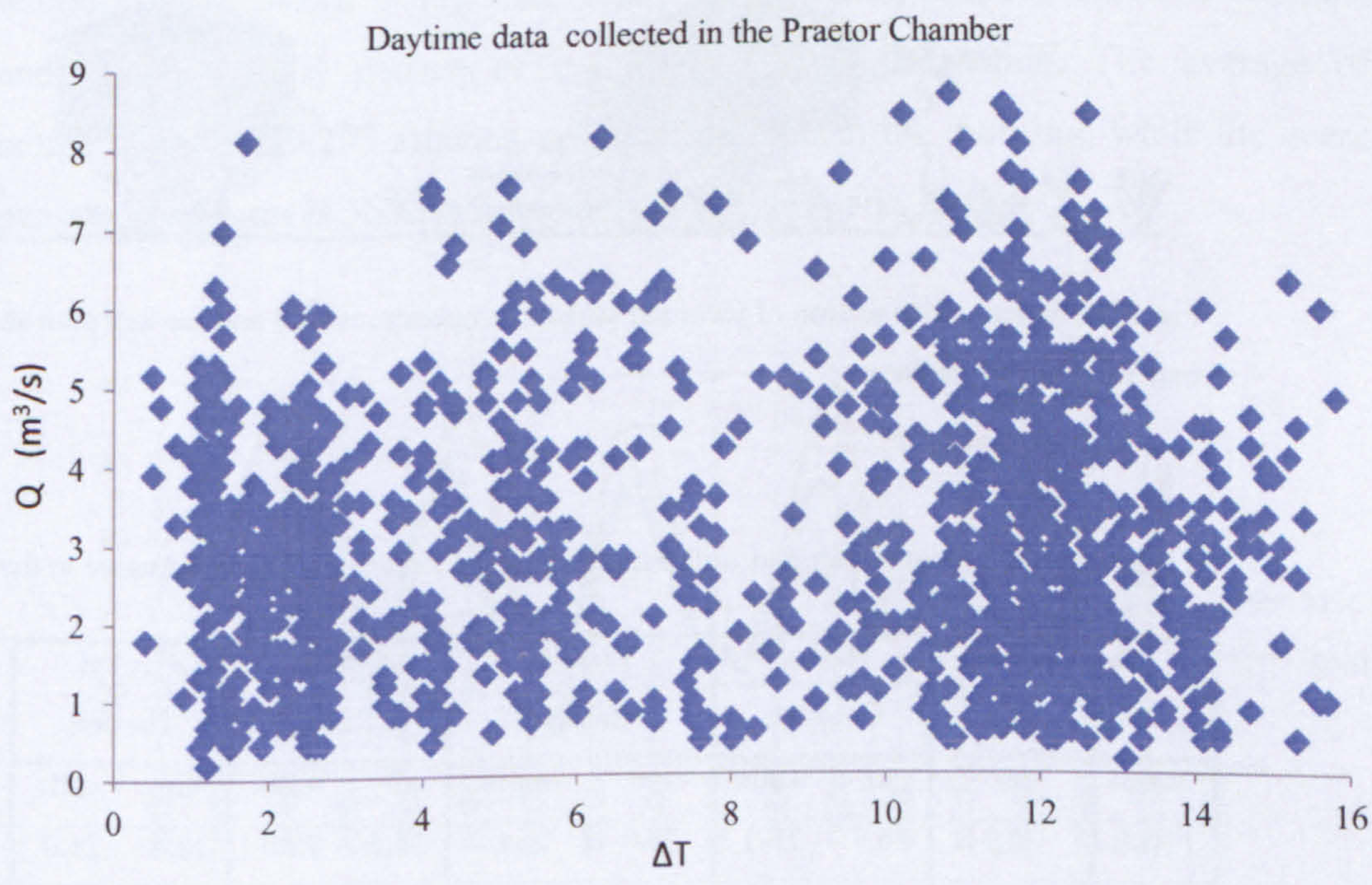


Fig. 5.37 A plot of daytime data for volume flow rates versus temperature differences in the Praetor Chamber

5.3.6 Surface temperatures

The surfaces temperatures are influenced by nocturnal cooling and exposure to solar radiation. Surface temperatures were taken by using infrared thermometer. This remote sensing equipment was used to detect temperature from physically unreachable surfaces i.e. ceiling and balconies (see fig.5.38). It can be seen in fig.5.38 that while the temperature of a vegetation surface and water surface are 28^{0}C and 23^{0}C respectively, the temperatures of interior and exterior surfaces have ranged between 30^{0}C and 60^{0}C. The temperature from vegetation and building surfaces would be useful in the determination of amount radiant cooling and thermal comfort. According to Balaras C.A. (1996), significant gains can be achieved from radiant cooling of buildings like Casa de Pilatos. Table-5.6 has jointly presented a summary of surface and air temperatures recorded in the Casa de Pilatos.

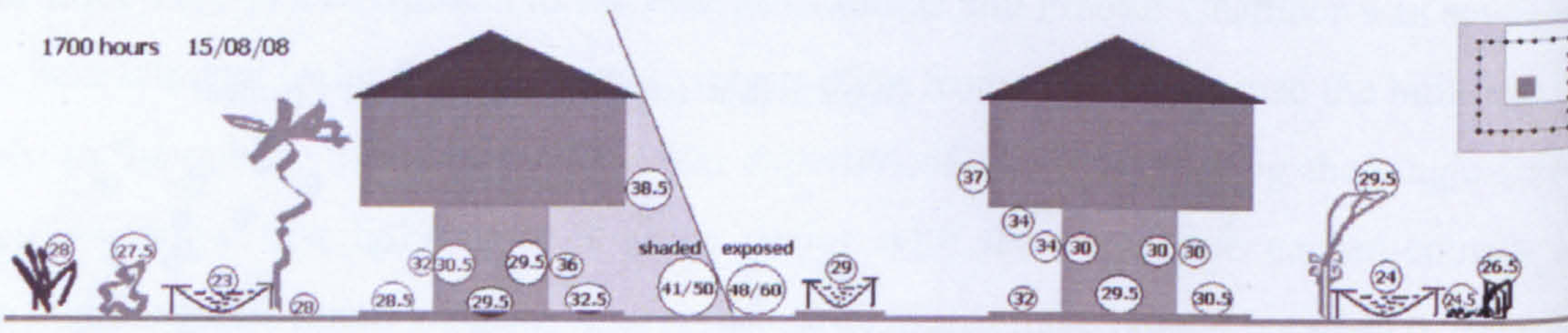


Fig. 5.38 typical cross section of recorded surface temperatures (^{0}C) and the key plan showing the shadow pattern in the Main Patio

Table 5.6: Field recorded air and wall temperatures (^{0}C) taken on the 16th August at the Casa de Pilatos

	Ambient (^{0}C)	Hall of Columns		Praetor Chamber		Main Patio		Grand Garden		Small Garden	
time	air	air	walls	air	walls	air	walls	air	walls	air	walls
1100h	35.9	26.5	27.3	25.0	26.0	38.4	28.0	28.4	21.0	28.9	22.0
1300h	34.4	29.4	28.0	28.9	27.8	38.9	37.3	30.7	25.0	30.6	35.0
1500h	35.6	31.0	28.8	30.1	28.3	40.2	40.2	32.6	30.0	31.0	31.0
1700h	31.6	31.8	31.0	30.3	30.0	34.2	43.0	32.3	29.0	30.0	30.0

The calculation of the potential radiant heat/cooling would also be used in computational fluid dynamics (CFD) calculations. CFD has used surface fluxes of heat in W/m^2 as a thermal boundary condition for thermal simulation. Surface temperatures would be used within heat transfer models.

5.4 Correlation with meteorological data

Meteorological data for the fieldwork period were secured through EnergyPlus website. This is important because the analysis of summer comfort need to be based on external climate. These data were taken from Sao Pablo meteorological station at the airport in Seville. Nicol (2001) has used meteorological data to determine the conditions required to maintain acceptable thermal comfort. The data will also be used to determine the driving forces for airflows in the multiple-courtyard environment.

Excel spreadsheet is used to organize the data and the graph for hourly variation in air temperature is shown in Fig.5.39. There is correlation between the collected field data and meteorological pattern of daily and hourly fluctuation. The average of low temperatures is 19.2^{0}C attained at around 03:00h in the morning, while the average of peak temperatures is 35^{0}C attained between 14:00h and 15:00h.

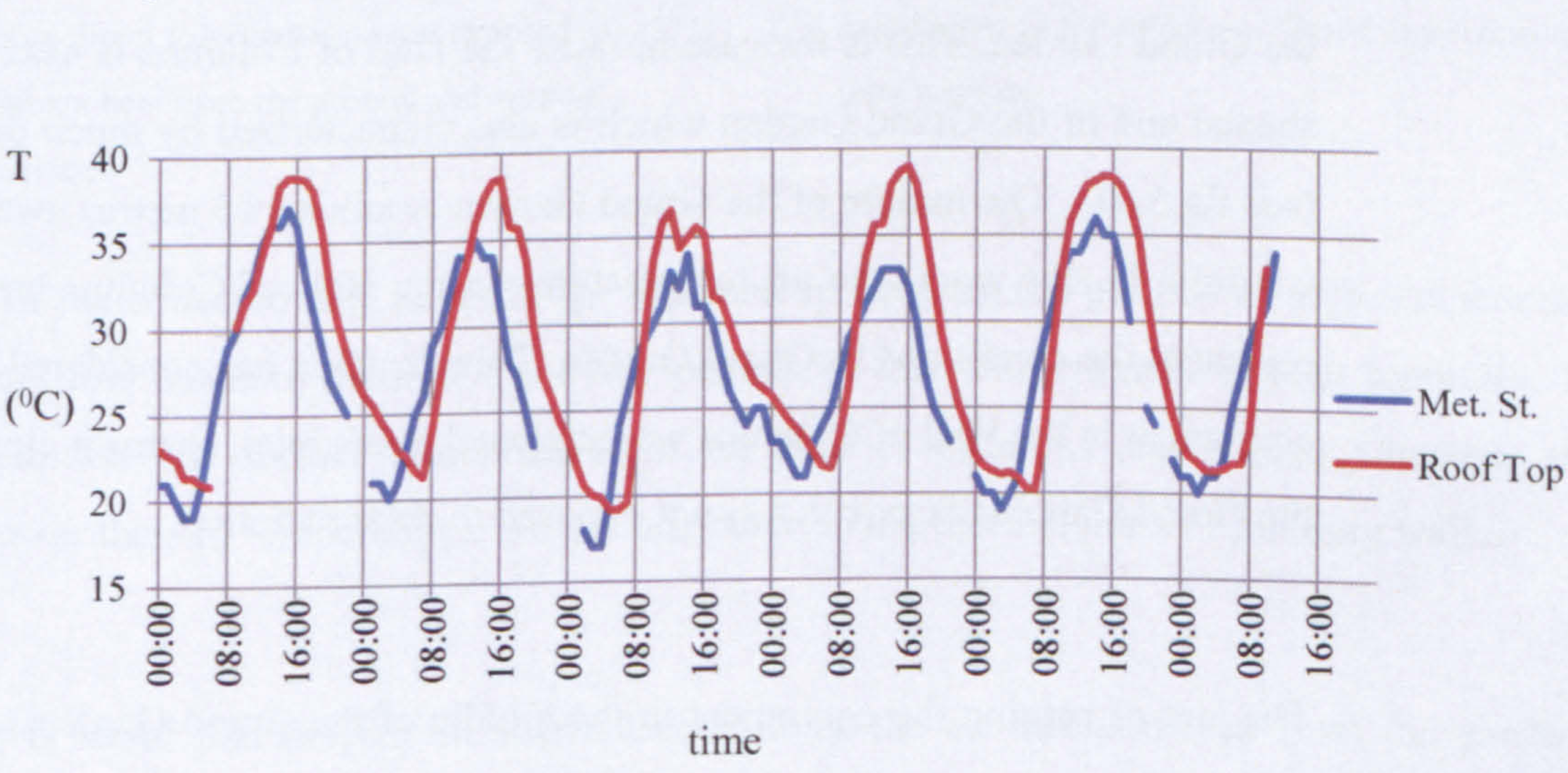


Fig. 5.39 The comparison between the pattern in the data from Seville's meteorogical station and the Roof-Top in the Casa de Pilatos; Source of weather data: Energy Plus website

5.5 Discussion

It has been observed that air temperatures are higher in the Main Patio due to unobstructed exposure to solar radiation, and much lower in the garden-courtyards and transitional spaces due to shading, evaporative cooling from vegetation and water surfaces, and radiant cooling from the building thermal mass.

Lower temperatures were expected in the Hall of Columns (T_{HC}) compared to the Grand Garden (T_{GG}). However, the fieldwork has recorded higher temperatures in the Grand Garden than the Hall of Columns. It can be argued that the temperature recorded in the Hall of Columns were lower than the Grand Gardens because the recording instrument was placed near the inlet window. The results seem to suggest that there is a temperature gradient and air was getting cooler as you migrate towards the boundary of the Grand Garden which is near the Hall of Columns.

The recording instrument 'data logger' was stationed in the middle of Grand Gardens (see fig.5.40). Consequently, there is a significant temperature gradient between the Grand Garden and the Hall of columns. This has caused the air which enters the Hall of Columns to be up to 3k cooler than the temperatures that were recorded in the middle of the Grand Garden. This is the case because the Hall of Columns is next to a completely shaded end of the Grand Garden which is also characterised by much denser vegetation (see fig.5.41). The middle of the Grand Garden is around 15 metres away from the inlet window. In this work, the air temperatures in the Hall of Columns have been used to represent the conditions in Grand Garden. This decision has considered the fact that the equipment in the Hall of Columns was stationed at the inlet, or much closer to the part of the Grand Gardens façade that is not exposed to solar radiation.

The aim of placing the equipment in the middle of the Grand Garden was to record the hourly average temperatures of the whole garden. However, proximity to the inlet in the Hall of Columns was influenced by issues related to security and safety of research equipment and visitors. It was also observed that there was dense vegetation in the area close to the Hall of Columns and less dense on the other end of the Grand Garden.

Fig. 5.40 The adjusted location of temperature recording instrument

Fig. 5.41 (a) The data-logger is protected from direct solar radiation but exposed to radiant heat from the ground and vertical surfaces

(b) Showing the distance from the location of the data-logger in the middle of Grand Garden to the inlet window

All the collected data have shown relationship between the periods of high temperature and low absolute humidity, and the periods of low temperatures to high humidity. In addition, the surface temperatures in the Hall of Columns and Praetor Chamber are lower than air temperatures. This is attributed to the thermal mass of building walls.

It is learnt that despite the thermal conditions, the air that is driven from the garden-courtyards has had influence on the physical conditions of the air in the Hall of Columns and Praetor Chamber. However, the RH humidity is still very low in the garden-courtyards; for example, the RH recorded in the Grand Garden at 15:00h has varies from 13.2 to 33.5% RH between 12th and 18th August 2008 (see fig.5.42).

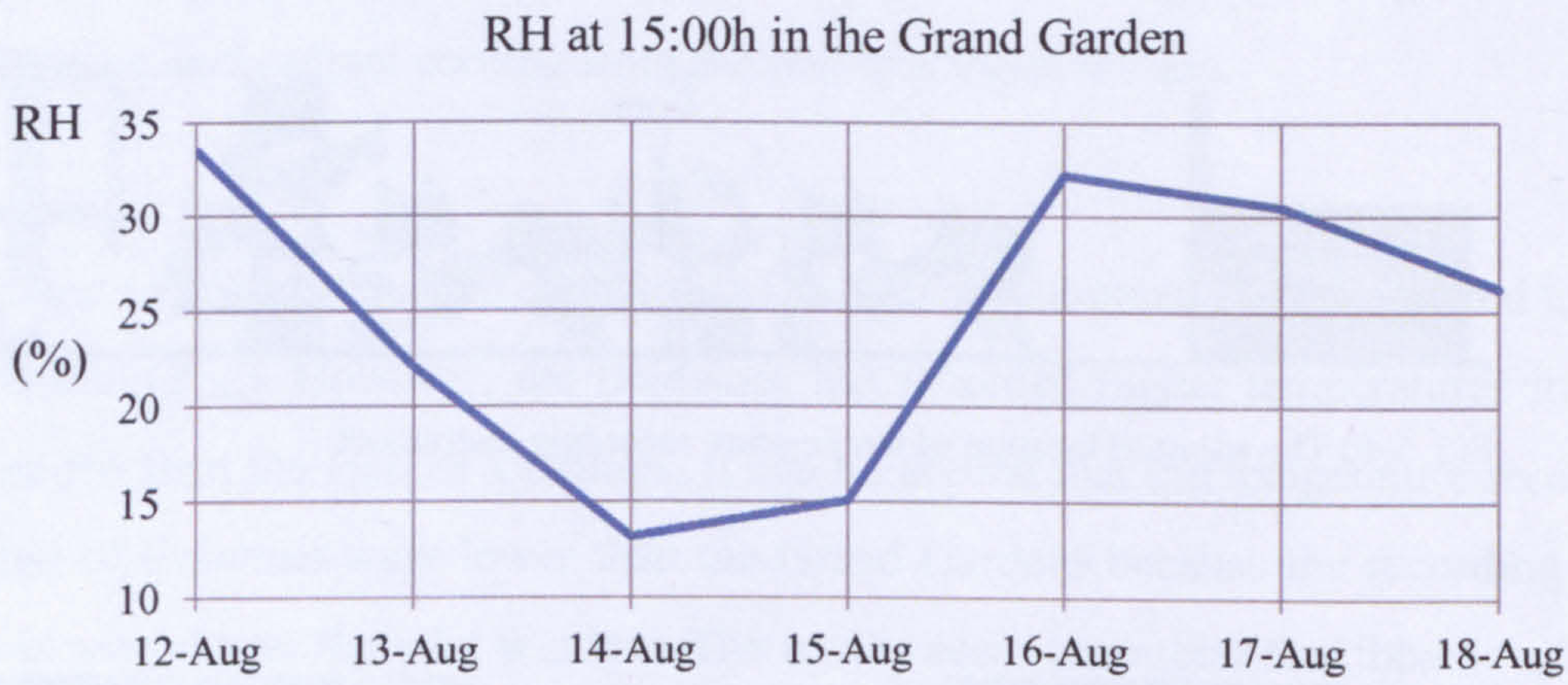


Fig. 5.42 The variation of the RH (%) at 15:00h in the Grand Garden in the field period

The fountain in the Main Patio is not a mere decorative feature. Although addition of moisture in hot and dry climates would reduce temperature, addition of moisture in the Main Patio has influenced air density. There is variation of up to 15K between the Main Patio and the garden-courtyards in the daytime. It can be suggested that the fountain in the Main Patio form part of the criteria for evacuation of air from in this courtyard.

5.6 Conclusion

This chapter has presented the data collected from the field study at the Casa de Pilatos. Excel data sheets are used to plot the hourly variation of air temperatures (DBT) and relative humidity (RH) from six locations where the recording instruments were stationed. These locations are the Roof Top, Grand Garden, Small Garden, Main Patio, Hall of Columns, and Praetor Chamber. The meteorological data were also compared to the recorded data.

The data has shown wide variation in DBT (19^0C – 48^0C) between daytime and night time. Similarly, RH varied as much as 40% in 24 hours period and from 9% to 77% in the field period. A variation of as much as 25%RH across the building suggests a wide range of DBTs and absolute humidity. The absolute humidity varied from 6g/m^3 to 15g/m^3, while the maximum moisture that air can take range from 16.5g/m^3 to 33.5g/m^3. This means the wet bulb temperature from all the collected data fall between 12.8^0C and 22.7^0C.

The collected data show air movement from garden-courtyards to the Main Patio through the intermediate spaces (the Hall of Columns and the Praetor Chamber). The data has indicated that the environmental conditions in the intermediate spaces are influenced by the radiant heat from the building thermal mass. Although nothing can substitute careful field measurements, field data is not as important as relationships within data. Next chapter presents analysis and discussion of the field data.

CHAPTER SIX: ANALYSIS AND DISCUSSION OF THE FIELD DATA

6.1 Introduction

This chapter presents analysis and discussion of the data collected from field studies at the Casa de Pilatos in Seville from 10th to 20th August 2008. Analysis is presented in four main parts. First, the analysis of various passive cooling strategies employed in the building. Then the drivers for yard-to-yard airflows are analysed in the second part. The amount of convective cooling that is attributed to these flows is estimated in the third part. Lastly, the criteria for thermal comfort are determined.

The field data is used to analyse passive cooling strategies by estimating the impact of nocturnal cooling and evaporative cooling from vegetation and water outlets. The impact of passive cooling from the building mass is also estimated. The impact of open sky on passive cooling strategies in courtyards is explored. The analysis shows how the combination of these features creates distinctive thermal environments in the courtyards and transitional spaces in the Casa de Pilatos.

The field data is also used to determine the drivers for field recorded air velocity through the transitional spaces (Hall of Columns and Praetor Chamber). The analysis focuses on thermal convection through buoyancy 'stack' forces. The calculation of the stack effect considers the inlet in the transitional space and the sky window in the Main Patio as the outlet. The volume flow rates attained through these calculations are compared with the values obtained from the field study. The impact of local wind regime and urban layout on airflows from garden-courtyards to the Main Patio is also evaluated.

The calculation of the convective cooling attributed to these flows has used the field recorded temperature differences and air velocity. The possibility for cooling is estimated by analysing the enthalpy of incoming air. The implication of additional heat loads in the Hall of Columns and Praetor Chamber is determined. The potentially low humidity in the garden-courtyards is used to determine the temperature difference that is suitable for variable heat loads in the transitional spaces. The study has also determined the implication of reduced DBT in the garden-courtyards on the flow rates through the transitional spaces.

The cooling sensation of airflow for subjects utilising the window-seats at the inlets in the transitional spaces is also estimated. The analysis of thermal comfort uses the adaptive comfort models provided by Humphrey and Nicol (2002) and Brager and de Dear (2001). Subject response to various thermal environments existing in the transitional spaces is also predicted. It is suggested that cooling sensation of airflow is part of the criteria for thermal comfort in the transitional spaces.

6.2 Passive cooling strategies

This section considers the impact of nocturnal cool air, and evaporative cooling from water fountains and vegetation on the thermal environment in the Casa de Pilatos. The variation of DBT, surface temperatures and RH are used to analyze the impact of these strategies on summer heat gains and losses across the multiple courtyards of the Casa de Pilatos. The analysis of nocturnal cool air shows the distinction between daytime and night time stratification of air in the garden-courtyards, Main Patio and Roof Top. Field data is used to contrast day and night time's influence from sky turbulence and stratification. The field surface temperatures are used to estimate the radiant cooling from the building mass. The evaporative cooling from vegetation and water sources is also evaluated. It is shown that the courtyards have had different roles in the daytime and night time.

6.2.1 Nocturnal cooling and exposure to sky conditions

Despite the need for a supply of natural light and ventilation to vegetation and courtyard spaces, the summer conditions above the courtyard's aperture are not advantageous. This is because the sky contains an undesirable heat wave and its atmosphere is generally characterised by fluctuations and eddies of airflow which bounce about in random motion. Campbell and Norman (1998) have observed that the ability of the atmosphere to transport heat or mass is directly influenced by the magnitude of vertical fluctuation of airflow and temperatures. The open air courtyards are directly influenced by atmospheric turbulence, however their thermal performance relies on the environmental conditions which are controlled and established.

The courtyards' height (up to 14 meters) that is recorded in the Casa de Pilatos is part of climatic strategy used to reduce interference from atmospheric turbulences. The depth of the courtyards reduces atmospheric turbulences which would withdraw cool air from vegetation and fountains. The depth of courtyards do also protect against direct solar radiation (see fig.6.1) and local wind regime. The impact of local wind regime is analyzed in the next section (6.3.4), where hourly changes in the local wind pattern are presented. A combination of deep courtyards and dense vegetation present a clear intention to reduce the mechanical turbulence of wind.

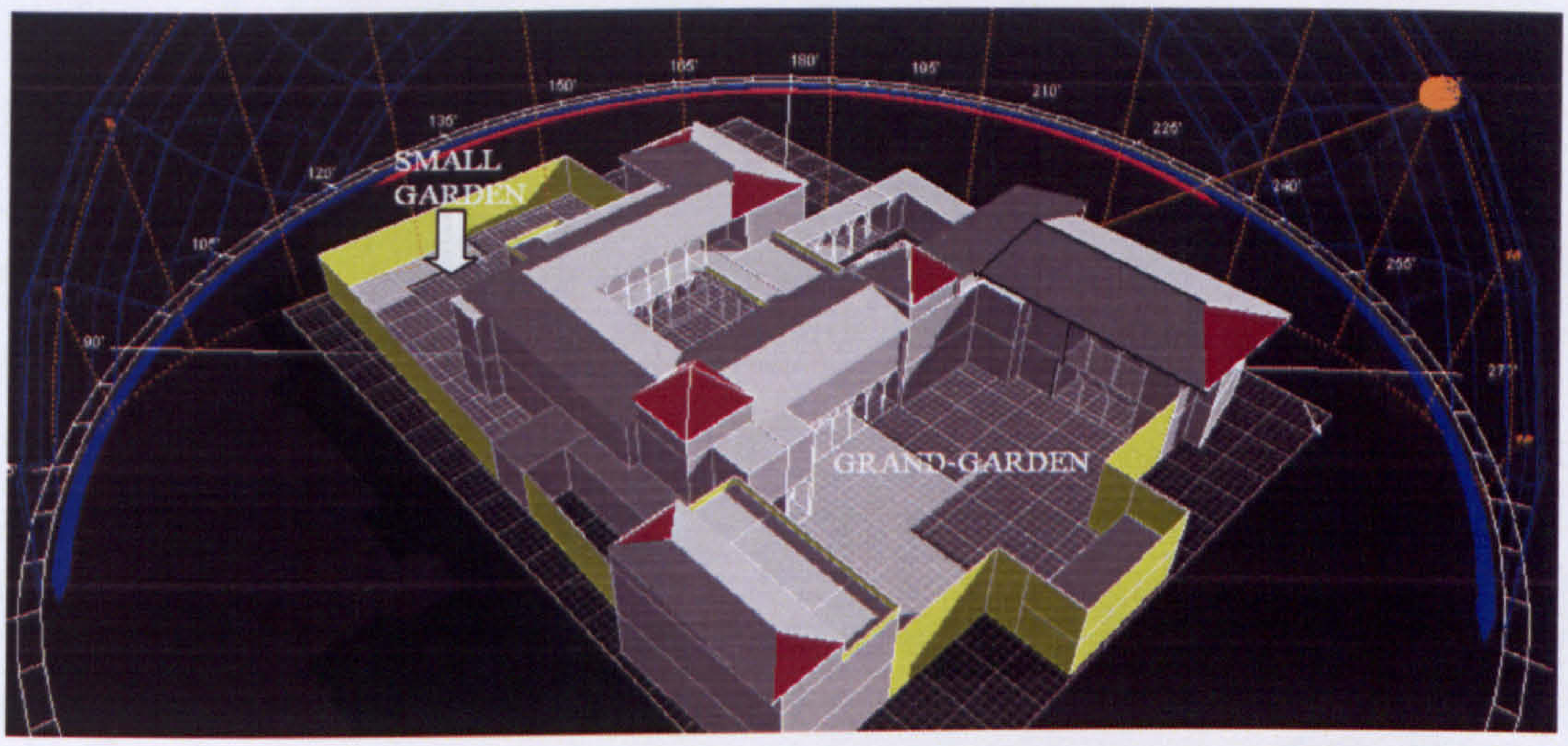


Fig. 6.1 The impact of building height on the shadow depth in the garden-courtyards of the Casa de Pilatos at 17:00h in August.

It is suggested that the interaction between the courtyards in the Casa de Pilatos and the open sky is different from one courtyard to another, in the day and night time. Unlike daytime, night time air temperatures taken in the garden-courtyards are higher than Roof-Top (see fig.6.2). For example at 06:00h in the night time, the average DBT recorded in the Roof-Top and Small Garden are 20.9^0C and 21.3^0C respectively, while at 15:00h in the afternoon, it is 39.1^0C and 30.3^0C respectively. However, the situation is different in the Main Patio, the recorded DBT are higher than meteorological station and Roof-Top data in both daytime and night time. In this case, it is predicted that the hot and buoyant air moves vertically to the open sky at all times and possibly cause the cool and denser air to move horizontally from the garden-courtyards through the spaces on the ground floor.

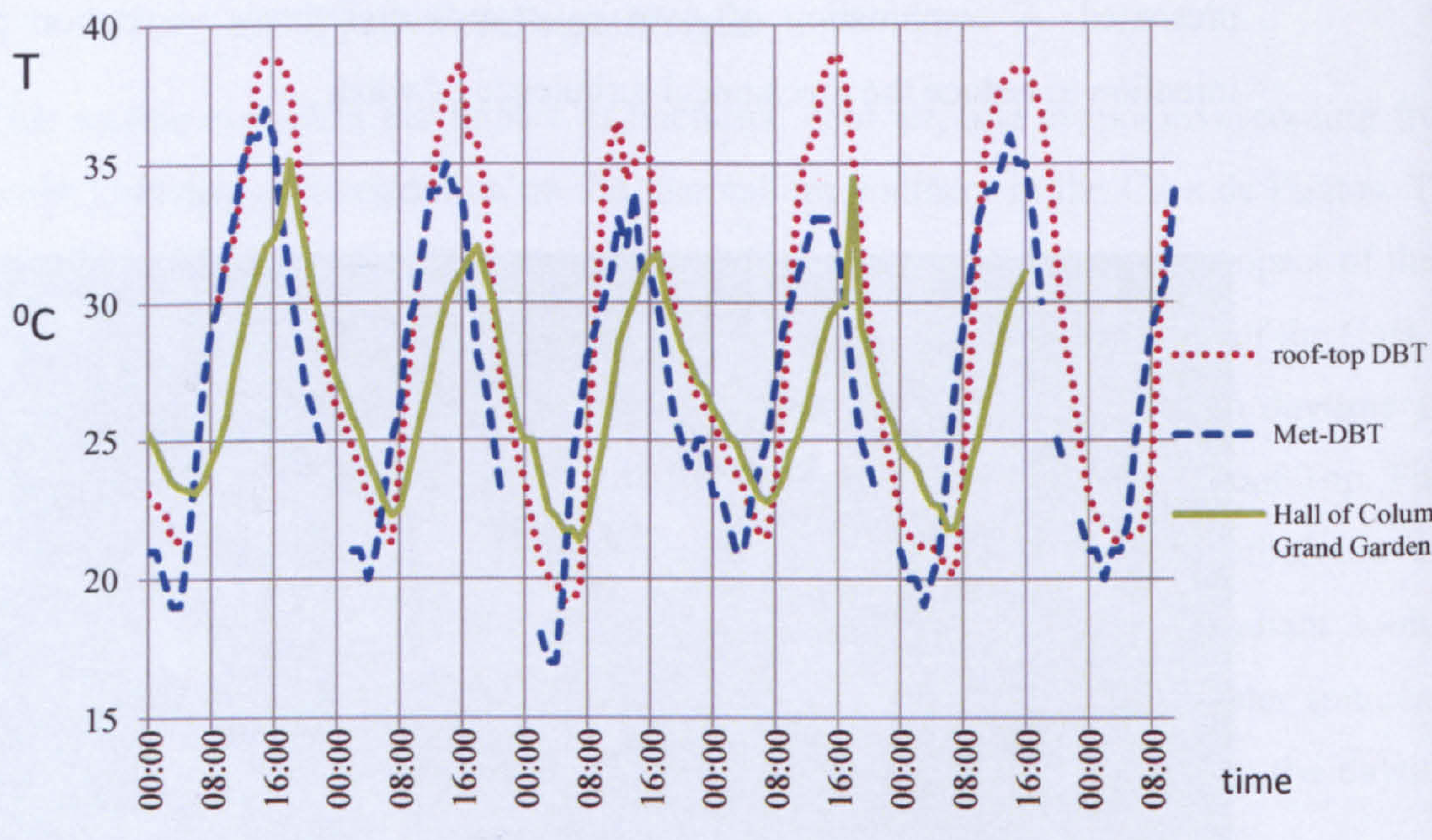


Fig. 6.2 the hourly variation of air temperature between the Roof Top, Grand Garden, and Meteorological station

It is predicted that in the night time when the general atmosphere is much cooler than the garden-courtyards, cool dense air descends from the open sky into the garden-courtyards (see fig.6.4). Sky conditions are different in the daytime when temperatures at the roof level are higher than temperatures in the garden-courtyards (see fig.6.3), which remain relatively cool throughout the day. It is predicted that the night time conditions cause nocturnal cool air to accumulate in the garden-courtyards and built spaces, and ultimately impact heat balance in the next day.

The field data shows nocturnal volumes of cool air accumulated in the courtyards space in the early part of the day. It is shown that the night time air temperatures from meteorological station for the period of study are as low as 17^0C (see fig.6.2). Low night time temperatures also impacted the building mass and consequently the thermal performance of the building. Heschong (1979) suggests that at night, cool air accumulate within courtyards in laminar layers and then settle in the surrounding rooms.

The low night time temperatures impacts the ground, building mass, water bodies and air.

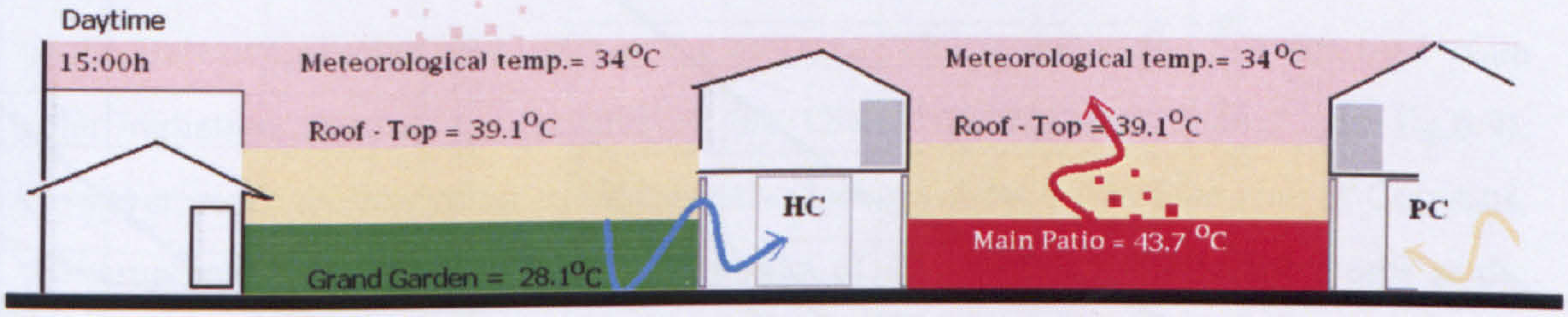


Fig. 6.3 The schematic diagram for stratification of air in the daytime at 15:00h in the Grand Garden and Main Patio

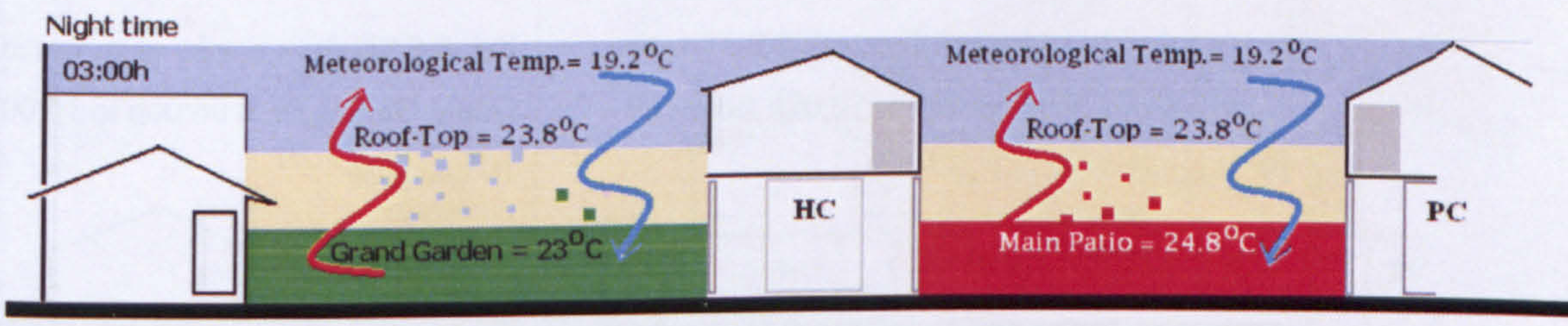


Fig. 6.4 The schematic diagram for stratification of air in the night time at 03:00h in the Grand Garden, and Main Patio

Daytime stratification of air is different from night time. Daytime stratification of air has the low temperature and dense air in the garden-courtyards, with hot and less dense air being at the Roof Top. This stratification naturally limits the movement of air between the open sky and the garden-courtyards (see fig.6.3). However, unlike the stratification in the garden-courtyards, daytime stratification in the Main Patio is different. The Main Patio has hot and less dense air at the bottom both in the daytime and night time (see fig.6.3 and fig.6.4). If daytime and night time temperatures are compared, the absence of solar heat results in narrower variation in temperature between the Main Patio and Roof Top. High temperature difference creates mutual air movement between the Main Patio and sky at all times. The field data suggests that daytime stratification do naturally isolate the conditions in the Grand Garden and Small Garden from the atmospheric turbulence; unlike night time when there is an inflow of cool air from an open sky (see fig.6.3 and 6.4).

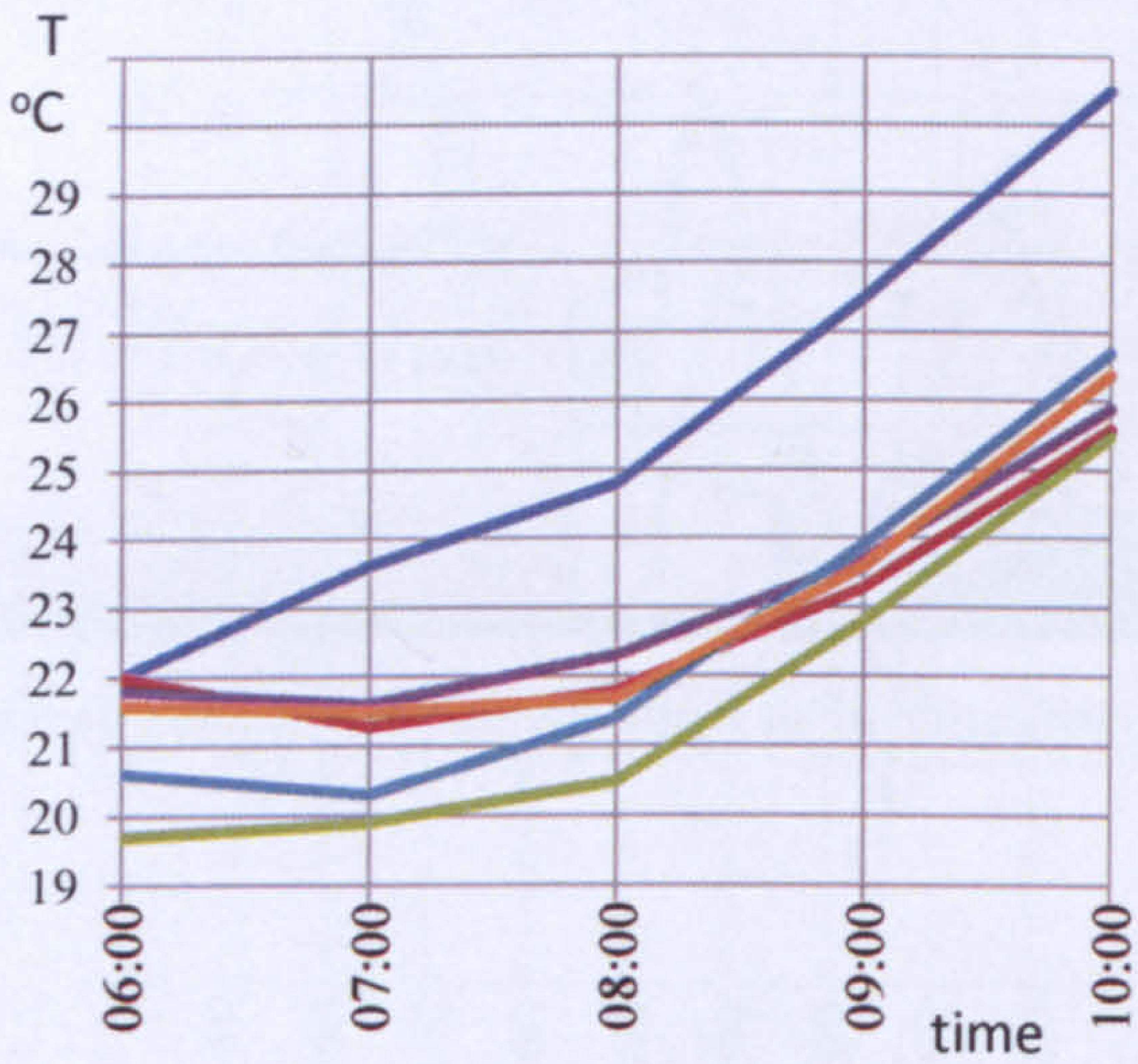


Fig. 6.5 Six days graphs of recorded DBT in the Small Garden from 06:00h to 10:00h from 13th – 19th August

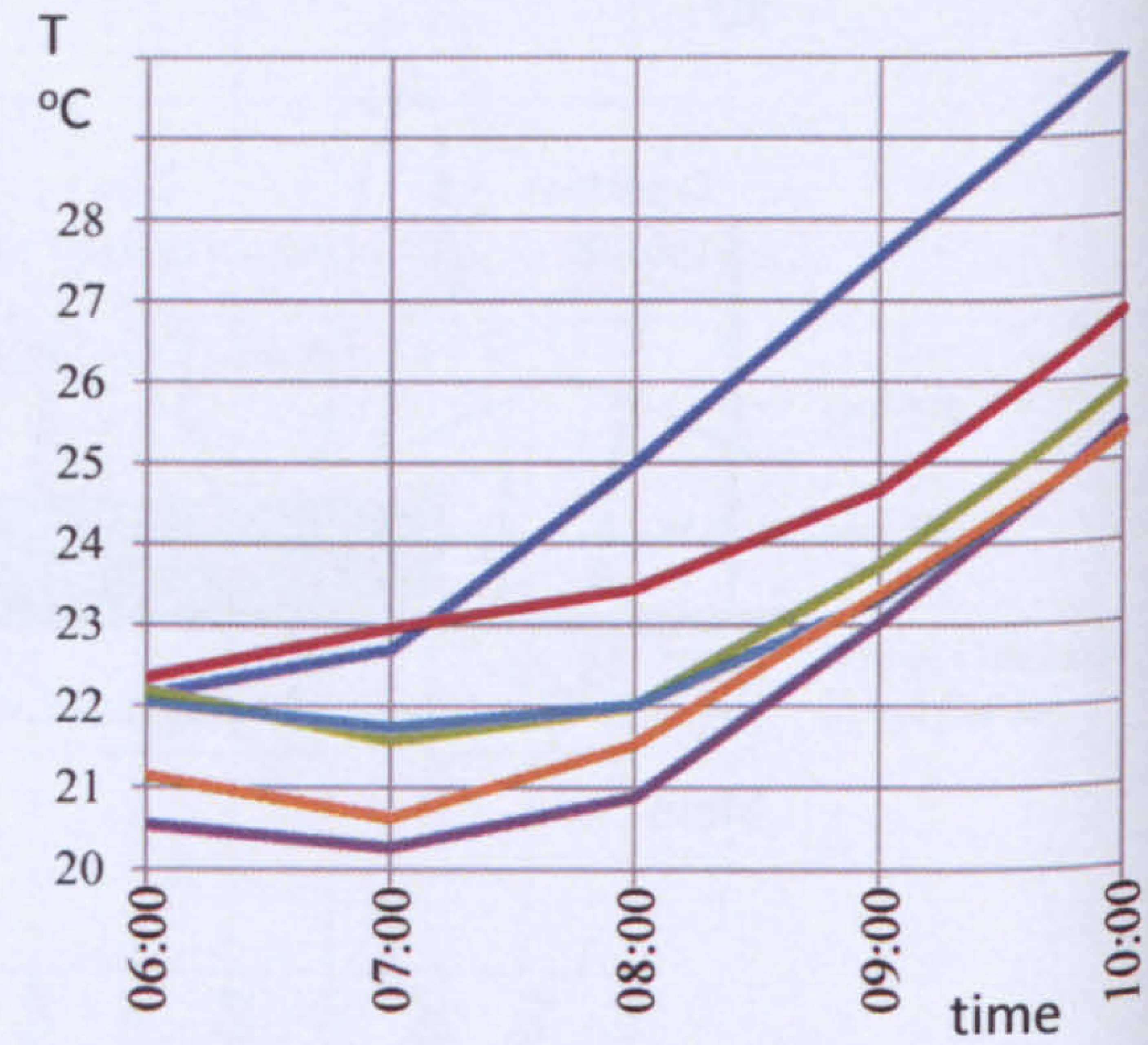


Fig. 6.6 Six days graphs of recorded DBT in the Grand Garden from 06:00h to 10:00h from 13th – 19th August

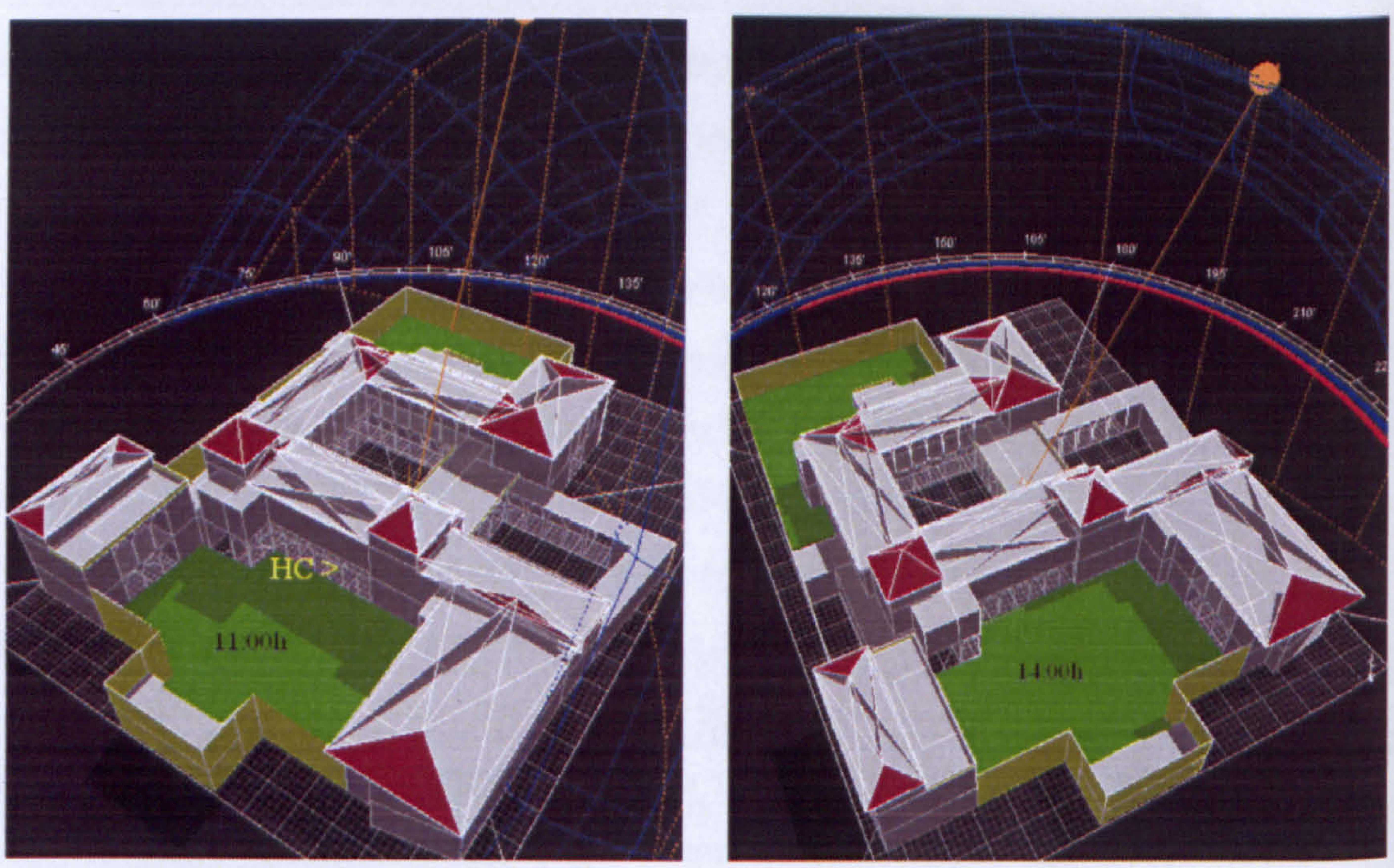


Fig. 6.7 Position of the shadow versus the Hall of Columns (HC) at 11:00h and 14:00h

In the daytime, the air temperature in the Grand Garden and Small Garden is affected by changing solar altitude (see fig.6.7 – 6.9). The recorded data shows that the air temperatures in the middle of Grand Garden rise above the air temperatures at the inlet of the Hall of Columns by 11:00h in the morning. This is due to the fact that by 11:00h solar radiation reaches the middle of the Grand Garden (see fig.6.7 and fig.6.9). However, since the recording sensors are also located at the inlet of the Hall of Columns, the temperatures that are recorded at the inlet (T_{HC}) represents the temperatures at the near end 'shaded part' of the Grand Garden.

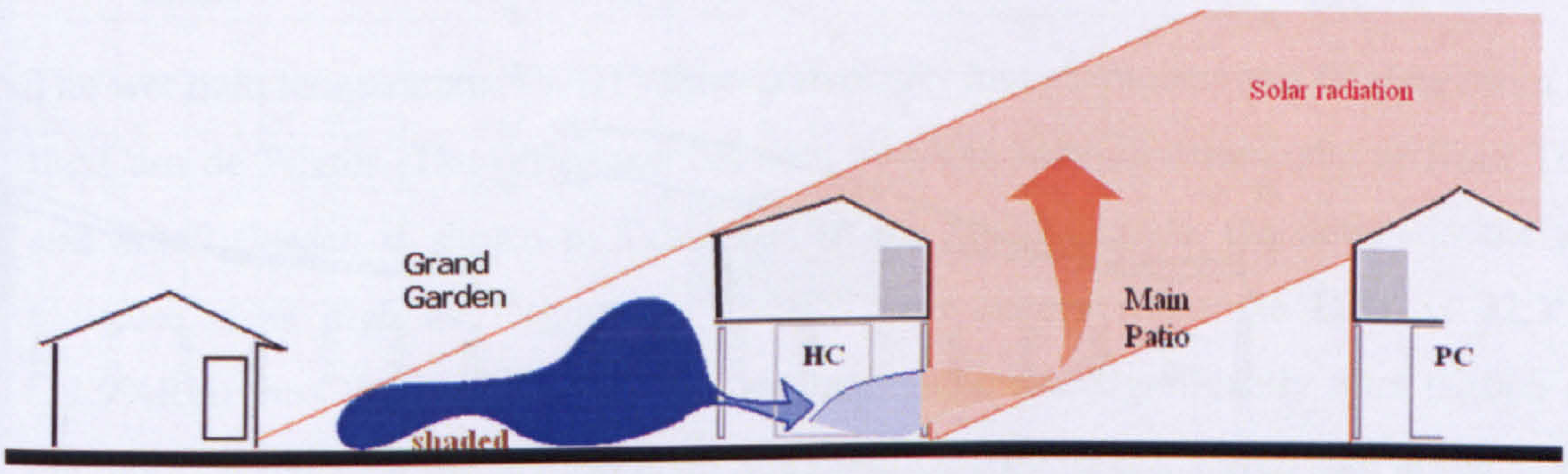


Fig. 6.8 Schematic diagram showing the possible model for evacuation of cool air and access to solar radiation in the Grand Garden (GG) at around 08:00h

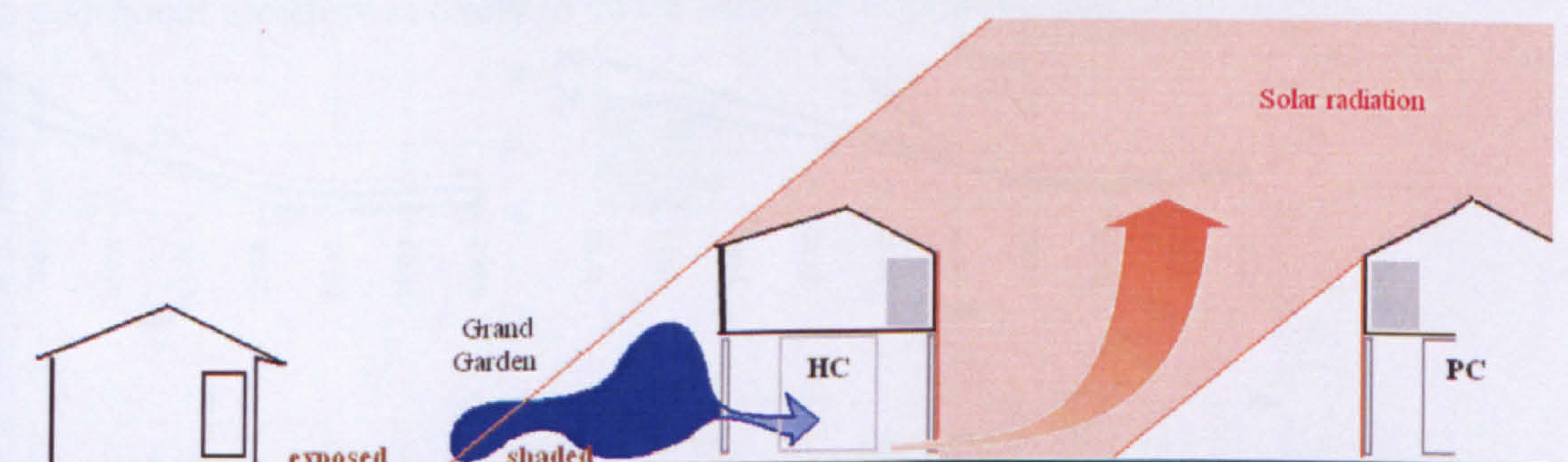


Fig. 6.9 Schematic diagram showing the possible model for evacuation of cool air and access to solar radiation in the Grand Garden (GG) at around 11:00h

Field data show that the temperatures in the middle of the Grand Garden rise to 30^{0}C by around 12:00h noon (fig.6.10). However, the temperatures that are recorded in the Hall of Columns have remained around 30^{0}C until 14:00h in the afternoon. It took around two hours (12:00h to 14:00h) for the temperatures on the shaded end of the Grand

Garden (T_{HC}) to rise to the level of the temperatures in the middle of the Grand Garden (see fig.6.10). The disparity is caused by the absence of vegetation in some parts of Grand Garden (see fig.6.16). Likewise, solar radiation has more access in the Main Patio due to absence of vegetation. The daytime temperatures in the Main Patio are as a result rising faster than the temperatures in the Grand Garden and Small Garden. It is evident that nocturnal cool air is lost when exposed to solar radiation unless it is kept under vegetation canopies.

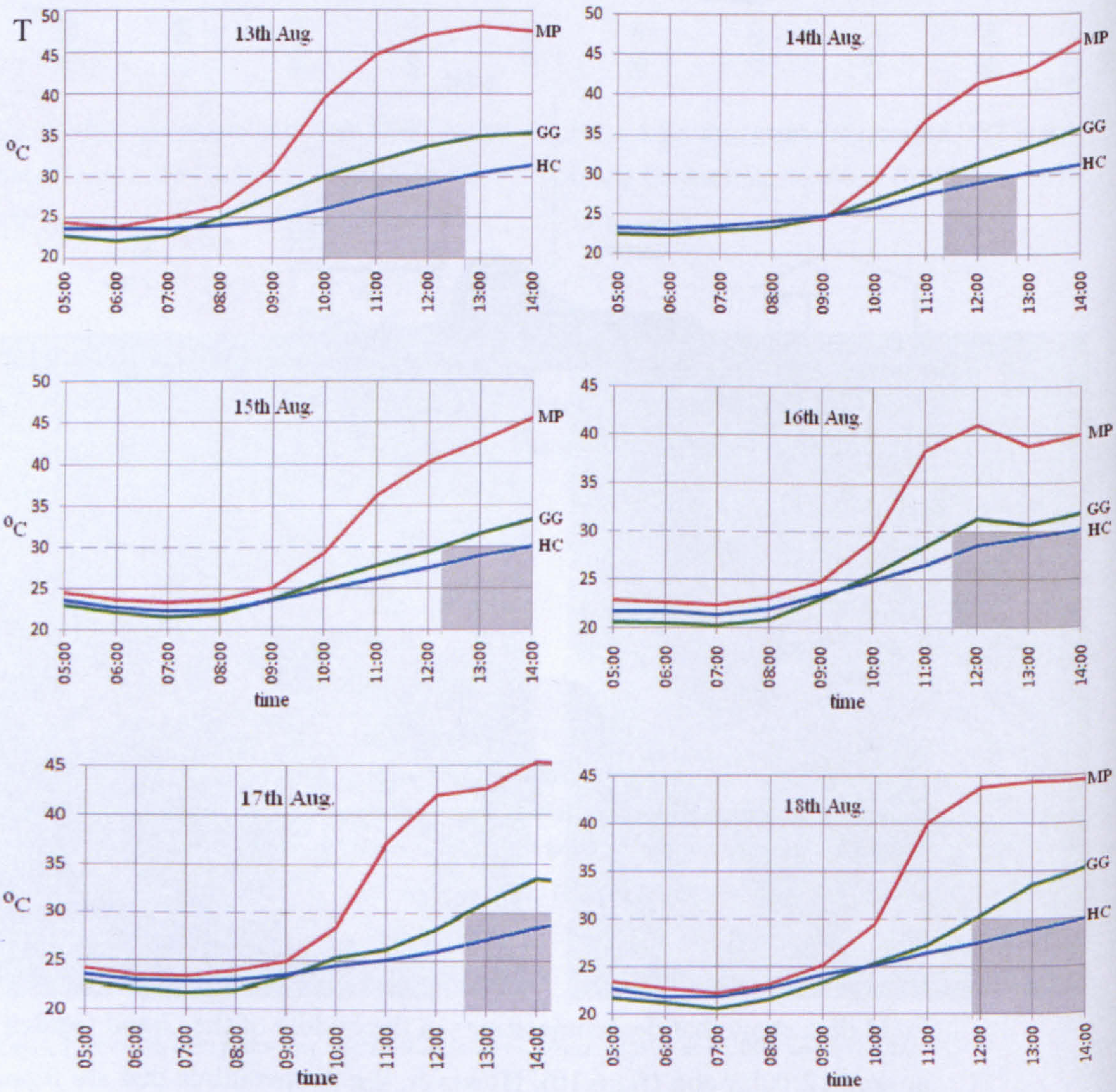


Fig. 6.10 The temperature swing between the Grand Garden (GG), Hall of Columns (HC) and Main Patio (MP) in the early part of the day

Although the physical space has remained stationary in the daytime; the radiant surfaces have changed with time; this happens as the solar altitude changes with time and suggests that the potential flow characteristics are also influenced by the changing location of irradiated surfaces. It is likely that although solar radiation does not move air through space, the location of irradiated surfaces changes, and hence relocate the driving force for thermal buoyancy within courtyards.

6.2.2 Evaporation from water and vegetation

The wet bulb temperatures (WBT) show potentially low air moisture in all data taken in the Casa de Pilatos. The difference between absolute humidity measured at Roof Top and Small Garden is shown in Table 6.1. In the Small Garden, the deficit in the air moisture is as high as 7.1g/m^3 by 13:00h. This occurs when the DBT is 32.3^{0}C (32.9%RH) thus WBT of 20.3^{0}C. The saturation line rise significantly after 09:00h in the morning reaching the highest level at 13:00h (see fig. 6.11). Given that at the same time of day the absolute humidity is greater in the Small Garden than at Roof Top, the additional moisture is likely to come from the vegetation and the fountains.

Table 6.1: The table showing the DBT, RH, WBT, humidity, and moisture to be added before saturation in the Small Garden (SG) and Roof Top (RT) on 15-Aug

Time (24h)	SG DBT (^{0}C)	SG RH (%)	SG WBT (^{0}C)	RT WBT (^{0}C)	RT Humidity (g/m^3)	SG Humidity (g/m^3)	Moisture required for saturation in the SG (g/m^3)
07:00	21.4	53.5	15.5	16.3	9.5	10.1	3.1
08:00	22.1	50.6	15.6	17.8	9.4	9.9	3.5
09:00	24.1	51.6	17.4	18.8	10.9	11.3	3.6
10:00	26.6	45.3	18.4	20.0	10.7	11.4	4.4
11:00	29.4	40.5	19.8	20.4	10.2	11.9	5.2
12:00	31.3	36.1	20.3	20.7	9.9	11.8	5.9
13:00	32.3	32.9	20.3	19.9	9.5	11.3	7.1
14:00	32.3	32.5	20.3	21.3	8.9	11.2	6.4
15:00	31.9	32.5	20.0	21.0	8.5	10.9	6.4
16:00	30.9	34.6	19.7	21.0	8.6	11.0	6.0
17:00	30.1	34.7	19.1	20.5	8.6	10.6	5.9
18:00	31.0	32.6	19.3	20.1	8.6	10.5	6.2
19:00	29.2	36.9	18.9	19.5	9.3	10.7	5.5

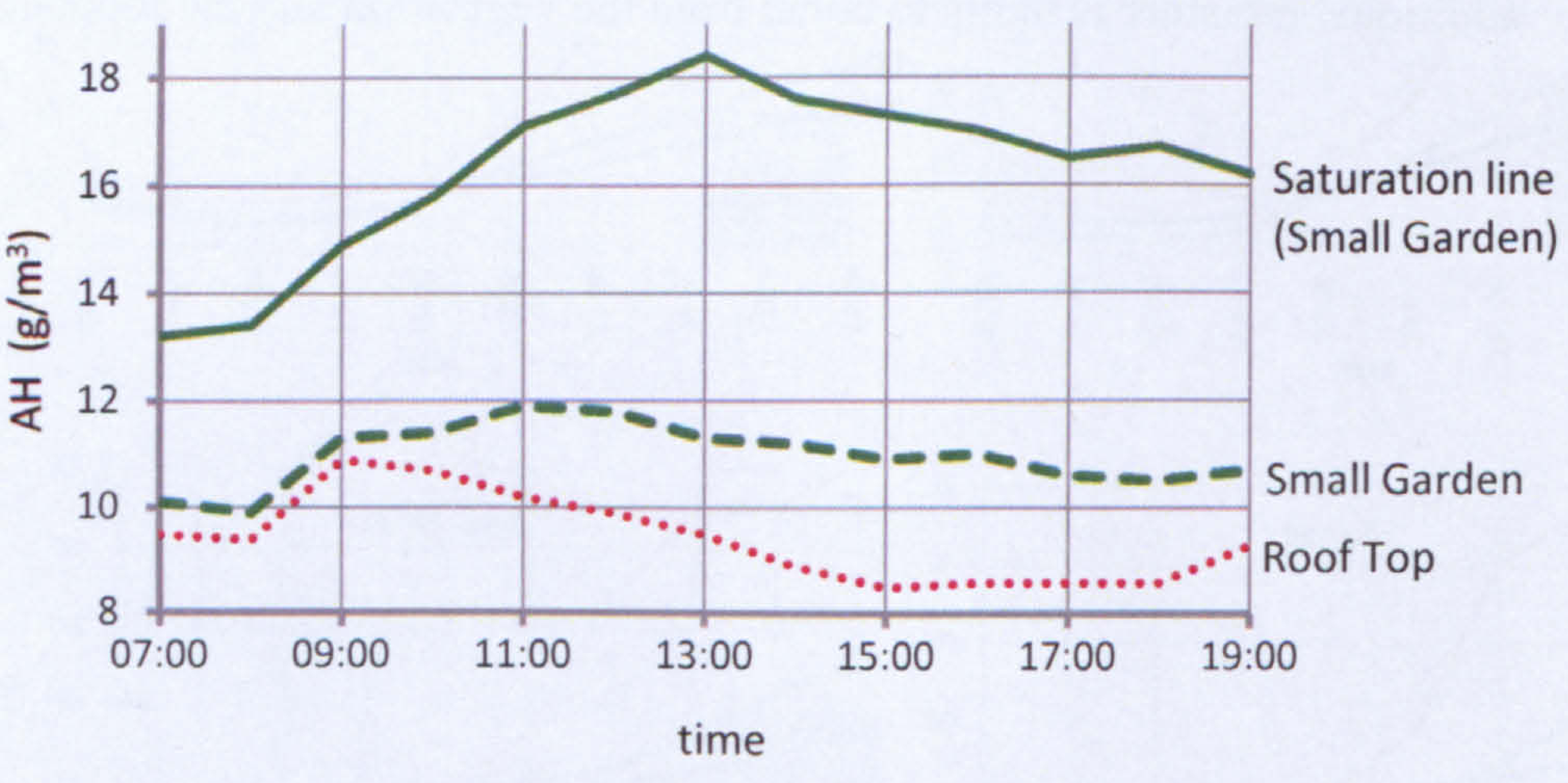


Fig. 6.11 Graph showing the relationship between the absolute humidity in the Small Garden and Roof Top

While the average temperature drops from 38.4^{0}C at the Roof Top to 31.9^{0}C in the Small Garden at 15:00h (a difference of 6.5k), the average moisture at the Roof Top is 8.5g/m^3 the average moisture in the Small Garden is 10.2g/m^3; a difference of 1.6g/m^3 (see Table

6.2). Unlike the conditions in the Small Garden, the data taken in the Grand Garden shows air with minor humidity variation in comparison to readings taken at the Roof Top (see fig.6.12). The average temperature drops from 38.4^{0}C at the Roof Top to 34.3^{0}C in the Grand Garden at 15:00h (a difference of 4.1K), and the average moisture increases by only 0.2g/m^3 (from 8.5g/m^3 at the Roof Top to 8.7g/m^3 in the Grand Garden). Low moisture in the Grand Garden is the evidence of the absence of vegetation coverage in some parts of this garden.

Table 6.2: Showing the hourly data recorded at 15:00h in the Grand Garden (GG), Small Garden (SG), and Roof Top (RT)

Date	Roof Top		Grand Garden		Small Garden	
	DBT	Humidity	DBT	Humidity	DBT	Humidity
13-Aug	40.2^{0}C	8.4g/m^3	34.6^{0}C	8.6 g/m^3	32.1^{0}C	10.2g/m^3
14-Aug	38.8^{0}C	4.3g/m^3	36.1^{0}C	5.5g/m^3	32.3^{0}C	6.8g/m^3
15-Aug	38.4^{0}C	5.1g/m^3	34.3^{0}C	5.8g/m^3	32.6^{0}C	6.4g/m^3
16-Aug	35.6^{0}C	11.7g/m^3	32.6^{0}C	11.2g/m^3	31.0^{0}C	13.3g/m^3
17-Aug	38.7^{0}C	11.1g/m^3	33.0^{0}C	10.9g/m^3	30.9^{0}C	11.8g/m^3
18-Aug	38.5^{0}C	10.5g/m^3	35.0^{0}C	10.4g/m^3	32.2^{0}C	12.4g/m^3
Average	38.4^{0}C	8.5 g/m^3	34.3^{0}C	8.7g/m^3	31.9^{0}C	10.2 g/m^3

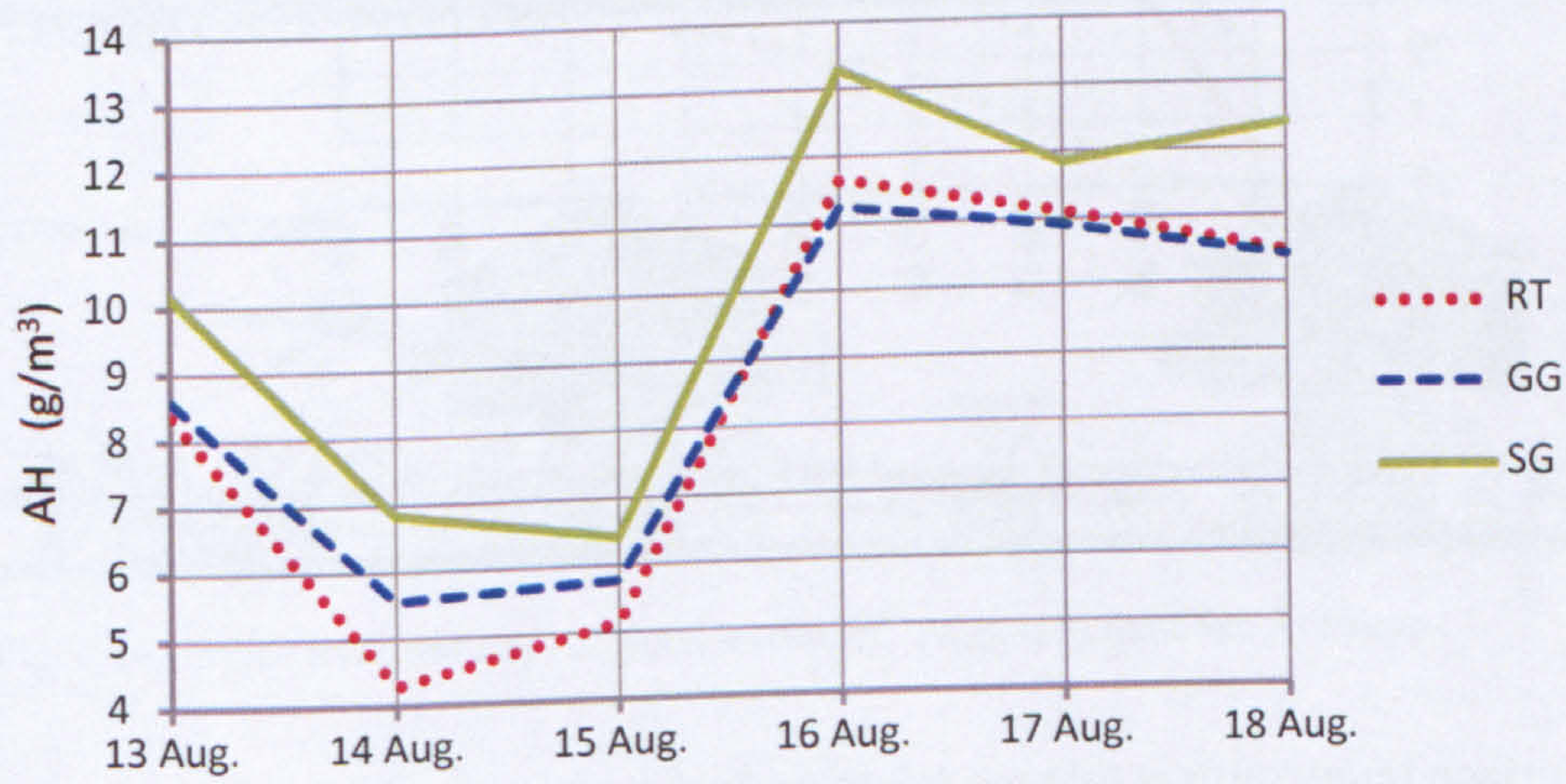


Fig. 6.12 The variation in the humidity (g/m^3) in the Grand Garden (GG), Small Garden (SG), and Roof Top (RT) at 15:00h

Although buildings mass impacts the environment in the garden-courtyards, lower DBT in the Small Garden and Grand Garden is mainly attributed to evapotranspiration. Through evapotranspiration, the plants naturally regulate their temperature and consequently the temperature of their surroundings. The impact of evapotranspiration from vegetation is evident in the difference between the data collected at the Roof Top and Small Garden. Evapotranspiration from an at least 1500m^2 of garden area has a big impact on the thermal properties of air in the garden-courtyards. Lower air temperatures are recorded in the Grand Garden and Small Garden as compared to the Roof Top and Main Patio (see Fig.6.13). With openings on either side, the Hall of Columns and Praetor Chamber provide a connection between the garden-courtyards and the Main Patio. It is suggested that these intermediate halls benefit from the conditions in the garden-courtyards.

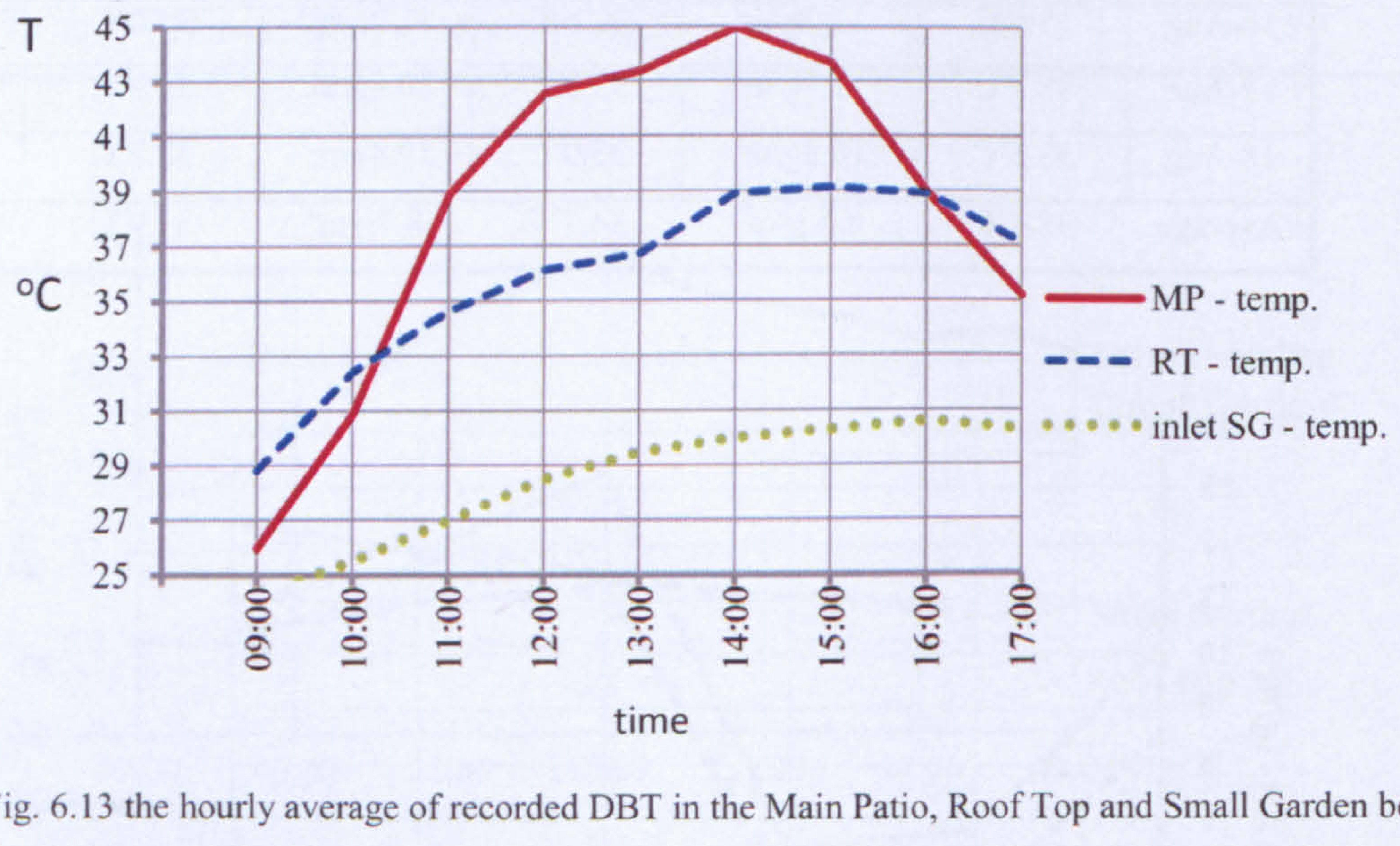


Fig. 6.13 the hourly average of recorded DBT in the Main Patio, Roof Top and Small Garden between 10:00h to 16:00h

Surface temperatures that are taken on leaf surfaces in the garden-courtyards are 2k – 7k lower than DBT (see fig.6.14). The surfaces of the vegetation on the lower level and shaded wet soil records the lowest temperatures (refer fig.6.14).This suggests that the garden-courtyards of the Casa de Pilatos held layers of stratified air with the coolest and most saturated air closer to the ground. More than half of lower level vegetation in the Small Garden is shaded by either the building or high level bushes or trees.

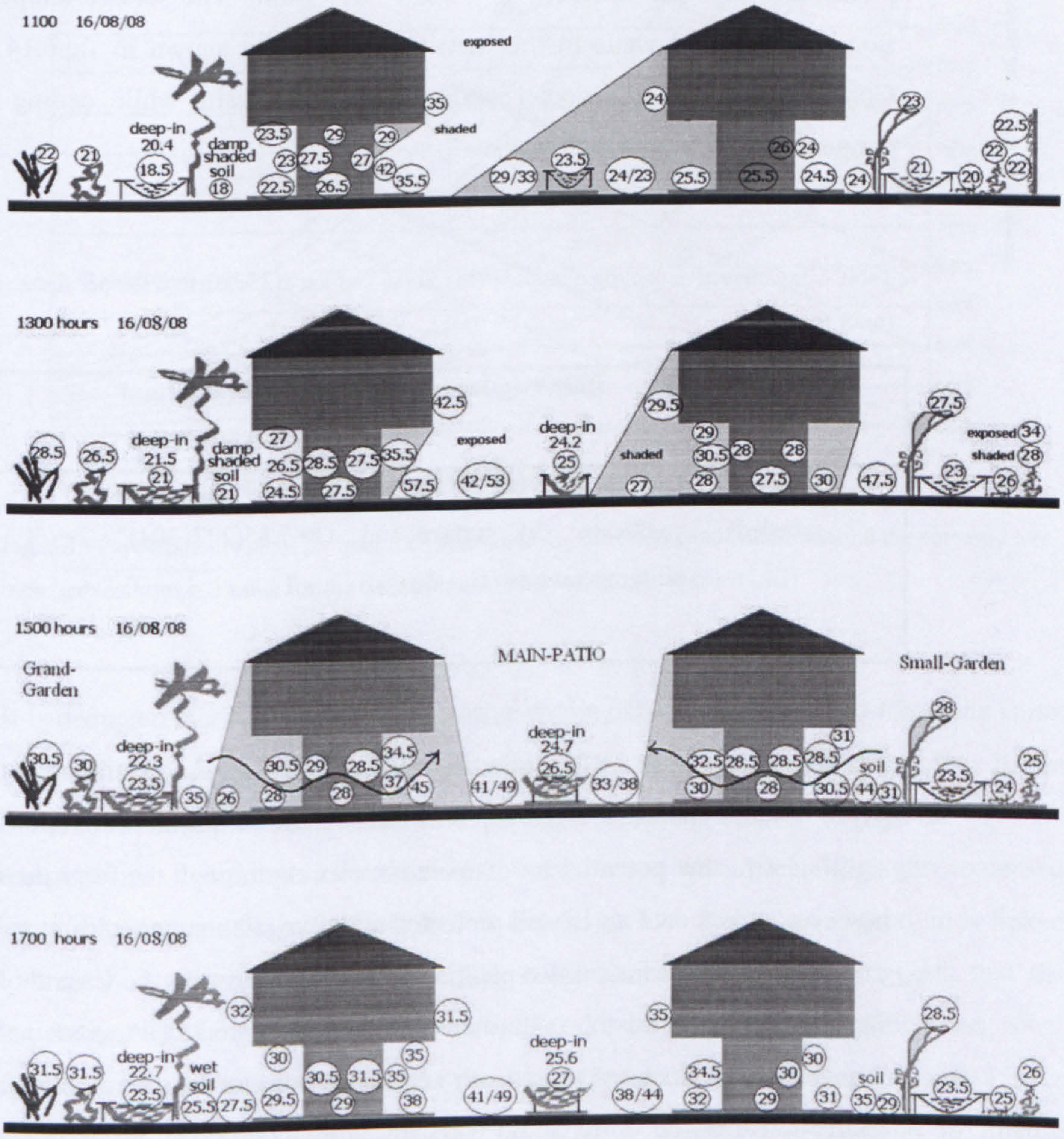


Fig. 6.14 surface temperatures recorded on the 16th August in the Casa de Pilatos

The calculations are carried out to estimate the amount of radiant cooling. The calculations in Table-6.3 use the surface temperatures taken from vegetation surfaces. The calculation of convective heat transfer in the Small Garden considers the convection coefficient (h_c) from Szokolay (2000 pp11). The h_c for a leaf assumes air velocity (v) of 0.5m/s and uses the equation; $h_c = 5.8 + 4.1v$ (ibid). The surface temperatures of the floor, ceiling, and walls in the transitional halls are shown in fig.6.14. The Hall of Columns floor records cooler temperatures than walls while ceiling has recorded temperatures 2k higher than walls.

Table 6.3: Convective cooling of a leaf in the Small Garden at 15:00h in watts per square metres (W/m^2) (refer fig.6.14)

	Item	Data required	Heat output calculation		Cooling output
	Leaf (shaded)	Convective heat transfer coefficient (h), surface and air temperatures (T_{wall} & T_{air})	$Q = h (T_{surface} - T_{air})$ Q= 7.85(297–304)		– 55W/m^2
			$T_{surface}$	T_{air}	
			24	31	

The data recorded at 15:00h over seven days in the garden-courtyards is plotted in the psychrometric chart (see fig.6.15). It is learnt from the psychrometric chart that there is significant further potential for evaporative cooling through the fountain and vegetation; however, unless cool air is well protected under vegetation canopies, it will be lost when exposed to solar radiation. Re-planting of the vegetation in the Casa de Pilatos reduces shading and exposed the nocturnal cool air (see fig.6.16). A combination of broken fountains and reduced shading from vegetation impacts the micro-climate in the garden-courtyards. Consequently, some parts of garden-courtyards are exposed to direct solar radiation.

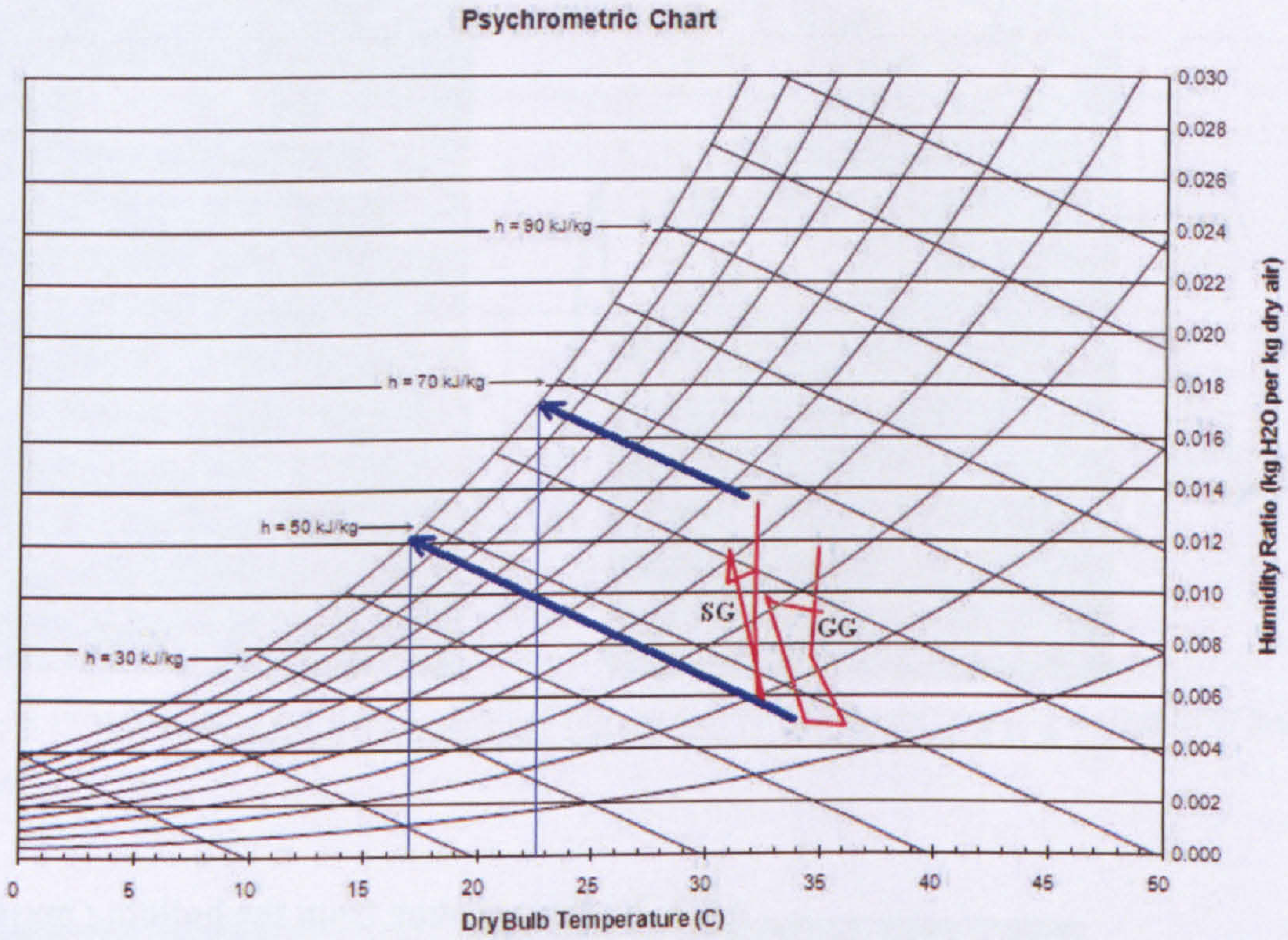


Fig. 6.15 Psychrometric chart plotting the variation in the environmental conditions and the potential wet bulb temperatures at 15:00h for the Grand Garden (GG) and Small Garden (SG)

It is deducted that the daytime evaporative cooling from vegetation and fountains is not sufficient to overcome the rate of dissipation that is instigated by solar heat; this is due to the temperatures in the middle of the garden-courtyards rising far beyond the wet bulb temperatures. It is possible the absence of vegetation in some parts of the garden caused a significant amount of cooling to be lost (fig.6.16). The absence of vegetation is linked to increased temperatures with changing solar altitude. This study suggests that the vegetation which is replanted before fieldwork and the mode by which the water fountains are operated has impact on the micro-climate in the garden-courtyards. Lower temperatures recorded at the inlet to the Hall of Columns are related to intense vegetation and absence of solar radiation at the near end of the Grand Garden.

Fig. 6.16 Replanting of vegetation in some parts of the Grand Garden

6.2.3 Radiant cooling from the building mass

This study suggests that the radiant heat gains from walls, floor and the ceiling do significantly influence the heat balance in the transitional spaces of the multiple-courtyards buildings. The impact of building mass is evident in three hours delay observed between the DBT taken at the Roof Top and Praetor Chamber (fig.6.17). The DBT in figure 6.17 starts at 28^0C to show the magnitude fluctuation beyond the range of thermal comfort (to be discussed later in the chapter), and surface temperatures recorded in the Praetor Chamber at 15:00h. The recorded surface temperatures do also show the floor consistently at lower temperature than walls, and ceiling at around 2k higher than walls (refer fig.6.14). This section uses convective heat transfer coefficient and surface and air temperatures to determine the flux of heat from the 166 square metres of walls in the Hall of Columns. For a summary of field data used in these calculations, refer Table-5.8. Hourly variation in heat balance is presented in Table 6.4 to Table 6.7. The aim of these numerical calculations is to determine the implication of the variation in the radiant heat on the heat balance in the Hall of Columns.

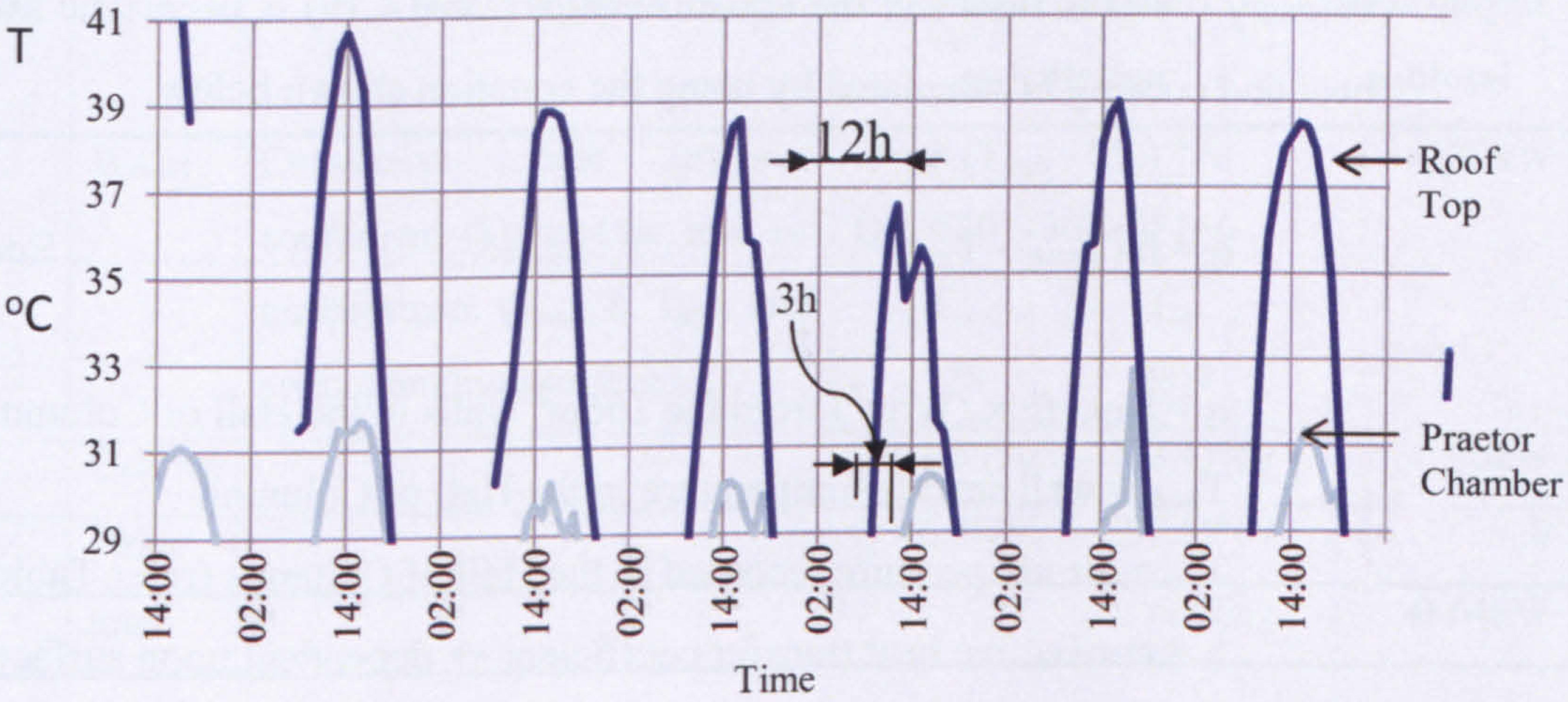


Fig. 6.17 The outdoor DBT taken at the Roof Top and the Praetor Chamber showing the impact of thermal mass

Fig. 6.18 Photograph of the Hall of Columns taken in the morning

The calculation of convective heat transfer in the Hall of Columns uses the convection coefficient (h_c) from Szokolay (2000 pp11). The Convective heat transfer coefficient (h_c)

for ceiling and walls assumes still air. The coefficient (h_c) on the floor assumes air velocity (v) of 0.1m/s and the equation ($h_c = 5.8 + 4.1v$) is used. The impact of radiant heat and cooling is calculated by using the equation shown below.

$$q = h\,(T_{wall} - T_{air}) \qquad \text{Equation (6.1)}$$

q = Heat flux (W/m^2) from the $166m^2$ walls in the Hall of Columns

T_{wall} = wall surface temperature in the Hall of Columns

T_{air} = air temperature recorded in the Hall of Columns (refer Table 5.8)

h = convective heat transfer coefficient → dependent upon surface orientation

Until 11:00h in the morning, the surface temperatures in the Hall of Columns are higher than its air temperature, and contribute around 0.7kW in heat gains (see Table 6.4). The air temperature remains below the surface temperatures in the halls until midday. Heat gains at 09:00h can be attributed to direct solar radiation on the floor surface of the hall when the solar altitude is low (see Fig.6.18). In this period, the building mass in the Hall of Columns and Praetor Chamber induce radiant heating and not cooling (Table 6.4). The Tables 6.4 to Table 6.7 are used to present the impact of building mass on the cooling loads in the Hall of Columns at 11:00h, 13:00h, 15:00h, and 17:00h.

Table 6.4: Indoor surface heat balance in the Hall of Columns at 11:00h

No.	Item	Data required	Heat output calculation	Heat output subtotal
1.	Walls	Convective heat transfer coefficient (h), surface and air temperatures (T_{wall} & T_{air}), and area of emitting surface (A).	$Q = h\,(T_{wall} - T_{air}) * A$ $Q = 3(300.3 - 299.5) * 166$ T_{wall}: 27.3, T_{air}: 26.5	0.40kW
2.	Ceiling		$Q = 1.5(302 - 299.5) * 69$	0.26kW
3.	Floor		$Q = 6.2(299.5 - 299.5) * 69$	0
4.	total		heating	0.66kW

Table 6.5: Indoor surface heat balance in the Hall of Columns at 13:00h

No.	Item	Data required	Heat output calculation		Heat output subtotal
1.	Walls	Convective heat transfer coefficient (h), surface and air temperatures (T_{wall} & T_{air}), and area of emitting surface (A).	$Q = h (T_{wall} - T_{air}) *A$ Q= 3(301–302.4)*166		-0.70kW
			T_{wall}	T_{air}	
			28	29.4	
2.	Ceiling		Q =1.5 (303 – 302.4)*69		0.06kW
3.	Floor		Q =6.2(299.5–299.5)*69		0
4.	total		cooling		-0.64kW

Table 6.6: Indoor surface heat balance in the Hall of Columns at 15:00h

No.	Item	Data required	Heat output calculation		Heat output subtotal
1.	Walls	Convective heat transfer coefficient (h), surface and air temperatures (T_{wall} & T_{air}), and area of emitting surface (A).	$Q = h (T_{wall} - T_{air}) *A$ Q = 3(301.8– 304)*166		-1.10kW
			T_{wall}	T_{air}	
			28.8	31.0	
2.	Ceiling		Q = 1.5(303.5 – 304)*69		-0.05kW
3.	Floor		Q = 6.2(301 – 304) *69		-1.30kW
4.	total		cooling		-2.45kW

Table 6.7: Indoor surface heat balance in the Hall of Columns at 17:00h

No.	Item	Data required	Heat output calculation		Heat output subtotal
1.	Walls	Convective heat transfer coefficient (h), surface and air temperatures (T_{wall} & T_{air}), and area of emitting surface (A).	$Q = h (T_{wall} - T_{air}) *A$ Q = 3(304–304.8) *166		-0.4kW
			T_{wall}	T_{air}	
			31.0	31.8	
2.	Ceiling		Q=1.5 (306 – 304.8) *69		-0.1kW
3.	Floor		Q =6.2 (302 – 304.8)*69		-1.2kW
4.	total		cooling		-1.7kW

It is observed that after 12:00 noon, the impact of building mass is desirable because the recorded air temperatures are higher than indoor surface temperatures. By 13:00h, cooling is estimated to be around 0.6kW (8.7W/m^2) (see Table 6.5). The walls in the Hall of Columns contribute up to 2.5kW (36.2W/m^2) in radiant cooling by 15:00h (see Table 6.6). Additionally, the impact of radiant cooling goes down to 1.7kW (24.6W/m^2) at 17:00h in the afternoon (see Table 6.7). At this time, the outdoor air temperatures 'Roof-Top' starts to fall. It is shown that lower night time temperatures remove heat from the building mass and reduce cooling loads in the following day.

6.3 Drivers for yard-to-yard airflows

The magnitude and pattern of natural convection flows through the transitional spaces between multiple-courtyards depends on the nature and strength of the driving forces. The DBT recorded in the garden-courtyards is much lower that the Main Patio due to trapping of night time cool air in the garden courtyards (in the morning), in conjunction with the evapotranspiration of vegetation and evaporative cooling from water sources (see fig.6.19). The layout of multiple-courtyards buildings encourages the flow path for natural convection through the Hall of Columns and Praetor Chamber, to take advantage of the temperature differences between the garden-courtyards and the Main Patio.

This section analyses the natural convection through the transitional spaces in the Casa de Pilatos. The impact of buoyancy 'stack' forces is calculated. The calculation of buoyancy effect take account of the height between the inlet and outlet of the airflow going through the Hall of Columns as an intermediate space located between the Grand Garden and Main Patio. The calculation of stack effect considers the high level sky window in the Main Patio as an outlet for air going through the Hall of Columns. The impact of local wind patterns and urban layout is also determined.

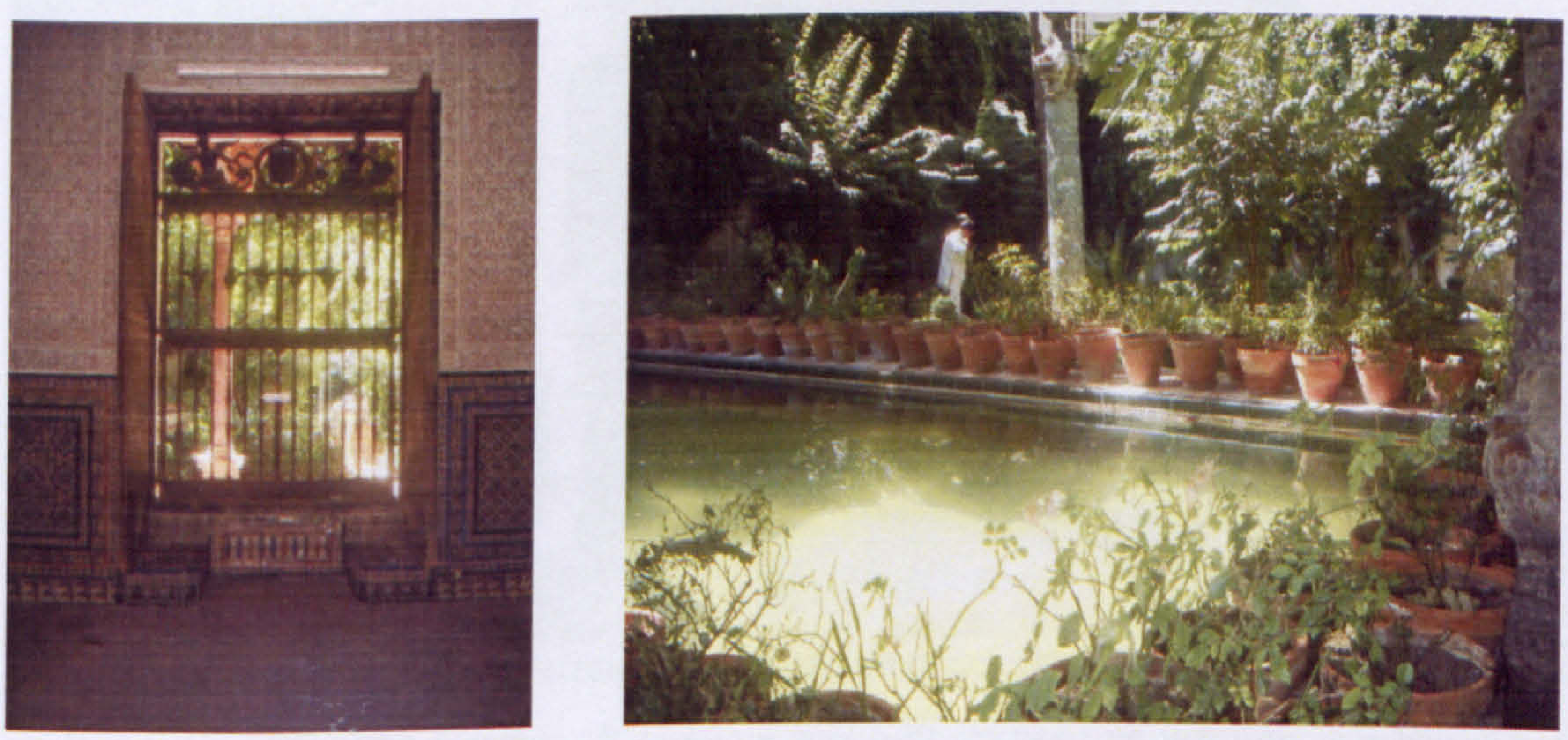


Fig. 6.19 The window inlet in the Praetor Chamber (left) and part of the Small Garden in the Casa de Pilatos (right)

6.3.1 Natural convection between courtyards

The drivers for natural convection of cool air through the transitional spaces combine factors such as buoyancy (stack forces), evaporative cooling, radiant heat, and the magnitude and direction of wind. The Hall of Columns and Praetor Chamber have a single inlet (two metres wide) each connecting the spaces to their respective gardens (see fig.6.19). The two outlets windows and the entry door on the opposite wall of both spaces (Hall of Columns & Praetor Chamber) links these spaces to the Main Patio. The area of the inlet window (2.4m^2) is used to calculate the volume flow rates. These are plotted against daytime hours (fig.6.21) and 24 hours period (fig.6.22). Unlike 24h period, daytime volume flow rates increase steady with time. This study suggests that the horizontal transfer of cool air experienced at the inlet is mainly attributed to natural convection.

Fig. 6.20 Cross section of the Hall of Columns showing natural convection from the Grand Garden

Fig. 6.21 volume flow rates over the daytime

Fig. 6.22 Volume flow rate over 24 hours period

The field data indicates that thermal equilibrium between the courtyards has a major role on the distinctive flow patterns. It is suggested that thermal convection is a result the variation of thermal condition between courtyards which happens when the air in the Main Patio becomes less dense and rises; the immediate cooler air from the garden-courtyards then moves to replace it. Cool air is then heated and the process continues, forming convection current. A steady flow of air is recorded in the transitional spaces, and the size and position of openings in the Praetor Chamber and Hall of Columns regulate the inflow of air. It is suggested that cooler air from the garden-courtyards replaces the hot buoyant air in the Main Patio, and the functional spaces between the cool and hot courtyards experience a constant flow of cool air through their inlet windows (fig.6.20 and fig.6.23).

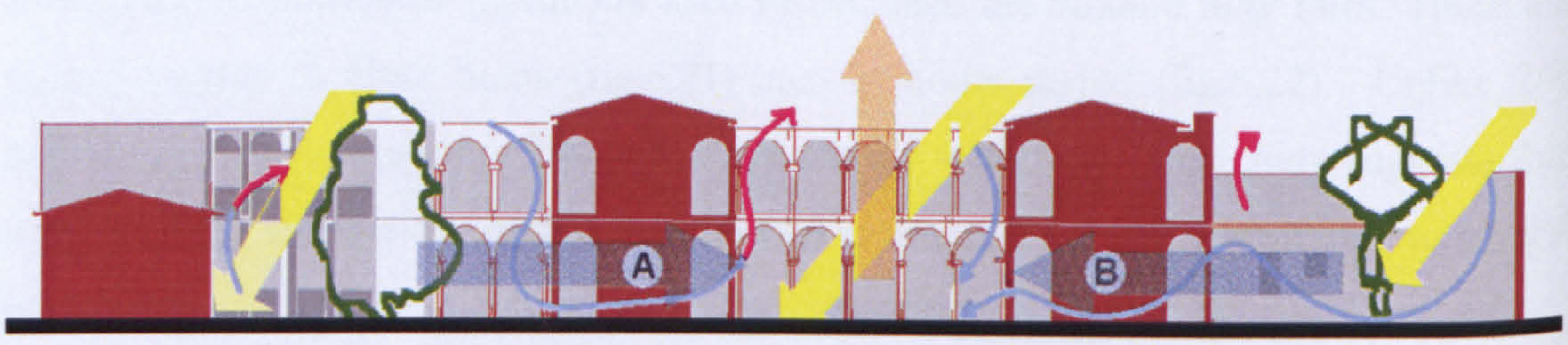


Fig. 6.23 Theoretical patterns of thermal convection flows

The temperature differences suggest that the variation of air density is largely influenced by the radiant heat from building and vegetation surfaces. Because solar radiation is the heat source, temperature in the Main Patio rises considerably after 09:00h when the paved courtyard is exposed to solar radiation. There is variation of up to 25K between the surface temperatures in the Main Patio and the garden-courtyards in the daytime (see fig.6.24). Radiant heat from the base of the Main Patio is transformed into convective energy and provides the mechanism for displacement of air.

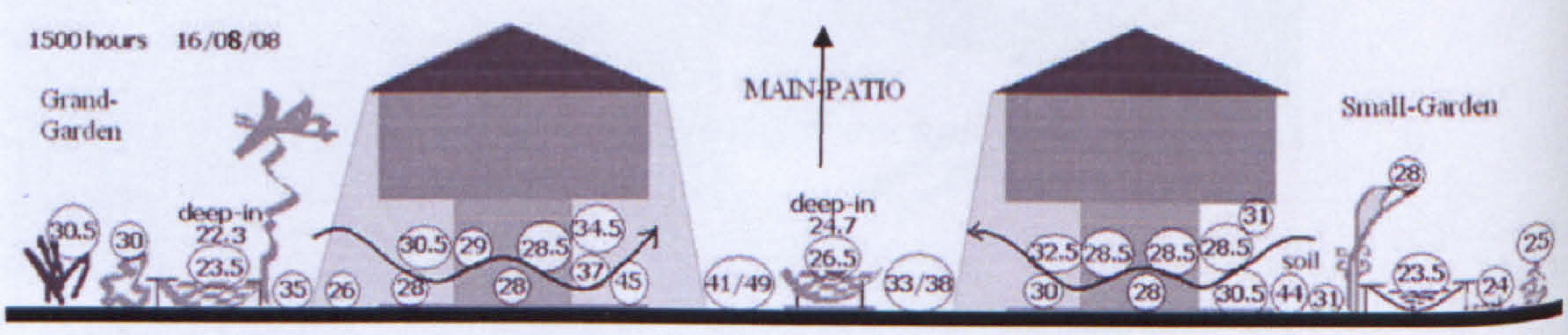


Fig. 6.24 Illustration of the impact of surface temperatures in the Casa de Pilatos

There is a wide difference in temperature between the Main Patio and garden-courtyards. And as such the temperatures in the Grand Garden rise on average by only 4k between 12:00h and 16:00h as opposed to the temperatures in the Main Patio which increase by 14k (fig.6.25). A difference of at least 10k is sustained across courtyards between 13:00h and 17:00h. The difference in the thermal properties of the air in the garden-courtyards and Main Patio indicates major influence on the convective flow of the air.

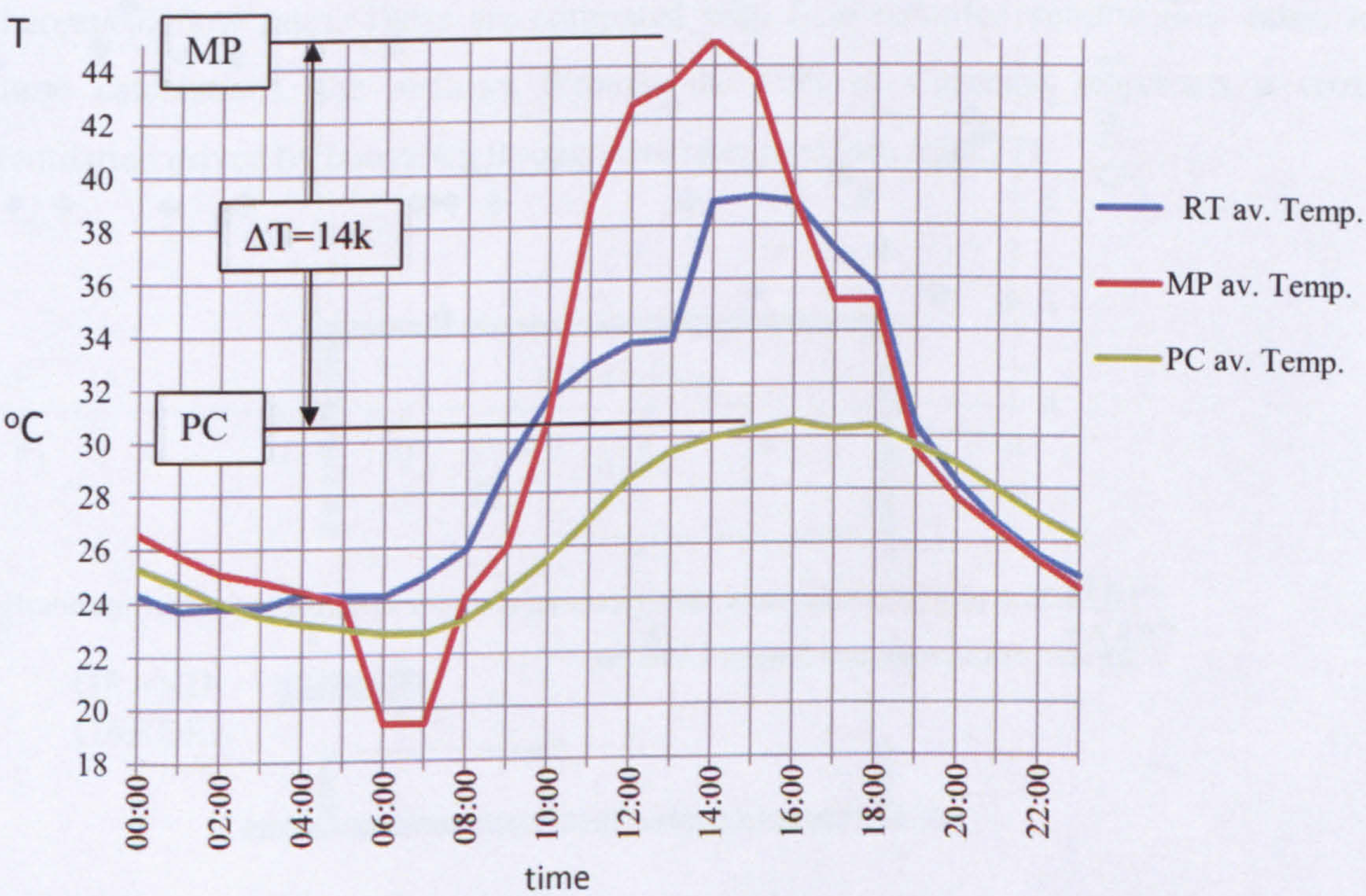


Fig. 6.25 The average of hourly DBT (^{0}C) recorded in the Praetor Chamber (PC) and Main Patio (MP) recorded on 12th – 19th August

The field data does not show a strong correlation between the volume flow rates and temperature differences (see fig.6.26), although, the site conditions suggest that advection has taken place at a rate that is driven by the variation in the thermal condition within courtyards. There is however multiple contributing factors that influence the flow of cool air from the garden-courtyards through the transitional spaces. It is conjectured that the changing solar altitude impacts the location of radiant surfaces and consequently the convective flow of air. In view of the fact that the location of radiant surfaces have significantly changed with time, the dynamic response in the flow field would also be affected by the position of the shade and shadow. Local wind regime is another factor that needs to be considered.

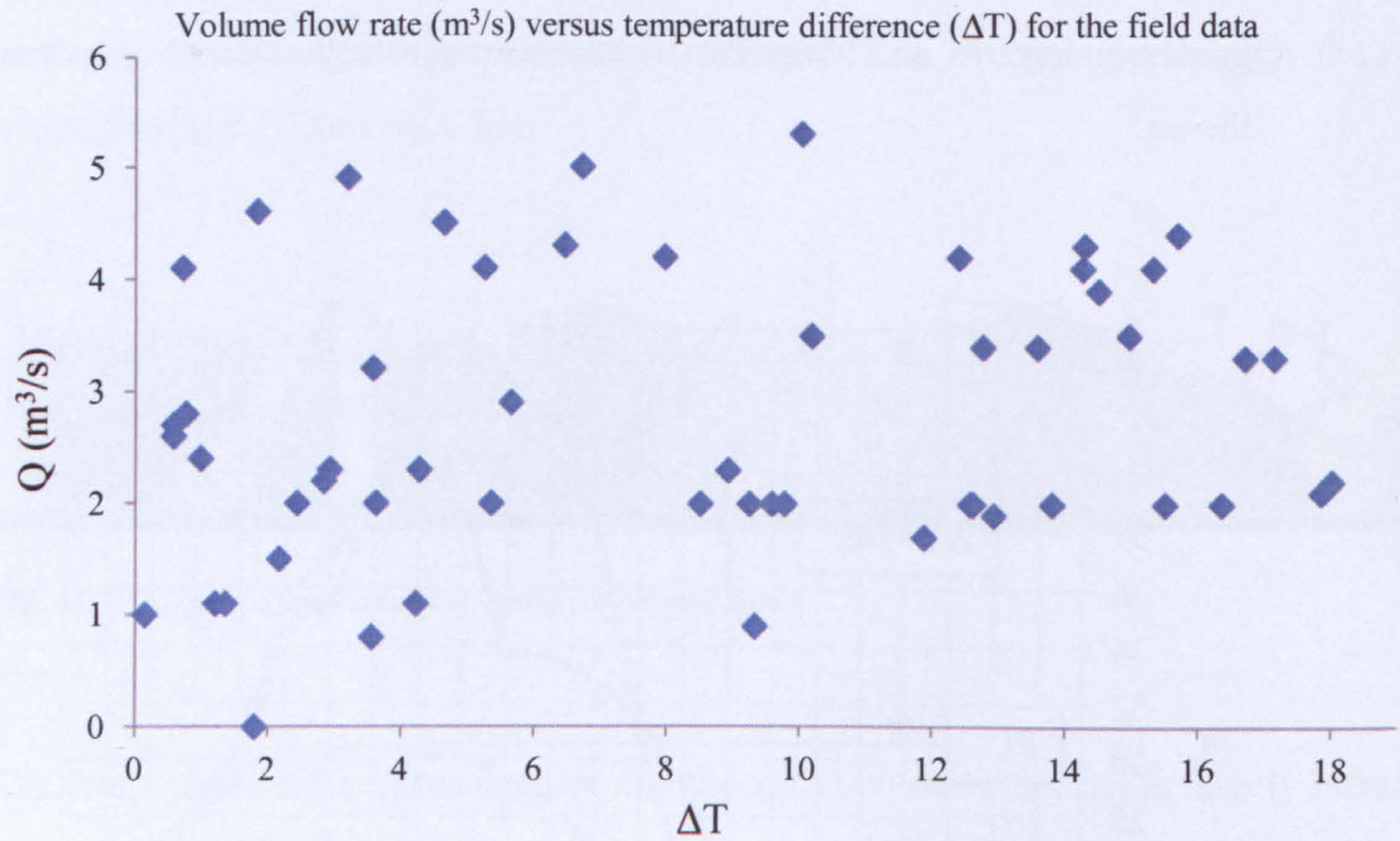


Fig. 6.26 A plot of volume flow rates versus temperature differences for daytime hourly data collected in the Hall of Columns and Praetor Chamber

6.3.2 Buoyancy as a driver

This section considers buoyancy-driven flows between the inlet and outlet openings in the Hall of Columns. It shows that the garden-courtyards store the cool and denser air while the air in the Main Patio is warm and less dense. This is because the garden spaces are shaded and insulated from solar radiation, and vegetation provides an environment in which thermal radiation is attenuated. The temperature differences between the Grand Garden and Main Patio are used in Equation 6.2 to calculate the theoretical flow rates. These are compared with field recorded volume flow rates. In these calculations, the airflows through the Hall of Columns represents a cross ventilation driven by buoyancy through two openings (see fig.6.27).

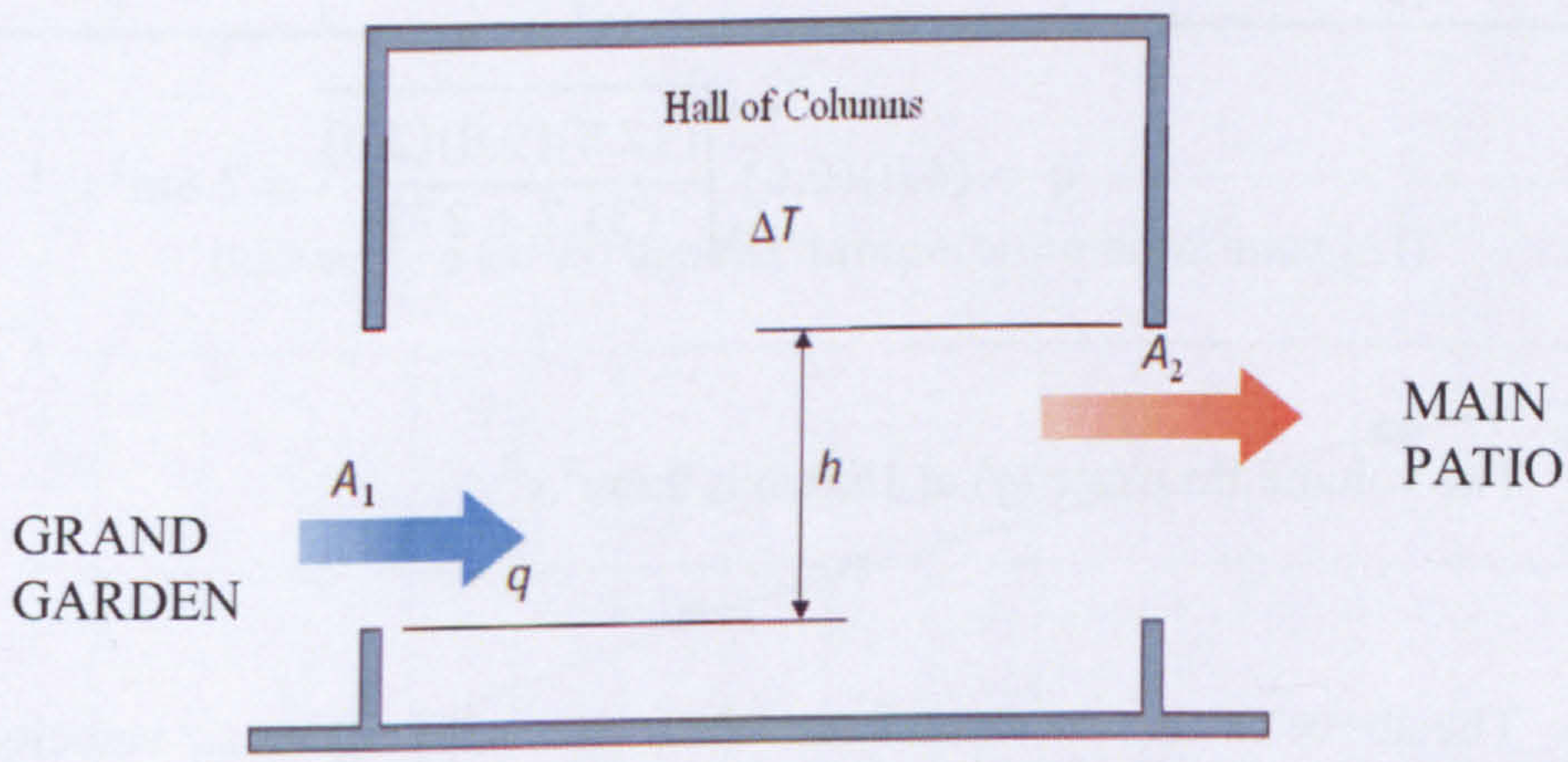


Fig. 6.27 Buoyancy driven cross ventilation

Area A of the opening is required to give a ventilation rate q for a specified value of h is:

$$q = AC_d\sqrt{\frac{\Delta Tgh}{(T_I + 273)}} \quad (source: CIBSE\ AM10\ pp45) \quad \ldots \quad (6.2)$$

Where q is the ventilation rate ($m^3.s^{-1}$), A is the area of an opening (m^2), C_d is the discharge coefficient, T_I is the internal temperature (^0C), ΔT is the difference between the internal and external air temperature (K), g is the gravitational force per unit mass ($m.s^{-2}$) and h is the height between openings (m).

A discharge coefficient C_d of 0.6 is used to account for frictional losses due to the configuration of the openings. Due to the law of conservation of mass, the volume flow rate (q) will be the same regardless of variation in sizes between inlet and outlet openings. The area A would represent the area of the inlet window which is $4.8m^2$. The internal temperature (T_I) is 31.2^0C at 15:00h is employed. The internal and external air temperature is represented by the temperatures taken at the inlet to the Hall of Columns and the one taken in the Main Patio respectively, hence a temperature difference (ΔT) of 12.5K at 15:00h is employed. The gravitational force per unit mass (g) is $9.8m/s^2$. The height between inlet and outlet openings (h) is approximately 2.0m. The volume flow rate (q) is shown below.

$$q = (4.8)(0.6)\sqrt{\frac{(12.5)(9.8)(2.0)}{(31.2+273)}} = 2.6m^3s^{-1}$$

The volume flow rate (q) at 15:00h is $2.6m^3.s^{-1}$.

The above calculated value for air flow rates suggests an air velocity (υ) of 0.5m/s. The field recorded air velocity through the Hall of Columns and Praetor Chamber ranges between 0.4m/s and 1m/s at 15:00h. The average of all air velocity data recorded at 15:00h is 0.7m/s. The results are shown in Table 6.8.

Table 6.8: The volume flow rates (q) through the Hall of Columns calculated using buoyancy equation 6.3 and the daytime temperatures difference (ΔT) taken from field study.

Time	T_{HC} (^0C)	T_{MP}-T_{HC} (ΔT)	T_{MP} (^0C)	Met. station DBT	Buoyancy flows q (m^3/s)	Theoretical Air Velocity (m/s)
08:00	23.1	1.1	24.2	28.4	0.8	0.2
09:00	24	2.0	26.0	29.8	1.0	0.2
10:00	25.2	5.7	30.9	31.4	1.8	0.4
11:00	26.6	12.3	38.9	32.6	2.6	0.5
12:00	27.9	14.7	42.6	33.6	2.8	0.6
13:00	29.1	14.3	43.4	34.2	2.8	0.6
14:00	30.4	14.6	45.0	34.6	2.8	0.6
15:00	31.2	12.5	43.7	34.0	2.6	0.5
16:00	31.7	7.3	39.0	33.0	2.0	0.4
17:00	32.1	3.1	35.2	30.8	1.3	0.3
18:00	32.8	2.3	35.2	28.6	1.1	0.2

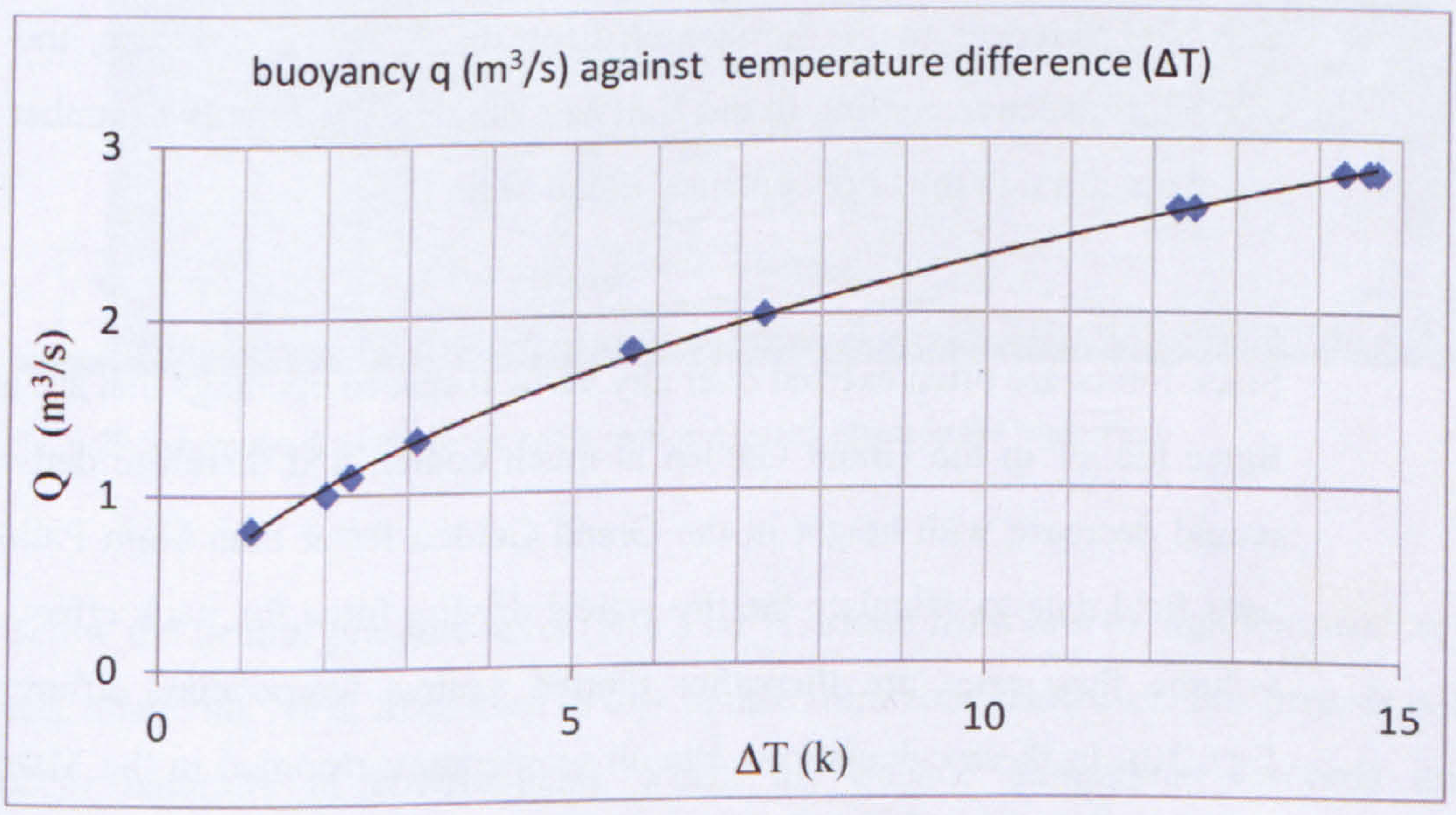


Fig. 6.28 Plot of volume flow rates from buoyancy flows against temperature difference

Buoyancy effect has produced volume flow rates of between $0.8m^3/s$ and $2.8m^3/s$ (see fig.6.28) between 08:00h and 18:00h. Low volume flow rates are reached at 08:00h in the morning, while higher volume flow rates are attained between 12:00h and 14:00h in the afternoon. However, field data produced much higher flow rates in some instances. The calculation of stack effect in the next section shows the implication of using the upper opening in the Main Patio as an outlet window.

6.3.3 Stack effect

In this section, the impact of stack effect between the inlet at the Hall of Columns and the outlet in the Main Patio is calculated. Hall of Columns, Praetor Chamber and adjacent spaces are connected to the Main Patio by openings that are much larger than openings in their respective external envelope. According to CIBSE (AM10 pp44), the Main Patio and surrounding spaces can, as a result, be considered as single space. However, the temperatures in the Main Patio 'stack' are not the same as surrounding spaces at any given height. This is due to the impact of direct solar radiation on the Main Patio. Hence, considerably higher temperatures are recorded in the Main Patio than surrounding spaces. Subsequently, the airflow from the Main Patio is supported by density differences in the horizontal direction. If this is the case, the air movement induces convective cooling in the Hall of Columns and Praetor Chamber with warm air going out through the upper opening in the Main Patio.

Stack forces are often exerted over any vertical spaced openings that are inter-connected. Since the air in the Grand Garden is much cooler, and therefore denser, the pressure would decrease with height in the Grand Garden faster than Main Patio. This analysis uses field data to calculate the theoretical driving force for stack effect. The calculated volume flow rates are thereafter plotted against temperature differences (ΔT) (see fig.6.30). In these calculations, the air temperature recorded in the Main Patio (T_{MP}) is considered to be an internal temperature, while the one recorded at the inlet to the Hall of Columns (T_{HC}) represents the Grand Garden's external temperature. As described in previous chapter, the sensors in the Hall of Columns and Praetor Chamber were placed near the inlet window. Hence, the detected temperatures can represent the DBT at the near end of the garden-courtyards. The results are compared with plot of field recorded volume flow rates against temperature difference (dt) shown in fig.6.26.

The air inlet windows in the transitional spaces are connected to the large stack 'Main Patio'. The sum of all the inflows has to balance the single high-level outflow through the Main Patio. Thus the Main Patio represents a solar-powered stack with temperatures which are considerably higher than those in the surrounding rooms. Temperature within the stack 'Main Patio' and the immediate spaces aren't the same due to access to direct solar radiation. As shown in Fig.6.29, the available pressure drop is made greater by having the neutral pressure level (NPL) at a higher level. The relatively bigger opening in the Main Patio makes the driving pressure at the ground floor inlet much greater than that at the top outlet.

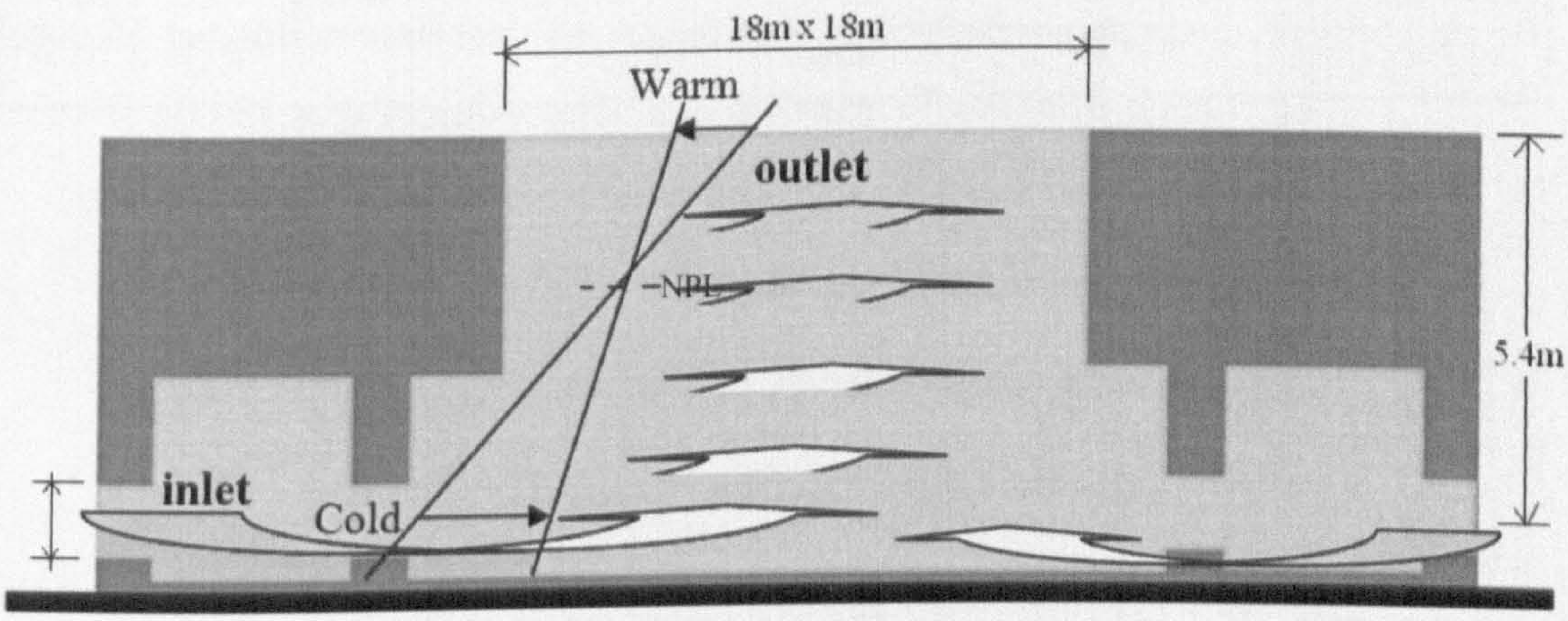


Fig. 6.29 Schematic drawing in the cross section of stack effect in the Main Patio

Below the neutral pressure level (NPL) air is driven from low to high temperature zone and, above the NPL, from high to low temperature zone. However, this process will not occur naturally in environments where the outside temperature exceeds internal temperatures (CIBSE AM10). While the general outside temperatures in hot and dry climate will exceed indoor temperatures, this is not the case with Casa de Pilatos where outer air is driven in from the garden-courtyards. Consequently, cool air is driven from the garden-courtyards to the Main Patio and hot air is driven from the Main Patio to the outer environment. This strategy has enables indoor temperatures to be higher than outside temperatures for the direction of flow to be maintained.

The big difference in opening sizes causes the outflow of air at the aperture in the Main Patio to be relatively at low speed as compared to inflows at the opening to the Hall of Columns and the Praetor Chamber. The process is influenced by the law of mass conservation. As the pressure drop across the upper opening decreases, that across the lower opening increases to equalize mass flow rates.

The calculations are carried out using a spreadsheet and results are presented in Table 6.9. The equation (Equation 6.2) used for buoyancy calculations is also employed in this occasion; with an alteration to the distance between the inlet and outlet window. Table 6.9 presents the meteorological data from Seville weather station at Sao Pablo airport for reference purposes. Using the average temperatures recorded at 15:00h, the calculation of volume flow rate is shown below. The value of q at 15:00h is calculated from the known internal T_{MP} (^{0}C) and external conditions T_{HC} (^{0}C), as follows:

— external temperature: T_{HC} (^{0}C) = 31.2 °C

— internal temperature: T_{MP} (^{0}C) = 43.7 °C

— temperature difference: T_{MP} - T_{HC} (ΔT) = 12.5 K

— Window area: A = 4.83m^2

— discharge coefficient: C_d = 0.6

— Height between the opening h (m) ≈ 5.4m.

— gravitational force per unit mass g ($m.s^{-2}$) = 9.8 $m.s^{-2}$

Refer equation 6.2;

$$q = AC_d\sqrt{\frac{\Delta Tgh}{(T_I + 273)}} = (4.8)(0.6)\sqrt{\frac{(12.5)(9.8)(5.4)}{(43.7 + 273)}} = 4.2m^3s^{-1}$$

Table 6.9: The volume flow rates calculated using the mathematical model for stack effect and daytime temperature difference recorded in the Main Patio and the Hall of Columns

Time	T_{HC} (^0C)	T_{MP} - T_{HC} (ΔT)	T_{MP} (^0C)	Meteorological	Volume flow rate q (m^3/s)	Air velocity (m/s)
08:00	23.1	1.1	24.2	28.4	1.3	0.3
09:00	24	2.0	26.0	29.8	1.7	0.4
10:00	25.2	5.7	30.9	31.4	2.9	0.6
11:00	26.6	12.3	38.9	32.6	4.2	0.9
12:00	27.9	14.7	42.6	33.6	4.6	1.0
13:00	29.1	14.3	43.4	34.2	4.6	0.9
14:00	30.4	14.6	45.0	34.6	4.6	1.0
15:00	31.2	12.5	43.7	34	4.2	0.9
16:00	31.7	7.3	39.0	33	3.2	0.7
17:00	32.1	3.1	35.2	30.8	2.1	0.4
18:00	32.8	2.3	35.2	28.6	1.8	0.4

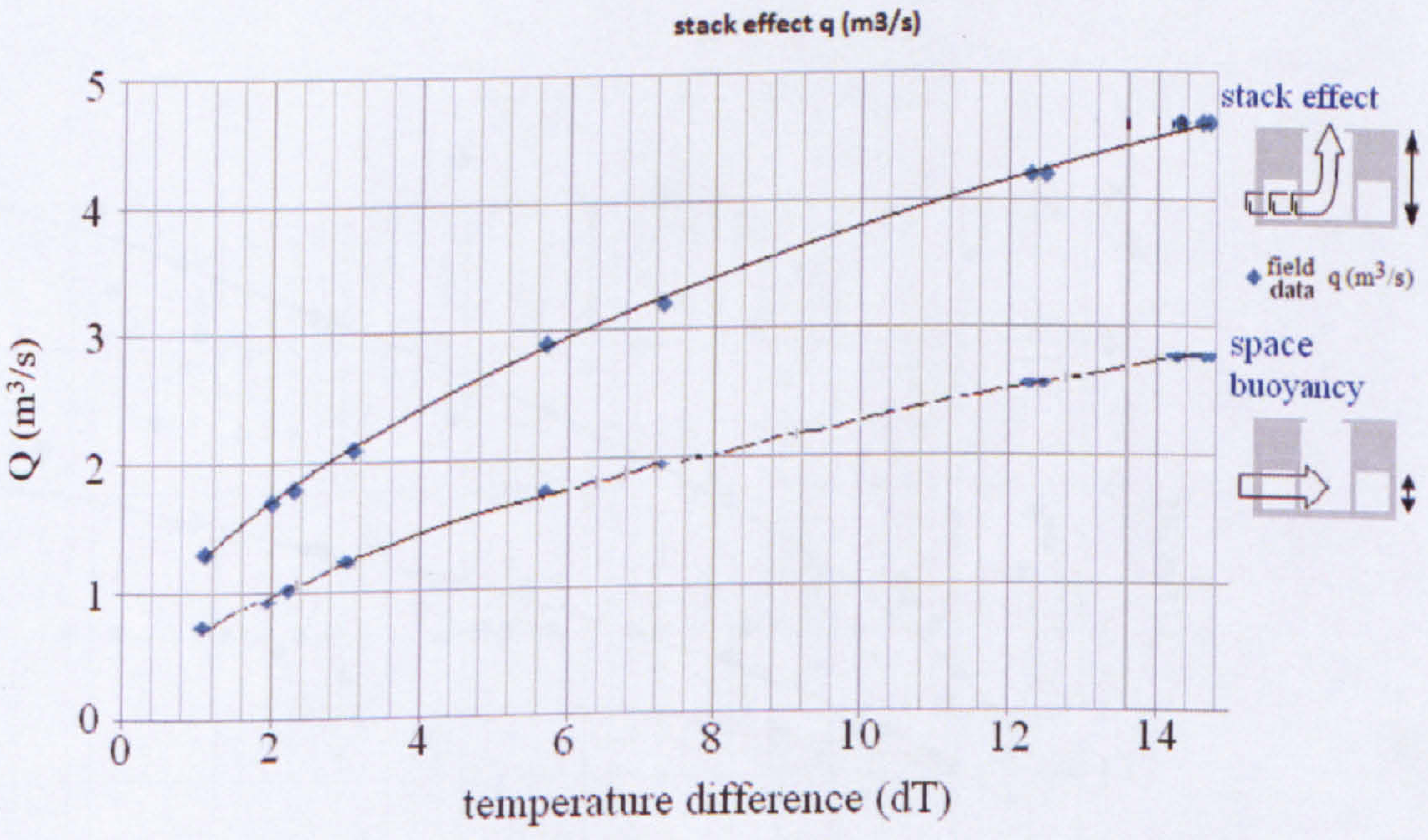


Fig. 6.30 Plot of theoretic flow rates against field recorded daytime temperature difference

Higher volume flow rates are attained through stack effect. Stack effect has produced volume flow rates of between $1.3m^3/s$ and $4.6m^3/s$ between 08:00h and 18:00h. Low volume flow rates are reached at 08:00h in the morning, while higher volume flow rates are attained between 12:00h and 14:00h in the afternoon. However, field data produced higher flow rates in some instance (see fig.6.31).

It has been observed that 70% of the data points fell beyond the lower boundary of buoyancy forces (see fig.6.31). Most of field data fall within or near the buoyancy and stack effects calculated boundaries (see fig.6.31). However, some of field data is still plotting outside the buoyancy 'stack' theoretical boundaries. There is nearly equal number of data points falling both below and above the buoyancy 'stack' effect boundaries respectively. This means that equal positive and negative forces are sustained this strategy. These are moments when either high volume flow rates are achieved at narrow temperature differences or low volume flow rates are attained when the temperature differences is big.

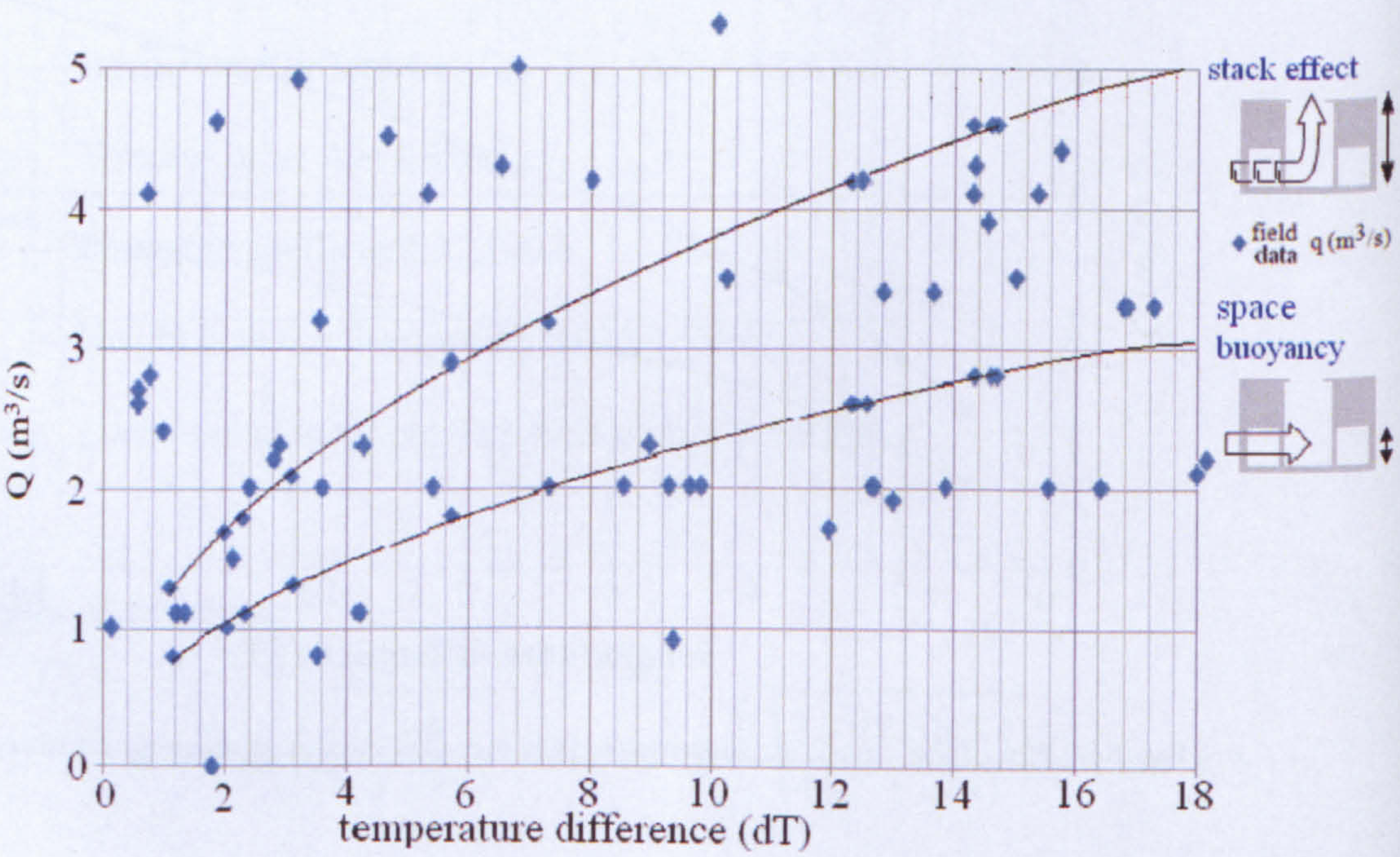


Fig. 6.31 Plot of daytime hourly recorded volume flow rates against temperature difference in the Hall of Columns and Praetor Chamber versus theoretical calculations

The inconsistency between the theoretical and field recorded flow rates is linked to factors such as solar radiation, radiant heat from building surfaces and wind. However, Around 50 per cent of field data are accommodated within the theoretical limits of stack and buoyancy forces. These forces are the possible drivers for the multiple-courtyards architecture in compact towns in semi-arid climate. The next section will analyse the impact of external pressure from wind.

6.3.4 The impact of local wind regime

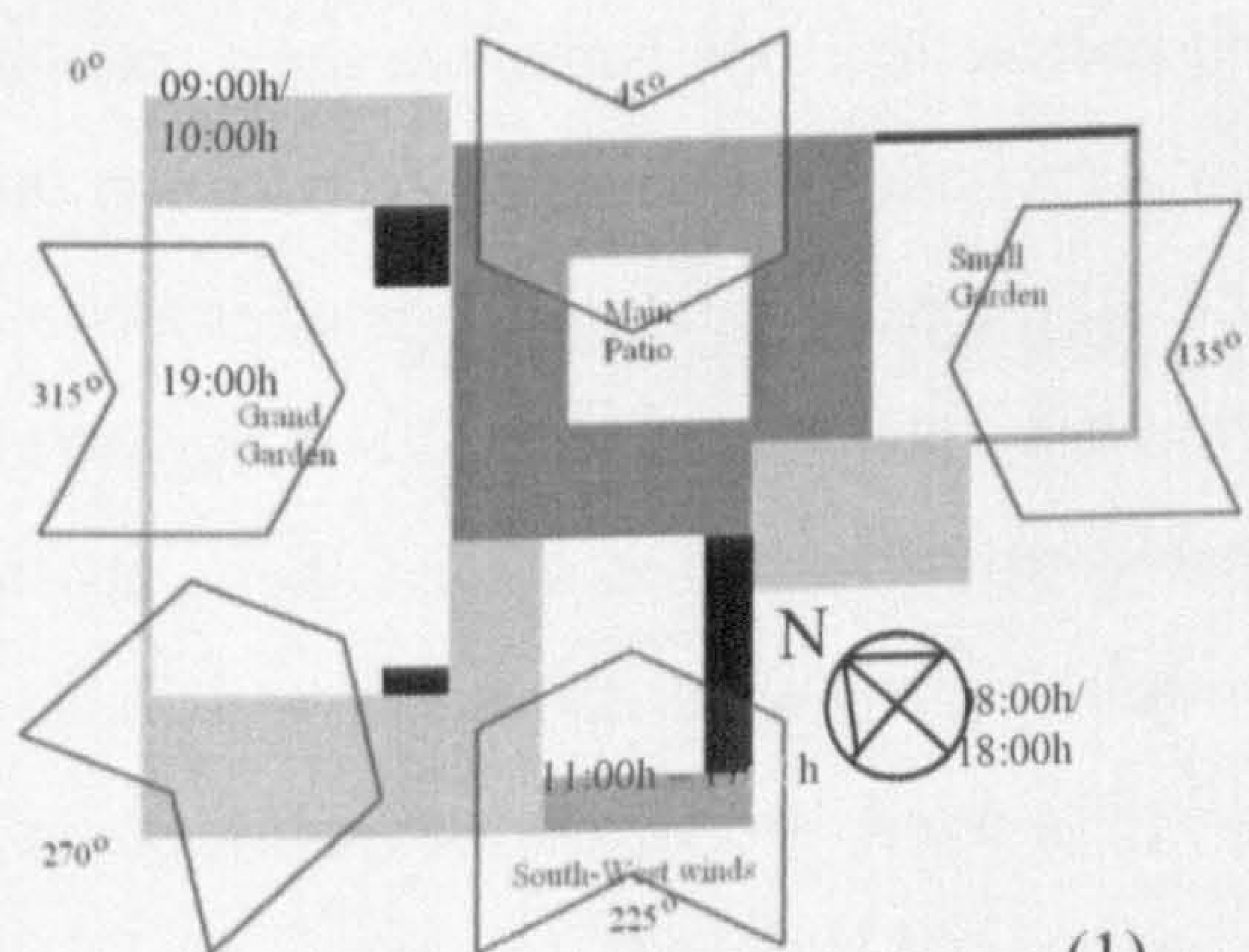
The variation between the field data and results from theoretical calculations of buoyancy and stack effect in the previous section shows that these forces are not the sole influence on the airflows through the Hall of Columns and Praetor Chamber. The distribution of pressure over the surface of the building is also affected by the wind speed and its direction relative to the building, and the shape of the building. Wind develops varying surface pressures across the envelope of the Casa de Pilatos adding to the hydrostatic pressure. As the wind approaches the façade of the building, the surfaces facing into the wind will experience positive pressures, while the leeward surfaces and those at right angle to the wind direction experience suction (CIBSE AM10 pp13). The potential variable magnitude and direction of wind poses a greater challenge in the analysis of field data.

This section analyses the field data by considering the magnitude and direction of wind at the period of measurement. The magnitudes and directions are taken from field data and meteorological data respectively. The wind speed recorded at the Roof-Top in the field work period is used in this analysis. The Seville's meteorological data presents hourly change in wind directions (Table 6.10 and fig.6.32→36). This means that hydrostatic pressure across the envelope of the building changes every hour. The table 6.10 presents a combination of field recorded wind speeds taken at the Roof Top and meteorological wind direction. The data recorded at the Roof-Top shows a constant fluctuation with hourly averaged wind speeds ranging between 0.3 and 1.6m/s. The building layout is taken into consideration in order to estimate the impact of a certain magnitude and direction of wind.

Table 6.10: The wind speed and directions in Seville for the period 14th – 19th August 2008 taken from meteorological station. Source: Energy Plus weather data

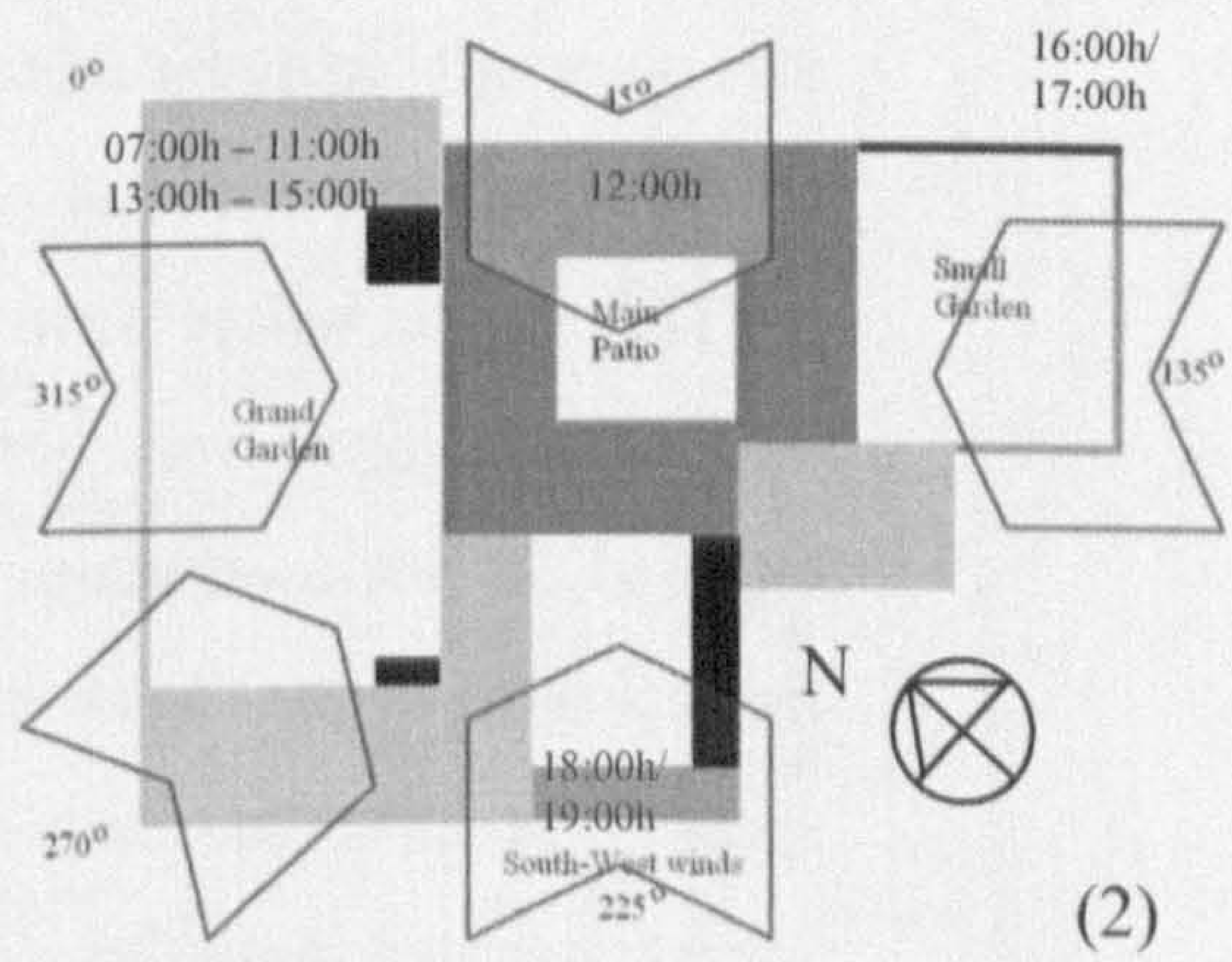
time	13-Aug.	14-Aug.	15-Aug.	16-Aug.	17-Aug.	18-Aug.
	Hall of Columns				Praetor Chamber	
08:00		S	0.5(N)	N	0.3(NE)	0.3(N)
09:00	0.53	N	0.6(N)	N	0.4(N)	0.3(N)
10:00	0.53	0.32(N)	0.5(N)	N	0.5(NE)	0.4(N)
11:00		0.49(SW)	0.5(N)	SW	0.5(NE)	0.4(N)
12:00		1.0(SW)	0.6(NE)	0.5(W)	0.6(NW)	0.4(N)
13:00		0.9(SW)	0.6(N)	1.6(SW)	0.6(W)	0.7(SW)
14:00		0.7(SW)	0.5(N)	1.0(W)	0.7(NW)	0.8(SW)
15:00	0.85	0.86(SW)	1.0(N)	1.0(SW)	0.6(NW)	0.7(SW)
16:00	0.67	1.04(SW)	1.1(E)	1.1(S)	0.6(NW)	1.3(SW)
17:00	0.78	0.99(SW)	1.6(NE)	1.6(SW)	0.6(SW)	1.2(SW)
18:00	0.89	1.24(S)	SW	SW	0.8(SW)	SW

14th August



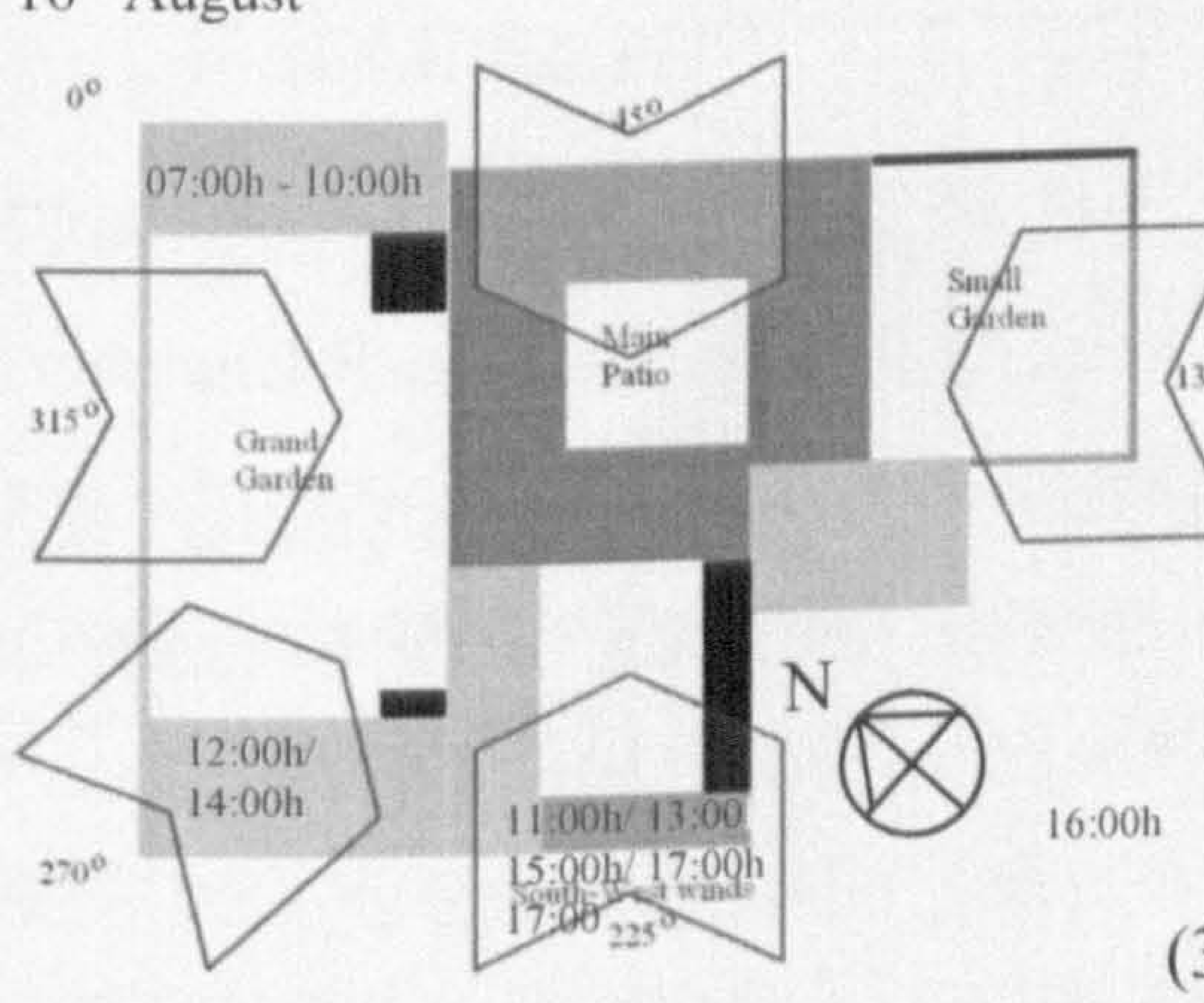
(1)

15th August



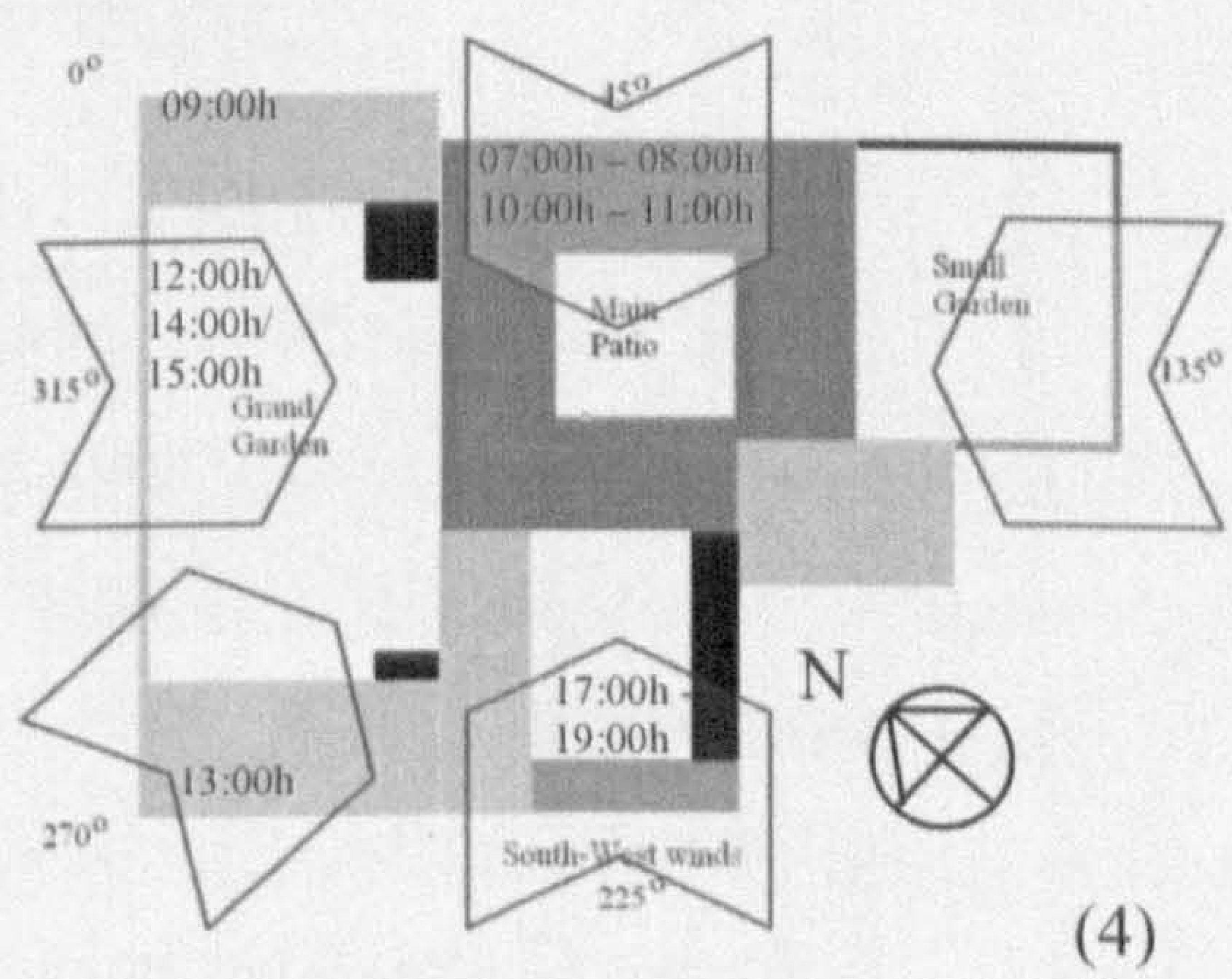
(2)

16th August



(3)

17th August



(4)

18th August

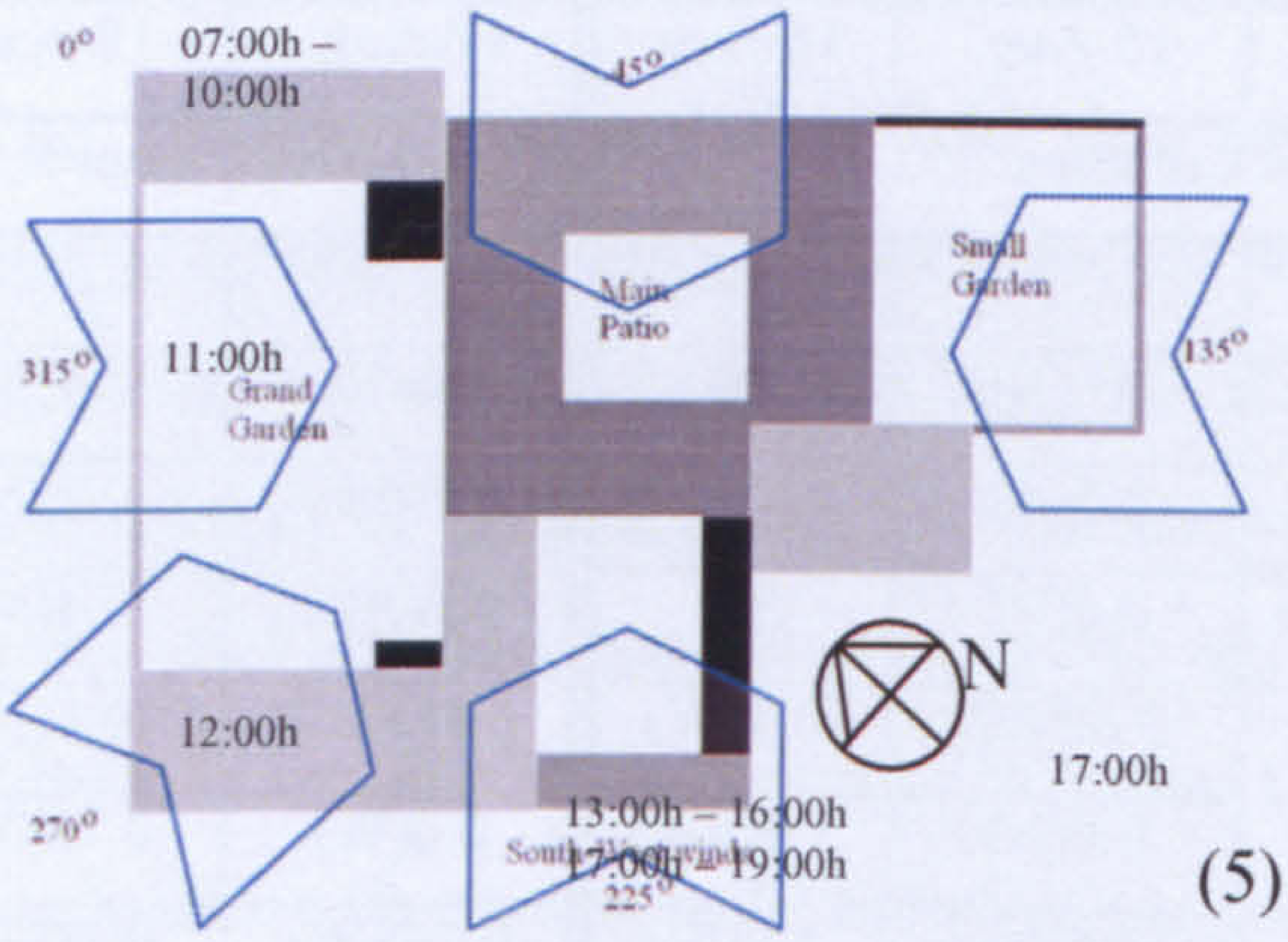


Fig. 6.32 the hourly changes in wind direction taken from meteorological station

Source: Energy-Plus weather files

The change in the magnitude and direction of wind recorded at the Roof Top is compared to the changes in air velocity recorded in the transitional spaces. The recorded data shows the increase in wind speeds at the Roof Top when the direction changed from north, north-east, and east to other directions. This is more apparent on the data taken on the 18th August where wind speeds at the Roof Top increases after a change in direction from north to southwest. However, the anemometer at the Roof Top was not completely exposed to north, northeast, and east winds. That means there are instances when inconsistency arises between meteorological wind directions and field values of wind speed. It is observed that the change in wind direction is not reflected on the air velocity values recorded in the Praetor Chamber and Hall of Columns.

The collected data for air velocity does not show sensitivity to meteorological changes in wind direction. For example, air velocity through the Praetor Chamber on 17th August has changed from 0.7m/s at 11:00h to 0.9m/s at 12:00h when the direction switched from 60^0 to 300^0. Similarly, air velocity through the Praetor Chamber on 18th August has changed from 0.8m/s at 12:00h to 0.7m/s at 13:00h when the direction switched from 0^0 (North) to 240^0. These changes were not evident in the Hall of Columns and Praetor Chamber consequently the impact of southwest winds was not apparent in the values of air velocity taken in the transitional spaces. The insensitivity of air velocity data to meteorological changes in wind direction means the condition at the street level could be the determining factor.

The data in Table 6.10 has patterns dissimilar from existing meteorological data. Meteorological wind speeds do progressively increase in magnitude throughout the morning reaching a peak in the afternoon, before decreasing in magnitude in the latter part of the day (refer fig.4.8). Meteorological average wind speeds for the period of study (12th – 18th August) is 2.1m/s (fig.6.33). Lower wind speeds of highly variable nature are recorded on the Roof Top calling into question the meteorological data (compare Table 6.10 and fig.6.33). These field readings are taken at a point 14 metres above ground while the inflow into the Main Patio takes place six metres above ground level. Much lower wind speeds are expected on the ground and first floors level of the building. Under these conditions, it is likely that buoyancy and stack forces will preside over wind forces.

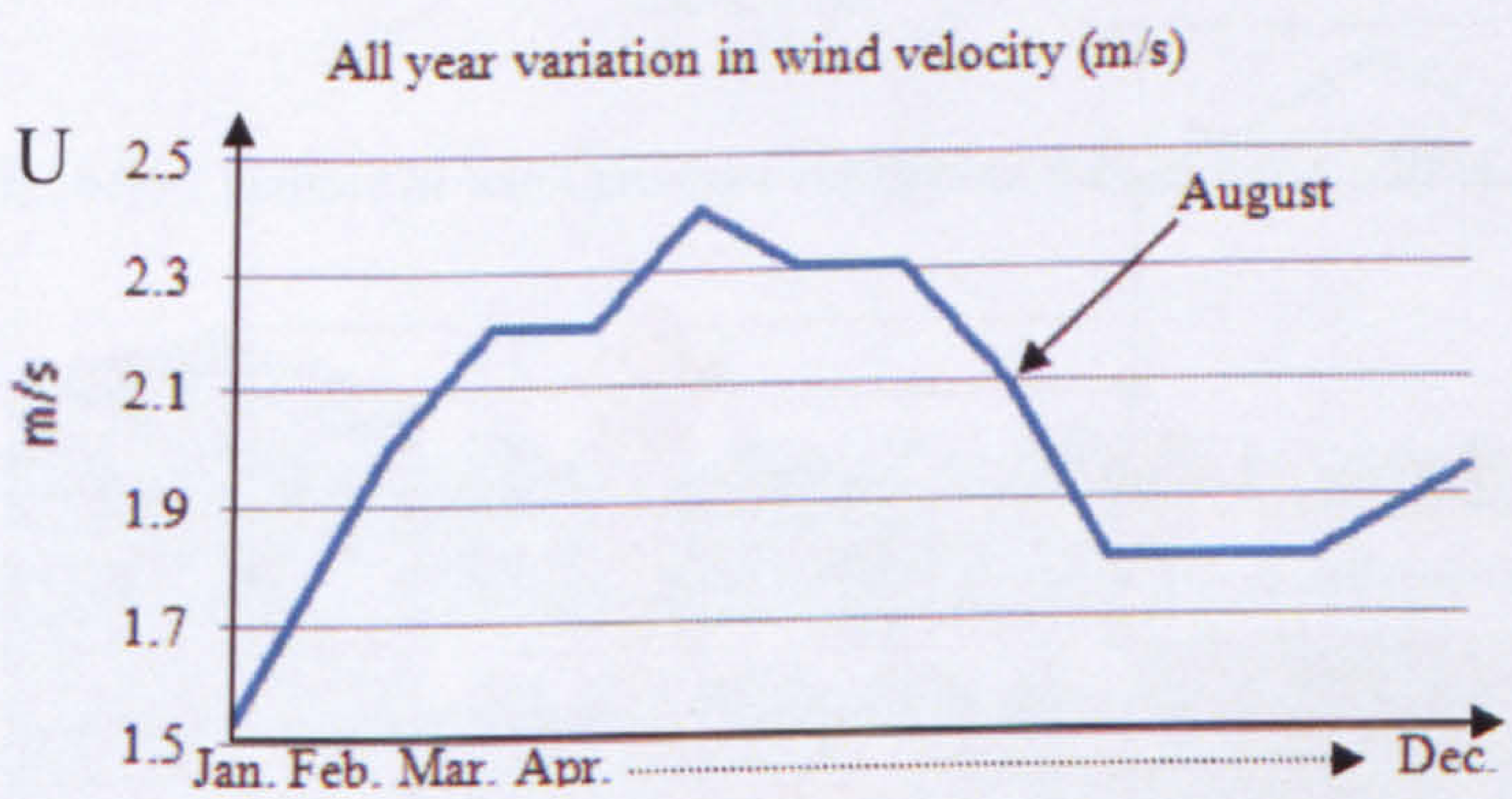


Fig. 6.33 Hourly variation in wind speeds in Seville for the whole year meteorological data

The building form and layout is used to predict the impact of certain magnitude and direction of wind. Although wind does not directly enter the Hall of Columns and Praetor Chamber, the inflow to any courtyard would have impact on these spaces. The Main Patio is enclosed on the ground floor while the south-west side of the upper floor is open to prevailing winds (see fig.6.34 and fig.6.35). The relationship between this opening and periods of higher flow rates recorded in the Hall of Columns and Praetor Chamber requires further investigation. It can be suggested that the design of Casa de Pilatos purposely exposes the Main Patio to south-west prevailing winds.

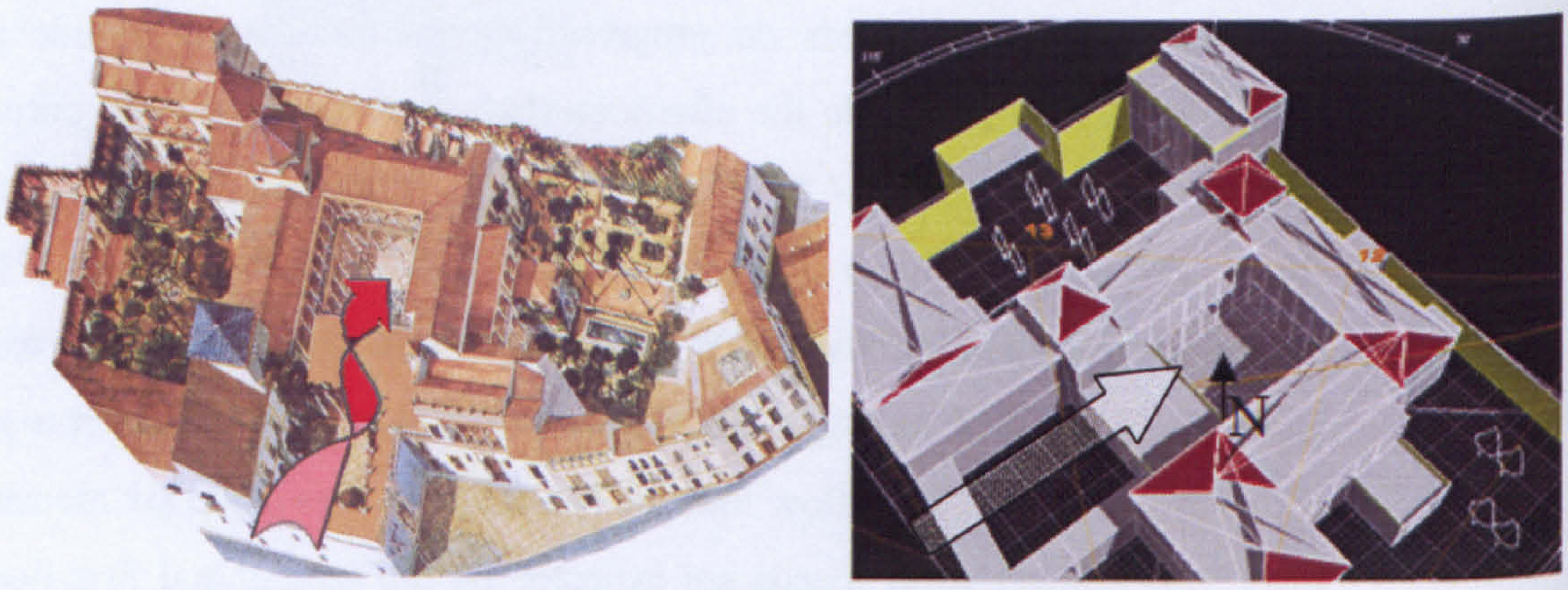


Fig. 6.34 Three dimensional (3D) model of Casa de Pilatos showing the geometric characteristics and inflow in South-West winds, Source: (right) created using Ecotect software, (left) modified from leaflet of the Fundación de Medinaceli

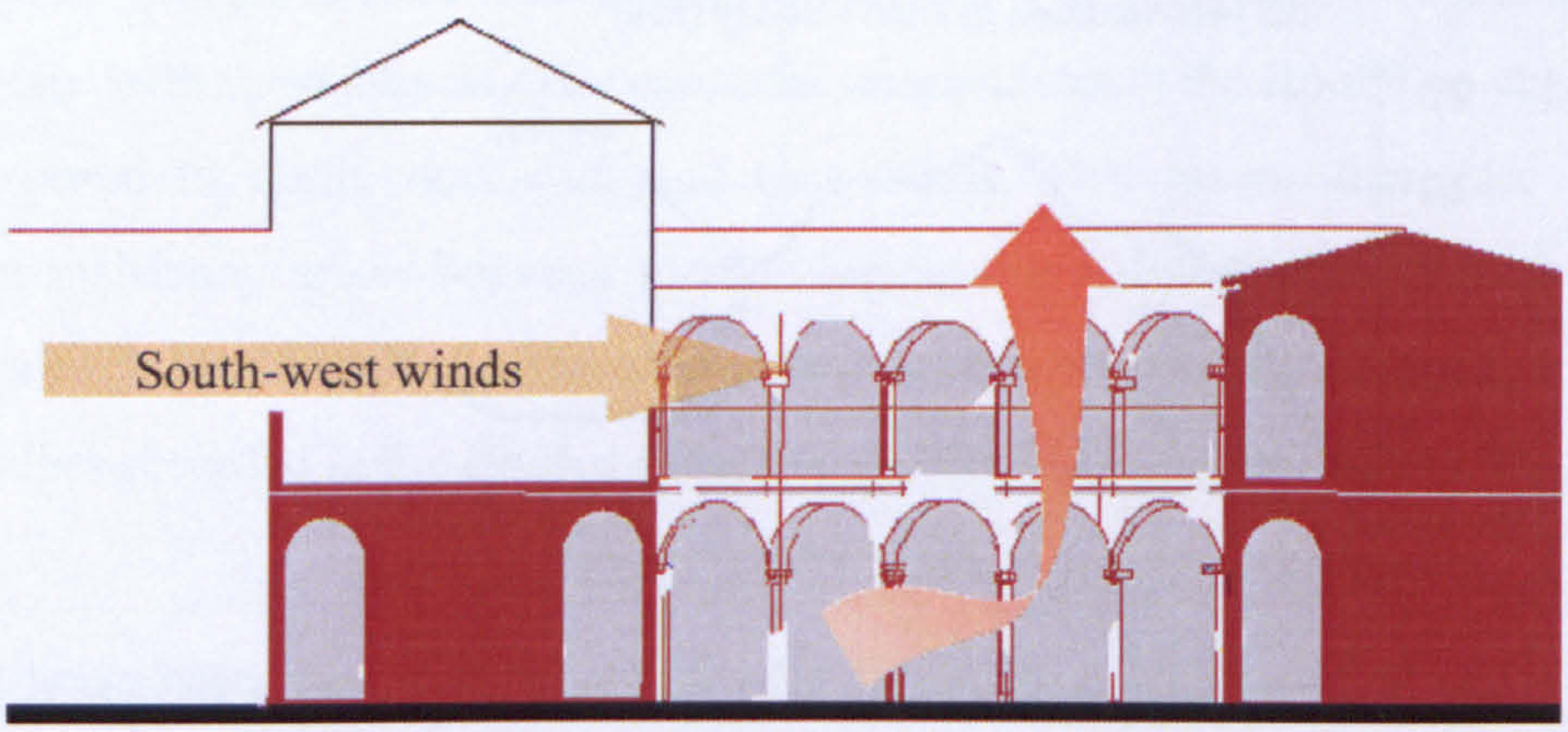


Fig. 6.35 Section across the Main Patio showing the prevailing southwest wind

Depending on the flow field developing around the building when southwest prevailing winds reach the Main Patio, they will either deduct or add to the hydrostatic pressure. When the conditions change from steady state, the hydrostatic pressure adjusts to reflect the magnitude and direction of incoming prevailing winds. According to CIBSE (AM10 pp54), pressure coefficient (C_p) does not vary greatly with wind speed (see fig.6.36), and its distribution depends only on wind direction and the position of the point where wind speed (U) is measured. Equation 6.3 shows the impact of wind speed on ventilation rate q for a specified value of ΔC_p. Area 'A' is the total ventilation area in m^2 and ΔC_p is the difference between wind pressure coefficients C_{p1} and C_{p2}. An example of wind pressure coefficient data is shown in fig.6.36. Determination of the impact of a given building shape and surrounding environment is a greater challenge when defining the wind pressure coefficient.

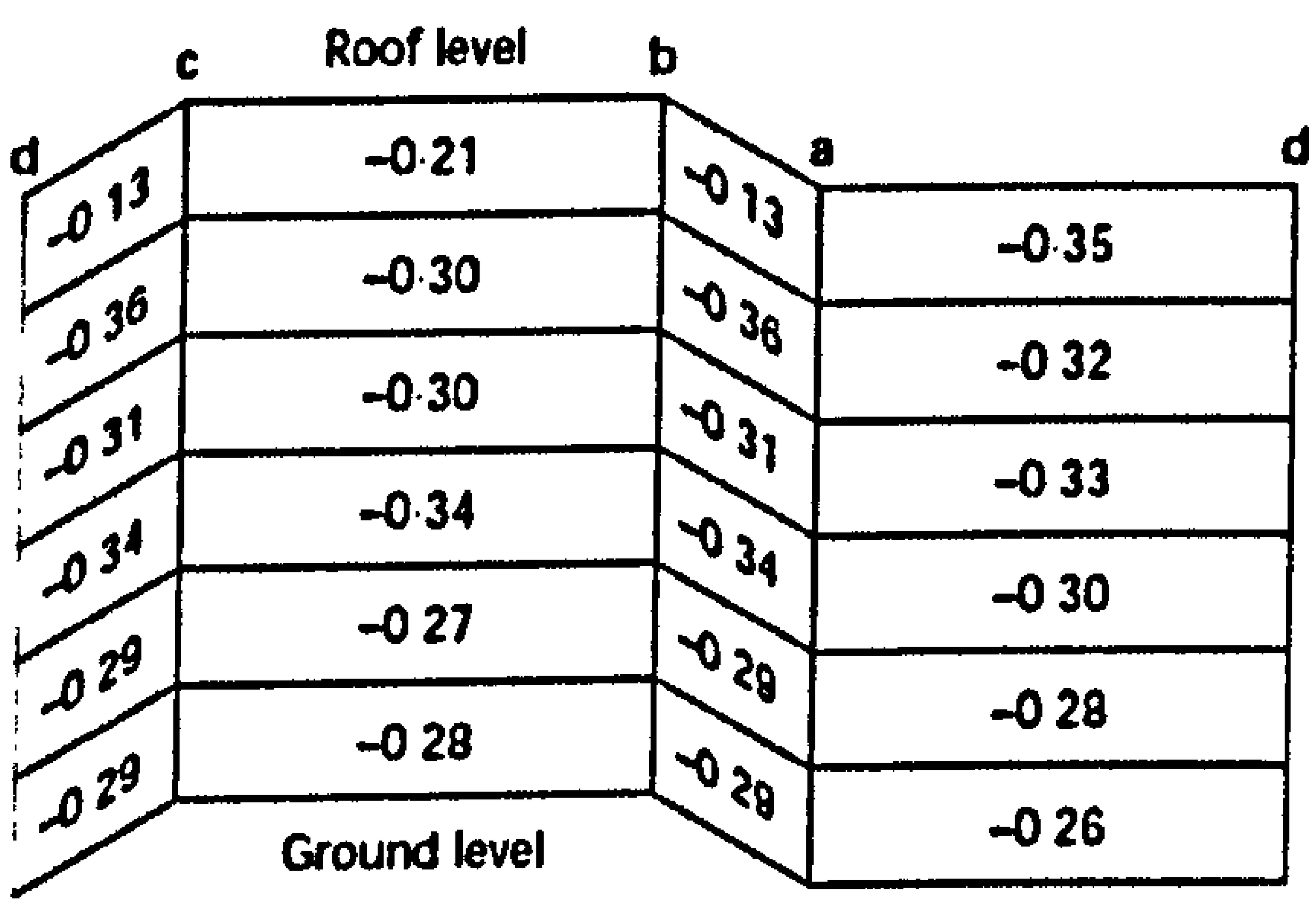


Fig. 6.36 Example of wind pressure coefficient data, Source: CIBSE AM10 pp54

The impact of wind speeds on the volume flow rates through the transitional spaces is estimated by using Equation 6.3. Because the southwest winds are passing through the Main Patio at the second floor level, these calculations have assumed a wind pressure coefficient (C_p) of -0.35. The C_p at the inlets to the Hall of Columns and Praetor Chamber are taken as 0.1 since they are on the leeward side next to the garden-courtyards. Seville's average wind speeds of 1.4m/s for August and September (Servando ed. 1991 pp156) are used to estimate the impact of prevailing wind on the volume flow rates. Ventilation rate (q) for a specified value of $\Delta C_{p\text{-}i}$ is given by:

$$q = AC_dU\sqrt{\frac{\Delta C_p}{2}}\ Source: CIBSE\ AM10\ pp46 \quad \ldots \quad (6.3)$$

$$q = 4.8 * 0.6 * 1.4\sqrt{\frac{(0.1-(-0.35))}{2}} = 1.9m^3/s$$

Volume flow rate of $1.9m^3/s$ is attained from Seville's average wind speed. These calculations are still optimistic if the impact of the surrounding buildings is considered. The positive impact of this wind forces on overall flow rates is shown in Fig.6.37. The hourly averaged wind speeds recorded at the Roof Top are far below the Seville's average wind speed of 1.4m/s used in this calculation. The average hourly volume flow rates calculated (using Equation-6.3) from the daytime wind speed hourly data recorded at the Roof Top were up to $5.3m^3/s$. The reduced volume flow rates are attributed to local wind regime. An additional source of uncertainty is the changing direction of wind, because wind is expected to impact the Main Patio through the dominant south-west direction. Wind promotes or impedes the air velocity through the Hall of Columns and Praetor Chamber according to the flow patterns in the Main Patio.

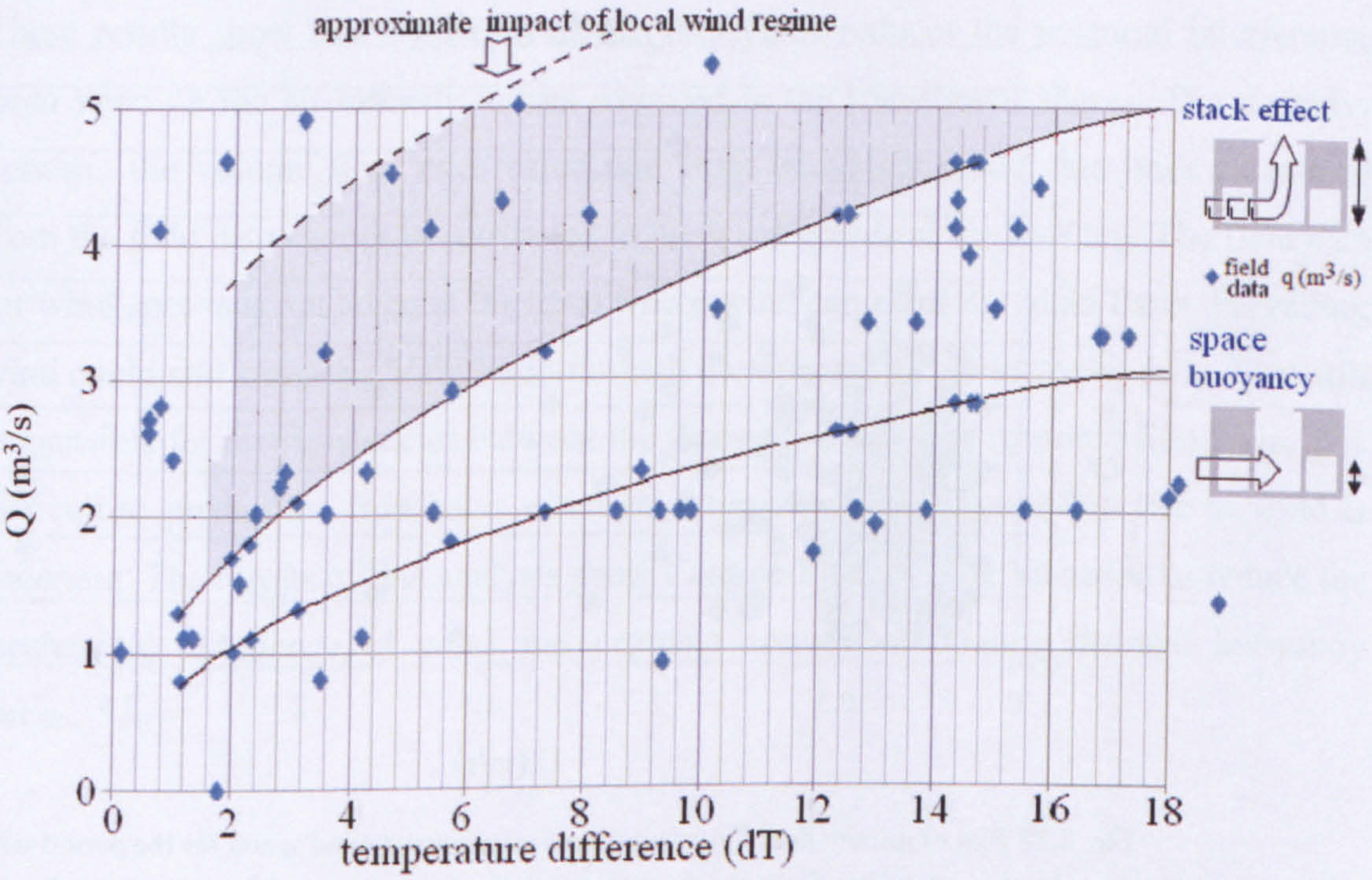


Fig. 6.37 Plot of volume flow rates against temperature difference showing the positive impact of local wind regime

In order to determine the driver for air velocity, the air velocity data collected in the Praetor Chamber is separated between periods of low (0 – 4) K and high (10-18) K temperature difference between the Small Garden and Main Patio. Volume flow rates in the Praetor Chamber are then separated between the two temperature ranges and plotted against the wind speeds recorded at the Roof Top. When there is a low temperature difference the impact of wind speed is expected to be evident, with more data points on the right side of the graph. This is not evident in fig.6.38. While the impact of high temperature difference is expected to reflect the large amount of data points on higher volume flow rates when the wind speed is low. This is partly reflected in fig.6.43. The results show no correlation between the wind speeds recorded at the Roof Top and the air velocity recorded in the Praetor Chamber (see fig.6.38 and fig.6.39). There is no indication that wind speeds recorded at the Roof Top have played an important role in the promotion of convective cooling through the transitional spaces.

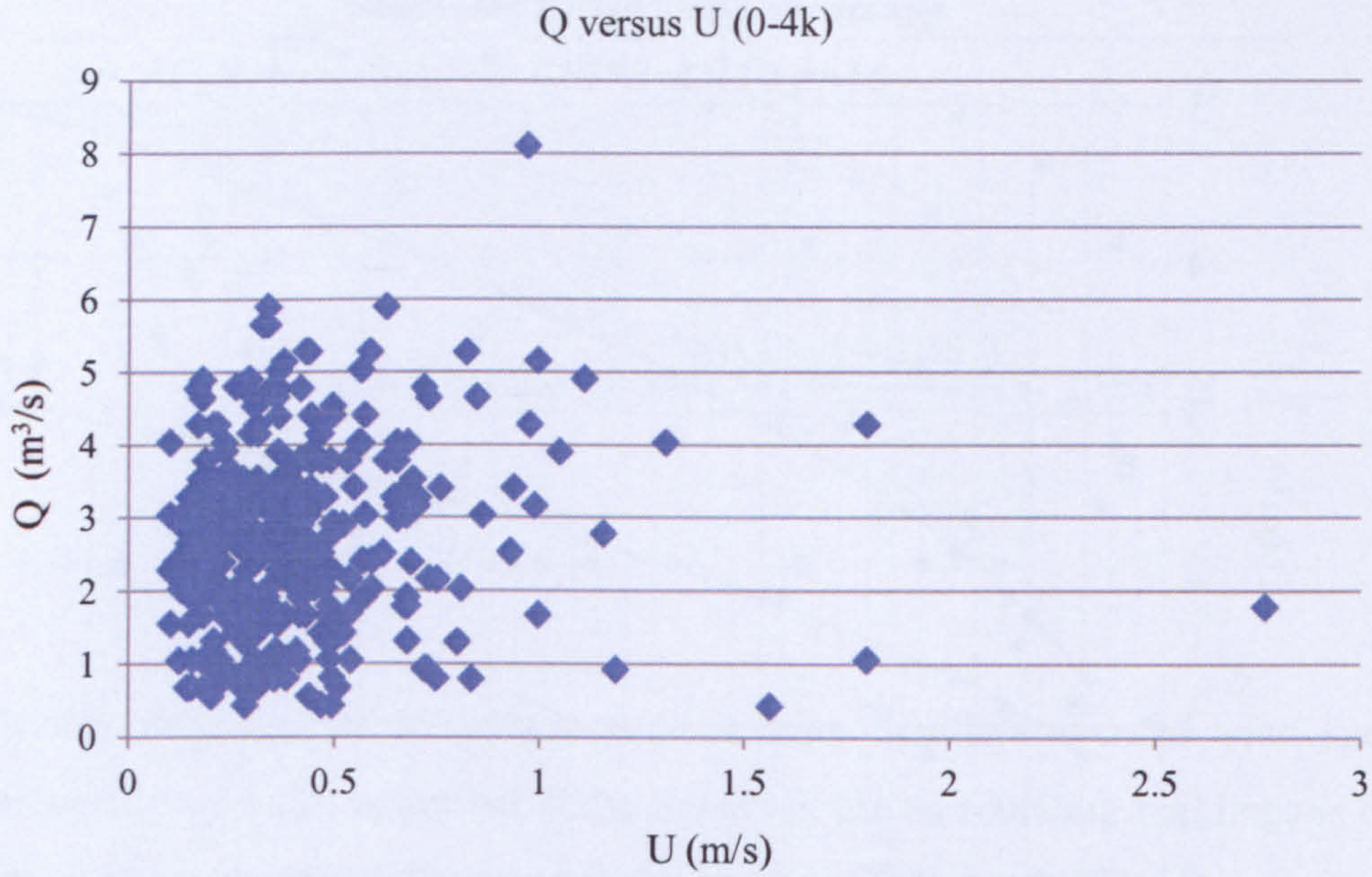


Fig. 6.38 Plot of minute data for volume flow rates versus wind speed for the period when temperature difference in the Praetor Chamber were (0-4) K

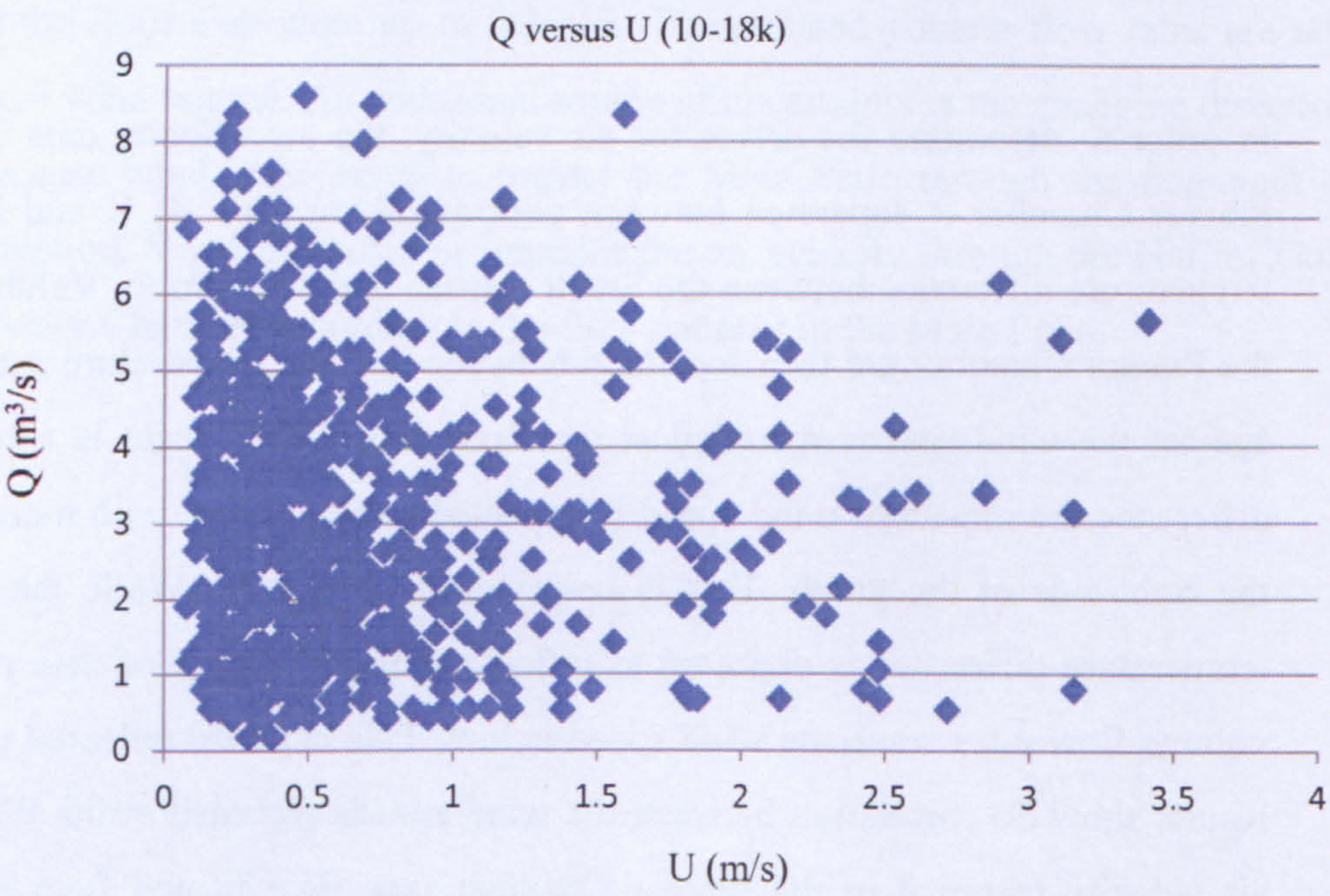


Fig. 6.39 Plot of minute data for volume flow rates versus wind speed for the period when temperature difference in the Praetor Chamber were (10-18) K

These results show that the depth of the courtyards reduces the potential interference from wind on the air velocity values recorded in the transitional spaces. The disparity between the volume flow rates calculated from buoyancy model and ones calculated from the field data cannot be attributed to the wind speeds at the roof top. The field data for wind speeds is not taken at the level where wind can enter the Main Patio. Prevailing wind could still enter the Main Patio through the opening at the lower level, and are still responsible for inconsistencies between the theoretical and field recorded flow rates. It is difficult to predict the flow rates when an external pressure fluctuation due to wind is uncertain. The results of this analysis show Casa de Pilatos' clear intension to reduce the mechanical turbulence of wind and promote convective cooling through buoyancy forces.

Another source of inconsistency is the urban layout. Despite enclosed garden courtyards, the Main Patio is exposed to street conditions and the building is surrounded by dense urban structure and street canyon. The layout suggests that increased air velocity at the inlet to transitional spaces is linked to increased outflow of air from the Main Patio which is linked to urban layout. Although the building is open to south-west prevailing winds, the complexity in the recorded air velocity values may originate from the conditions at the street level. Strong flow patterns may evolve from canyon effect of narrow streets which characterise the historic town.

6.3.5 The impact of urban layout

The impact of urban layout on air flow through the Casa de Pilatos is predicted by using the general relationship between the wind velocity υ, within the canyon, and above-roof free stream wind speed U provided by Santamouris (ed.2001). Strong flow patterns may evolve from the canyon effect of narrow streets which characterise Seville's historic town. A further order of difficulty is introduced by the changing urban context because the historic parts of Seville are currently in the middle of a sprawling modern city, unlike the period when it was surrounded by suburban areas. This is important because the complexity in the recorded air velocity values can also be caused by the conditions at the street level.

Unlike modern cities, old cities have visible boundaries. The city of Seville was surrounded by a network of walls of which there is no trace left today (Rafael C. Mantero, 1992 pp22). According to Mantero, It was a mirror of Rome with its characteristic twisting narrow streets and irregularly shaped houses in a great variety of sizes. However, the outer edge of the modern Seville is not a physical feature that strikes the eye (see fig.6.45/46). Currently, each neighborhood in urbanized Seville is part of a large built-up area, and it is unclear where one unit ends and another begins.

The Moorish architecture inherited the strong tradition in Arabic cities of enclosing nature as a private interior garden full of trees, shrubs, flowers and fountains. They designed white towns with narrow streets which would be shaded from solar radiation (see fig.6.40). The dense urban structure with narrow and deep streets in historic Seville is used to avoid direct exposure to undesirable solar heat and maritime hot and dry air currents. Moorish plan of the plain exterior and richly decorated interior which persisted in the Southern Spain presents the buildings which have adhered to the character in the neighborhood. In most cases the building were separated from each other by party walls, garden-walls, and narrow streets.

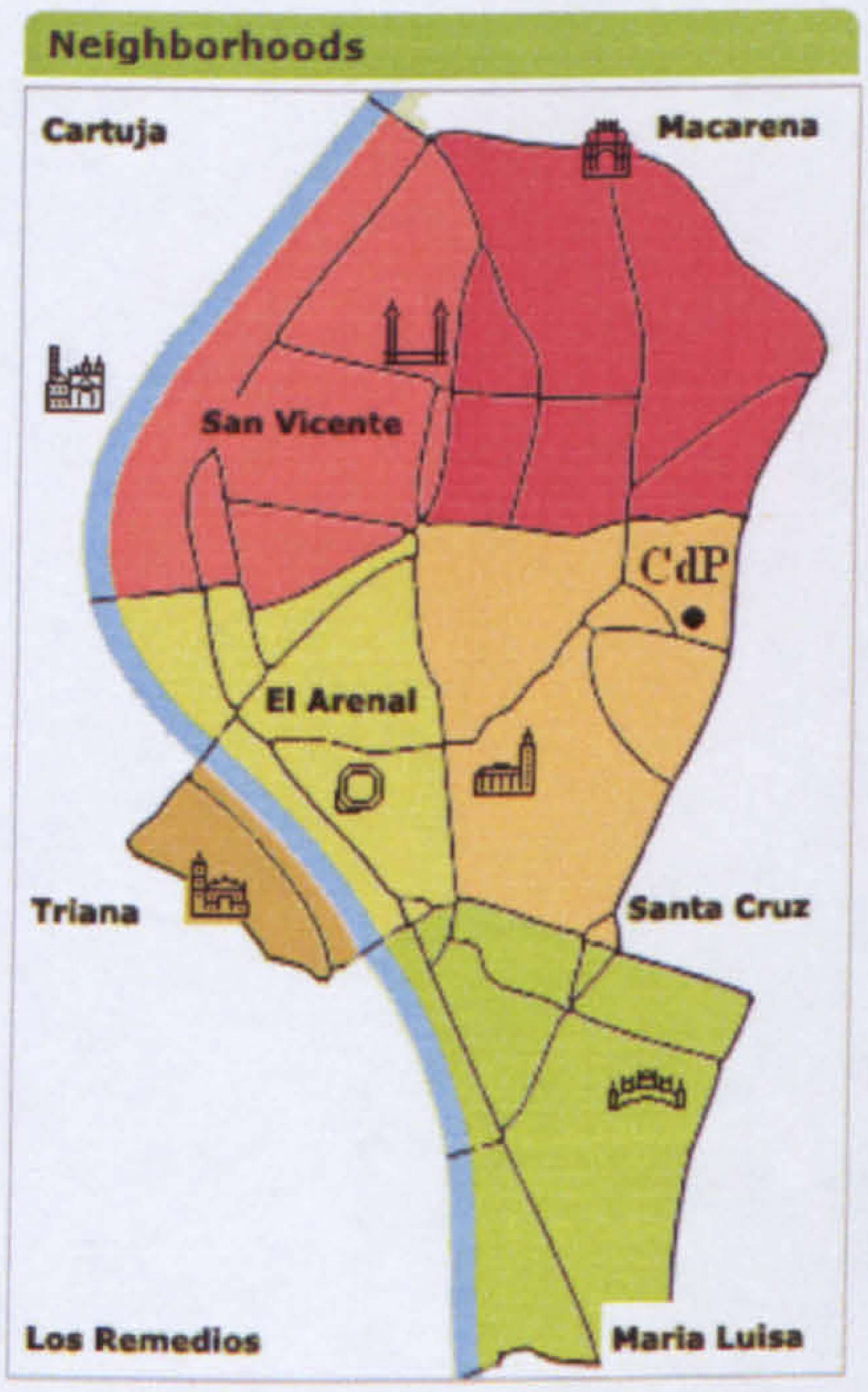


Fig. 6.40 (left) The neighbourhoods of the historic Seville showing the location of Casa de Pilatos (CdP) within Santa Cruz area, Source: Sevilla5.com; (right) St. Stephen street (Calle San Esteban) leading to the Casa de Pilatos

It is certain that urban air canopy has significantly changed over the past 400 years when the Casa de Pilatos is part of Santa Cruz neighborhood (see fig.6.41). Unlimited number of microclimates is generated by changing urban configurations. Unlike the historic city, the modern Seville is characterized with tarmac and paved spaces, high building density, and a high anthropogenic emission rates. Santamouris (ed.2001 pp48) gives indicative values of the strength of various sources of anthropogenic heat in modern city environment. The rates for some US city centers range from 20 to 40W/m^2 in summer and 70 to 210W/m^2 during winter. While the presence of trees and green spaces in the vicinity of historic city created cooler urban canopy layer, the urban canopy layer in modern Seville adds a significant amount of heat to its neighborhoods.

Fig. 6.41 A satellite map showing the location of the historic city and Casa de Pilatos in urbanised Seville

Source: Google satellite maps

A combination of narrowness and overhanging upper storeys of the houses on each side of the canyons in Santa Cruz area is used to keep the streets in continuous shade and low temperature (see fig.6.42). Temperature in a canyon is influenced by the temperature of the canyon surfaces and higher temperature in the canyon increases the heat convection to the buildings (Santamouris ed.2001 pp71). However, Ibid (pp75) has also shown that air temperature measured in the middle of the canyon is not influenced by the orientation of the street, either during the day or during the night. This suggests that the temperature distribution within shaded streets of Santa Cruz neighbourhood does not impact on the thermal performance of the Casa de Pilatos.

Fig. 6.42 A satellite map showing the Casa de Pilatos and its current neighbourhood,

Source: Google satellite maps

Knowledge of the airflow characteristics in urban canyons is necessary for all studies related to natural ventilation of buildings (Santamouris, pp75). Each street canyon represents a set of buildings or surface areas. The wind pattern in the canyon is a secondary circulation feature, influenced by specific design details of buildings and streets, and especially the relative height between buildings, and orientation of these to the wind. Canyon airflow is characterised by a velocity along the canyon that is almost always parallel to the axis of the canyon (Ibid pp82). According to Santamouris (ed.2001 pp35), airspeeds in urban canyons may be higher under two specific conditions. The first is when the high speed air layers are either deflected downwards by tall building or channelled as 'jets' along canyons in the same direction as the flow. Second is when the induced low-level flow from the countryside is strong enough to overcome the frictional drag of the canyon walls. These are unlikely events in Santa Cruz neighbourhood where Casa de Pilatos is located because variation in building height is not significant, and the urban expansion has interrupted all the possible paths for low level airflows from the countryside region. It is suggested that the impact of wind in the streets surrounding the Casa de Pilatos is very limited.

Regarding the relationship between the wind speed out of the canyon and the corresponding air velocity inside the canyon, Nakamura and Oke (1988) suggests that for wind speeds up to 5m/s, the general relationship between the wind velocity υ, within the canyon, and above-roof free stream wind speed U, appears to be linear, $\upsilon = pU$. Santamouris (ed.2001 pp36) measurement of wind speed in canyons observes that, although the wind speed above the canyon and meteorological station may reach values up to 5m/s and 6m/s respectively, the air speed within canyons never exceeds 1m/s. This observation is critical for analysis of the data collected in the Casa de Pilatos because the Main Patio is open to air movements on the street canyon.

Generally, wind speeds which are below 1m/s have no influence on natural displacement flows. The impact of buoyancy forces is shown in fig.6.37 with at least 55 per cent of data points falling within the theoretical extent of buoyancy (stack) forces. This is confirmed in fig.6.38 and fig.6.39 where at least 70% of data plots below the wind speed of 1m/s. It is confirmed that since the air speed on the street canyon does not exceed 1m/s, buoyancy is the dominant force for air velocity through the transitional spaces in the Casa de Pilatos. The next section examines the amount of convective cooling energy attributed to airflows through the transitional spaces.

6.4 Convective cooling in the Hall of Columns

The primary challenge in the application of natural ventilation in semi arid climates is summertime temperatures. In summer seasons, the cooling potential of natural ventilation is limited by the prevailing climate and by occupancy expectation of thermal comfort. Factors such as solar radiation, outdoor temperature, humidity and internal loads (human activity, lights, and equipment) impact the performance of natural ventilated buildings.

In the case of the transitional spaces in the Casa de Pilatos, the thermal conditions in the Main Patio and Grand Garden represent the outside environment on either side of the Hall of Columns (see fig.6.43). Similarly, the Main Patio and Small Garden represent the outside environment on either side of the Praetor Chamber. The air temperatures recorded in these courtyards represent summertime outdoor temperatures for these transitional spaces. Subsequently, the variation of temperature across the courtyards will have a considerable impact on air convection through these spaces.

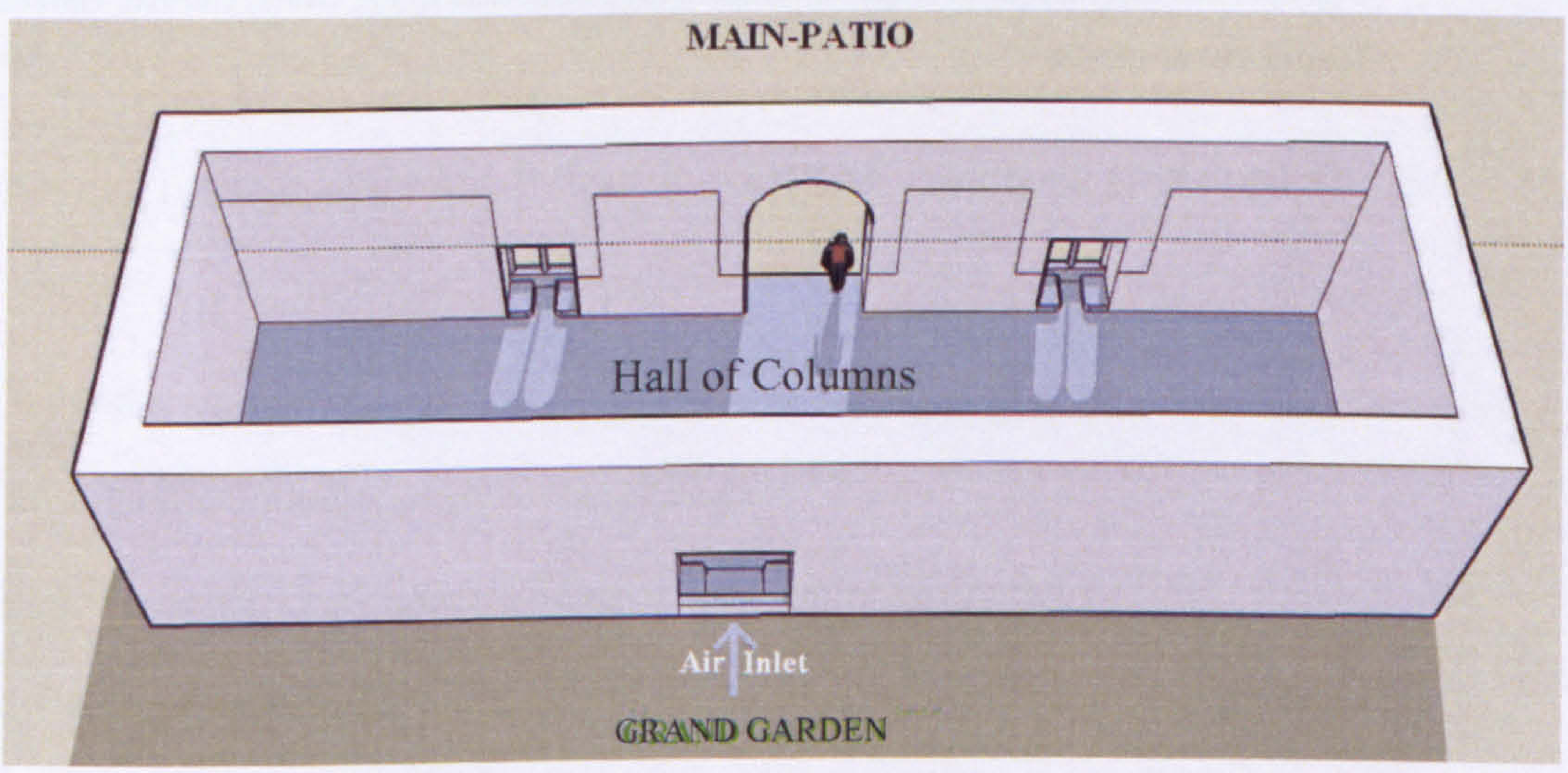


Fig. 6.43 The physical configuration of the Hall of Columns showing the air inlet and outlets

A theoretical approach is used to calculate convective cooling in the Hall of Columns in order to determine the impact of yard-to-yard convective cooling. The Hall of Columns and Praetor Chamber are situated on either side of the Main Patio. The calculation considers air speed at the inlet, area of inlet, volumetric size of the spaces, and the air temperature recorded in the garden-courtyard and within space. Because DBT's recorded in the Grand Garden were higher than the Hall of Columns (see fig.6.44), calculations have taken into consideration the fact that the air temperatures in the Hall of Columns were recorded near the entry window. As indicated in the previous chapter, the readings at the entry to the Hall of Columns more accurately represent the conditions in the near end of the Grand Garden, and would therefore be considered as outdoor temperatures. The possibility of cooling is considered by determining the enthalpy of incoming air.

Fig. 6.44 the variation of average air temperatures measured in the Grand Garden, Hall of Columns, and Main Patio at 15:00h

6.4.1 The enthalpy of incoming air

The enthalpy or heat content (*h*) is a quotient or description of thermodynamic potential of a system and a measure of the total energy in humid air. Enthalpy represents the sum of sensible and latent heat transferred between the air and its environment. The potential for heating or cooling is quantified by determining the enthalpy of air. According to Lazzarin Renato (2007), free cooling is possible when the specific humidity is sufficiently lower and the enthalpy of the outside air is lower than the ambient enthalpy.

The enthalpy of the air on either side of the Praetor Chamber 'chamber of governors' is calculated in order to determine the possibility for cooling in this transitional spaces. The thermal conditions in the main patio represent indoor air while the conditions in the small garden represents outside air. The variation in the enthalpy at 15:00h is calculated by using Equation 6.4 below, when the air in the Small Garden is at 31.4 ^{0}C and 38.3%RH, with the air in the Main Patio at 43.6^{0}C and 19.7%RH.

Specific enthalpy of moist air can be expressed as:

$$h = c_{p(a)}\, t + w\, [c_{p(w)}\, t + h_{w(e)}]$$ Source: ASHRAE Handbook (1997 pp6.9) ... (6.4)

Where;

h = specific enthalpy of moist air (kJ/kg)

$c_{p(a)}$ = specific heat capacity of air at constant pressure (kJ/kg.°C)

t = air temperature (°C)

w = humidity ratio, kg (water)/kg (dry air)

$C_{p(w)}$ = specific heat capacity of water vapour at constant pressure (kJ/kg.°C)

t = water vapour temperature (°C)

$h_{w(e)}$ = evaporation heat of water at 0°C (kJ/kg)

Specific heat capacity for air at constant pressure $c_{p(a)} = 1.006$ *(kJ/kg°C)*

For water vapour the specific heat capacity $c_{p(w)} = 1.805$ *(kJ/kg.°C)*

The evaporation heat of water $h_{w(e)} = 2{,}501$ *(kJ/kg)*

The enthalpy of air in the Small Garden at 31.4°C and 38.3%RH, hence humidity ratio (w) = 0.010935 kg/kg, can be calculated as:

h = 1.006 (kJ/kg.°C) 31.4°C + 0.010935 (kg/kg) [1.84 (kJ/kg.°C) 31.4°C + 2,502 (kJ/kg)]

= 31.5884 (kJ/kg) + 0.63178 (kJ/kg) + 27.359 (kJ/kg)

h = 59.58 (kJ/kg)

The enthalpy of air in the Main Patio at 43.6°C and 19.7%RH, hence humidity ratio w = 0.010918 kg/kg, can be calculated as:

h = 1.006 (kJ/kg.°C) 43.6 °C + 0.010918 (kg/kg) [1.84 (kJ/kg.°C) 43.6°C + 2,501 (kJ/kg)]

= 43.8616 (kJ/kg) + 0.87588 (kJ/kg) + 27.3168 (kJ/kg)

h = 72.05 (kJ/kg)

The difference in the enthalpy (Δh) of the air in the Small Garden and the Main Patio (fig.6.45);

Δh = (72.05 – 59.58) kj/kg

Δh = <u>12.48 kj/kg</u>

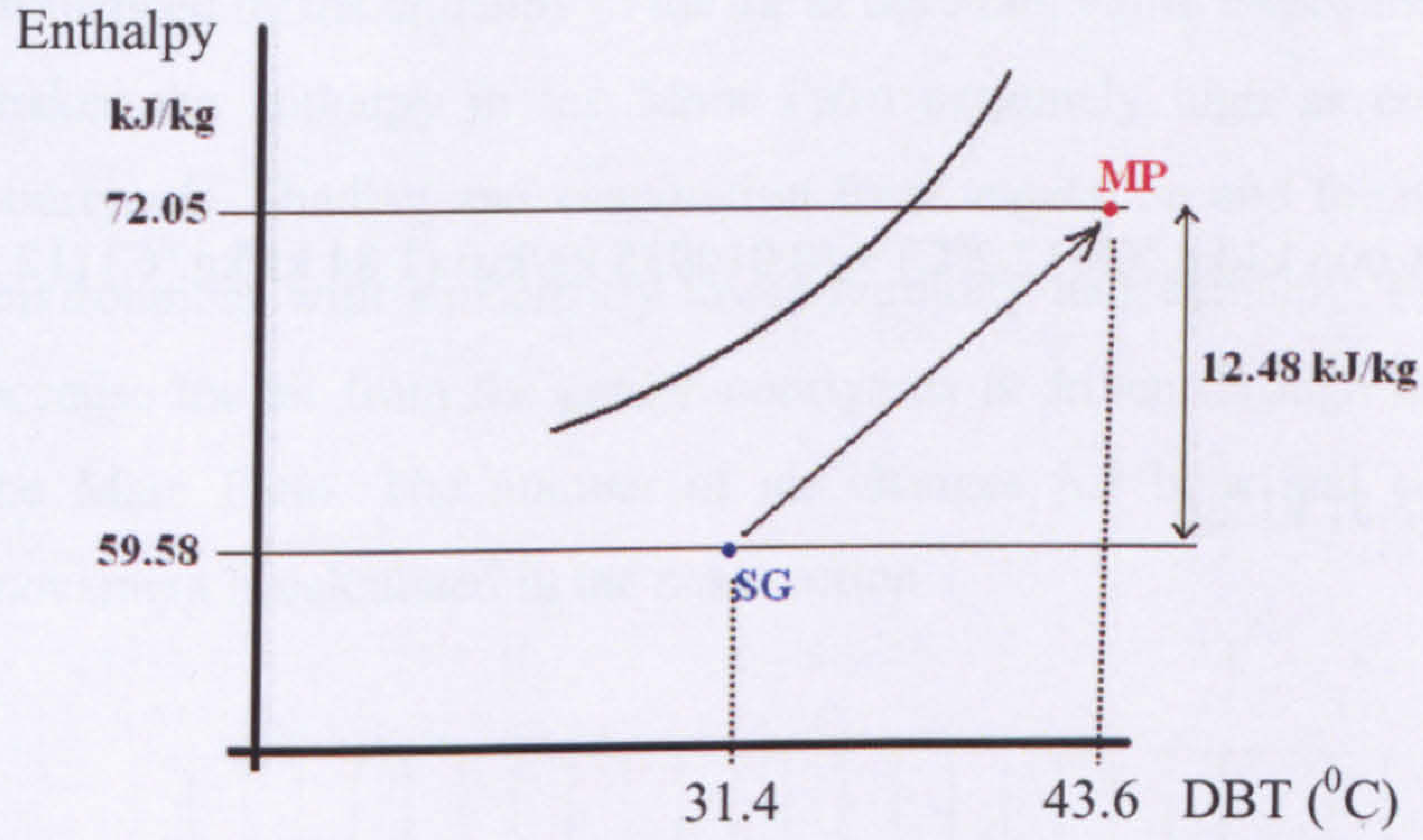


Fig. 6.45 The enthalpy variation between the Small Garden (SG) and Main Patio (MP)

The Enthalpy Difference

Instead of calculating the enthalpy of air in the Small Garden and Main Patio separately; the calculations below considers an increased temperatures at constant humidity in the Small Garden. The DBT of 31.4^{0}C (at 15:00h) in the Small Garden is increased to the level of temperature in the Main Patio (43.6^{0}C) while maintaining the moisture level recorded in the Small Garden. Hence, with recorded DBT of 31.4^{0}C and 38.3%RH in the Small Garden, DBT of 43.6^{0}C and 38.3%RH is considered in the Main Patio. The level of humidity is maintained to determine the relative impact of temperature difference.

The enthalpy difference when the temperature of the air in the Small Garden has risen to the level of the temperature in the Main Patio without changing moisture content is expressed as:

$$\Delta h_{A\text{-}B} = c_{p(a)}\, t_B + w\,[c_{p(w)}\, t_B + h_{w(e)}] - c_{p(a)}\, t_A + w\,[c_{p(w)}\, t_A + h_{w(e)}]$$

$$= c_{p(a)}(t_B - t_A) + w\, c_{p(w)}\, (t_B - t_A) \quad (2)$$

Sensible heat latent heat

The variation in enthalpy with the rise of DBT to 43.6°C in the Main Patio is calculated as:

$$\Delta h_{A-B} = (1.006\ kJ/kg.^{o}C)(12.2^{o}C) + (0.010935\ kg/kg)\ (1.84\ kJ/kg.^{o}C)\ (12.2^{o}C)$$

$$\Delta h_{A-B} = 12.51\ kJ/kg$$

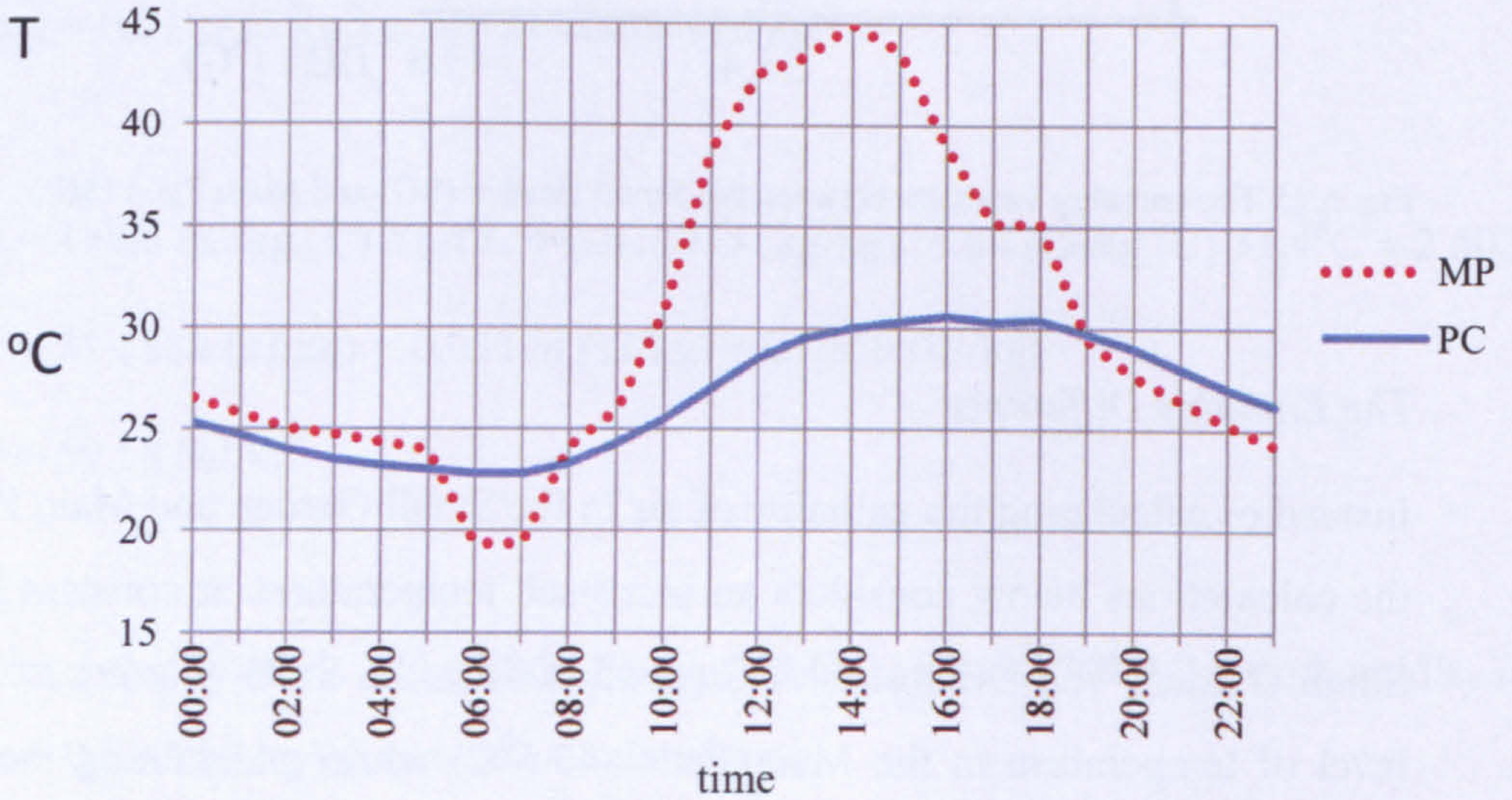


Fig. 6.46 The average hourly variation in DBT recorded in the Praetor Chamber (PC) and Main Patio (MP) recorded on 12th – 19th August

The calculations show that a considerable part of the enthalpy difference is due to variation in DBT (see fig.6.46). The impact of air moisture on the enthalpy difference between the Small Garden and the Main Patio is insignificant (0.03kJ/kg). These calculations suggest that adiabatic cooling is possible because the specific humidity is sufficiently low and the enthalpy of air from the garden-courtyards is significantly lower than the enthalpy of air in the Hall of Columns and Main Patio.

Casa de Pilatos is designed such that the conditions in the transitional spaces are influenced by the enthalpy of the air in the Main Patio. Exposure to direct solar radiation makes the enthalpy in the Main Patio extremely high as compared to the garden-courtyards. Shading and evaporation from vegetation and fountains creates an outdoor environment with sufficiently lower humidity and enthalpy. Free cooling is achieved because the air from the garden-courtyards is driven through the transitional spaces to the Main Patio. The number of air changes per hour and cooling attributed to air movement is calculated in the next section.

6.4.2 The number of air changes

The Hall of Columns and Praetor Chamber are facing the garden-courtyards (Grand Garden & Small Garden) on either side of the Main Patio. Average air speed of 0.7m/s was recorded from the $4.8m^2$ inlet to the halls at 15:00h. The discharge coefficient (C_d) of 0.6 is applied to calculations of volume flow rates through the Hall of Columns. The discharge coefficient takes account of the friction as the volume flow rates are lower in some parts of a rectangular opening. This provides a volume flow rate of $2.3m^3/s$ at 15:00h and is calculated from the volumetric size of $310m^3$ (15x4.6x4.5m 'Hall-of-Columns'). The cumulative size of the three outlets on the opposite side of the inlet window is $9.5m^3$. Equation 6.5 is used to calculate the number of air changes per hour.

$$N = \frac{3600Q}{Vol.} \quad (Source: AM10) \quad \dots \qquad (6.5)$$

N = number of air changes per hour

Vol = volumetric size of the hall = $310m^3$

Q = volumetric flow rate of air

Q = A (area of the inlet) x υ (air speed) x C_p (discharge coefficient)

Q = $4.83m^2$ x 0.7m/s x0.6= 2 m^3/s

$$N = \frac{Q(2.3m^3/s)}{Vol(310m^3)} X3600$$

N = 23/hour

6.4.3 Calculation of convective cooling

The daily variation of temperatures between the Hall of Columns and Grand Garden ($T_{HC} - T_{GG}$) are used for calculation of convective cooling energy. The calculated air changes per hour (N) and a theoretical temperature difference (ΔT) of 2k are used to calculate the convective cooling energy in the Hall of Columns (see fig.6.47). Since the inflow of cool air from the Grand Garden was evident at the inlet to the Hall of Columns, the convective cooling experience could certainly be attributed to temperature difference. There is a temperature increase from one end of the room to another when moving towards the Main Patio. The data taken at the window-inlet is used to represent the near end of the Grand Garden, while the air temperature in the middle of the Hall of Columns is considered to be 2k higher.

The methodology and equations show step-by-step calculation of the cooling energy at 15:00h in the afternoon. This provides a figure for the hottest time of the day. The calculation of convective cooling considers a temperature difference of 2k ($T_{GG} - T_{HC} =$ 2k) between the recordings taken at the inlet and middle of the Hall of Columns. The same method is used to generate hourly cooling energy for all daytime data. The results are presented in Table-6.11. Hourly variations of air changes are calculated by using Equation-6.5, while convective cooling is calculated by using Equation-6.6. The temperature difference is used to calculate the convective cooling energy in kilowatts and watts per meter square. The hourly variation of the convective cooling energy is shown in Figure 6.48.

Fig. 6.47 The Hall of Columns (left), and the location of recording equipment at the inlet to the Hall of Columns (right)

The calculation of convective cooling energy at 15:00h;

$$Q_v = \frac{Sp.HeatxNx\Delta T}{3600} \quad Source: AM10 \quad .... \qquad (6.6)$$

Q_υ = energy in Watts

N = Air Changes/hr

V = volume m^3

ΔT = temperature difference

Sp.Heat = Volumetric specific heat of air = 1200 J/ m^3.K

Hence;

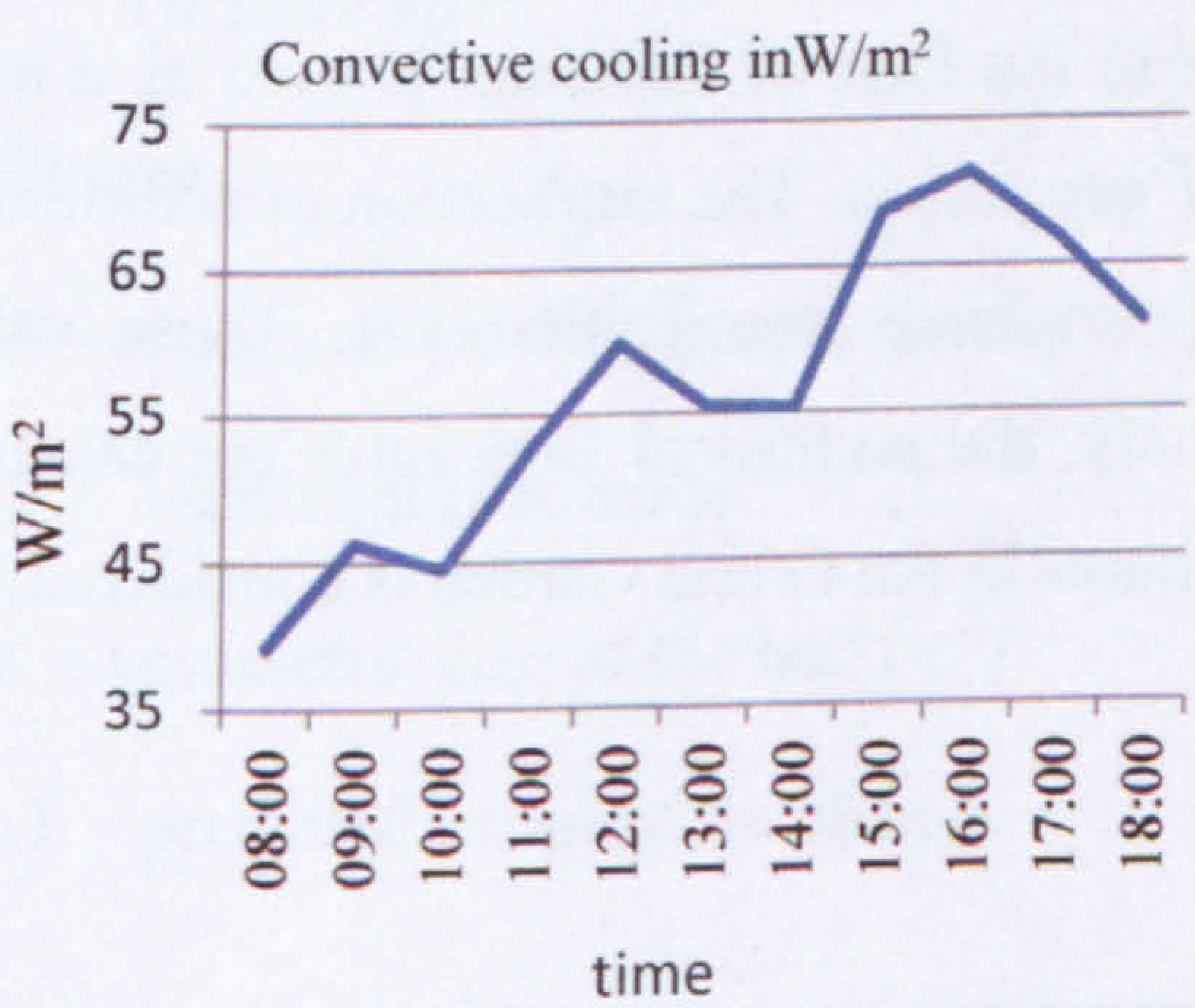
$$Q_v = 0.33xNxVx\Delta T$$

$$Q_v = 0.33x\,{}^{23}/_{s}\,x310m^3x2k$$

$Q_v = 4700\ Watts\ \approx 4.7kW$ at 15:00h

Table 6.11: The figures for convective cooling Q_v(kW) by considered temperature difference (ΔT) T_{GG}-T_{HC}=2k. Volume flow rates (Q), air changes per hour (N), and the cooling energy (Q_v); Temperatures are seven days average; N and Q_v are calculated from equation (6.5) and (6.6).

TIME	T_{HC} (^0C)	$T_{Roof\text{-}top}$ (^0C)	Estimated (ΔT) T_{GG}-T_{HC}	Q m^3/s	N (/hr)	Q_v (kW)	W/m^2
08:00	23.1	25.1	2k	1.1	13.1	2.7	39.2
09:00	24	28.8	2k	1.3	15.5	3.2	46.3
10:00	25.2	32.4	2k	1.3	14.9	3.1	44.5
11:00	26.6	34.6	2k	1.5	17.6	3.6	52.7
12:00	27.9	36.1	2k	1.7	20.1	4.1	59.9
13:00	29.1	36.7	2k	1.6	18.6	3.8	55.5
14:00	30.4	38.9	2k	1.6	18.5	3.8	55.3
15:00	31.2	39.1	2k	2.0	23.0	4.7	68.7
16:00	31.7	38.9	2k	2.1	23.9	4.9	71.4
17:00	32.1	37.1	2k	1.9	22.4	4.6	67.0
18:00	32.8	35.7	2k	1.8	20.5	4.2	61.1



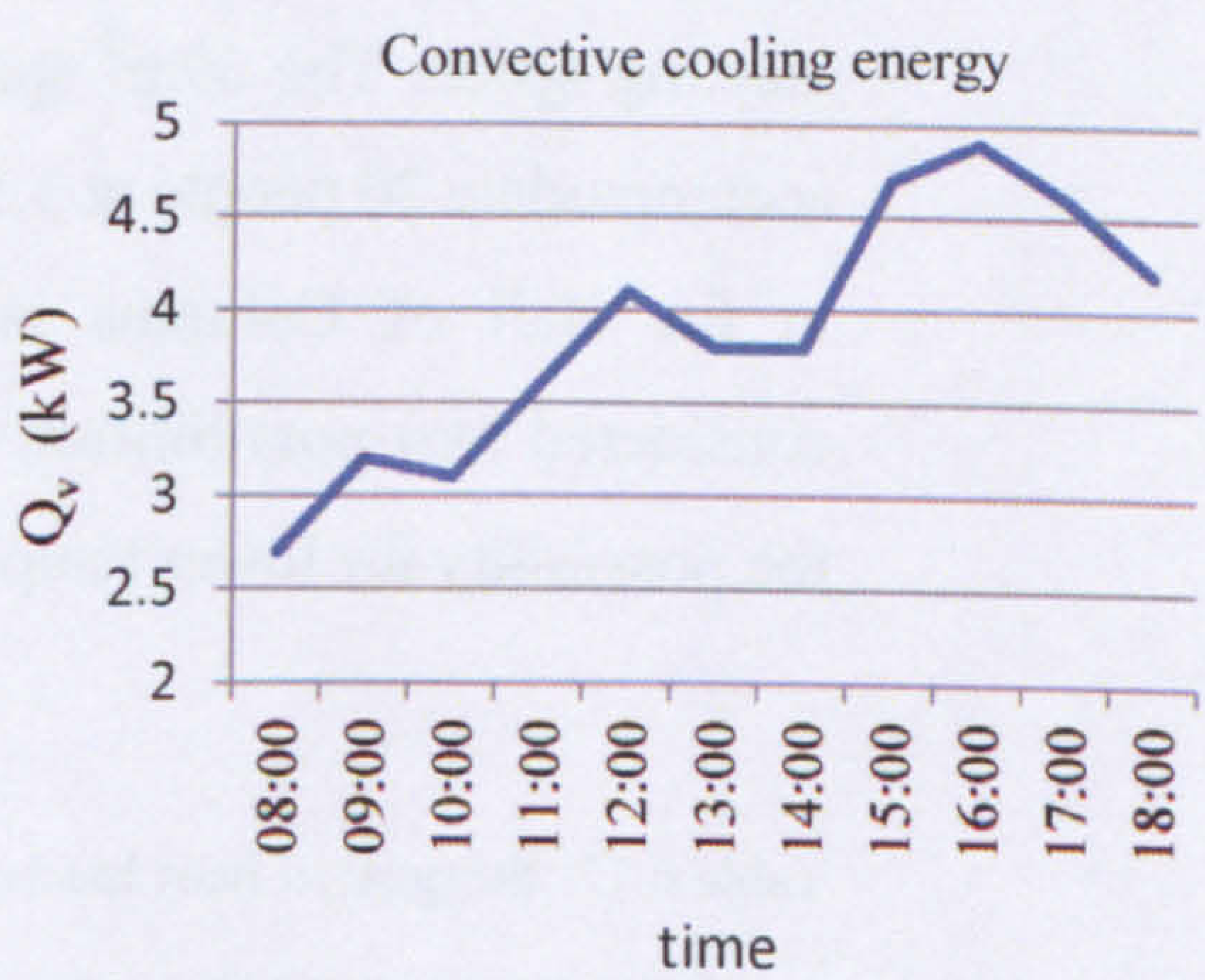


Fig. 6.48 The variation in convective cooling energy

The results in Table-6.11 use the temperature difference of 2K between the Grand Garden and Hall of Columns. This temperature difference produces convective cooling energy of 2.7kW (39.2W/m^2) at 08:00h and 4.9kW (71.4 W/m^2) at 16:00h. The temperatures recorded near the opening to the Hall of Columns are considered as a representative of the conditions in the Grand Garden. However, it is likely that the airflows through the Hall of Columns are driven by much bigger temperature difference. While higher temperatures in the Main Patio can influence the movement of air through the Hall of Columns, these convective cooling calculations have considered much a smaller temperature difference because actual reading were not taken in the middle of the transitional spaces due to healthy and safety reasons.

6.4.4 The implication of additional heat loads

This section determines the implication of additional heat loads to the environment in the Hall of Columns. The numerical calculation of additional heat loads on the thermal conditions in the Hall of Columns is important because fieldwork was undertaken in unoccupied spaces. The Hall of Columns assumes a conventional function in order to determine the limitations of the existing thermal environment. This will help to determine the limitation of existing convective cooling strategy in a conventional environment. In order to determine the impact of additional heat loads and the means of mitigating these gains, the calculation in this section considers the Hall of Columns as a meeting space. The 69m^2 space in the Hall of Columns is used as a meeting room to accommodate 20 people at 3.5m^2 per person. The implication of additional 1.8kW added in the Hall of Columns is determined (see Table-6.12). These calculations have considered two possibilities; firstly, the additional flow rates are calculated; secondly, the possibility for lower temperatures in the Grand Garden is considered.

Table 6.12: Suggested heat loads:

No.	Item	Data required	Heat output calculation	Heat output subtotal
1.	People	Max # of personnel in the Hall of Columns	70watts x Max # of personnel	70 x 20 = 1.4kW
2.	Latent heat allowance	30% of item No.1		0.4kW
3.	**Total**			1.8kW

- Requirement for additional flow rates (Q)

An attempt is taken to determine the additional flow rates required to mitigate the impact of additional heat gains. The estimation of additional air movement required for summer cooling is based on recorded summertime conditions. This establishes the airflows required to maintain the existing thermal environment. Table-6.11 has shown the flow rates calculated from the field studies where the air changes at 15:00h is 23/h. The increment of 1.8kW in 69m^2 space (3.5m^2/person) is equivalent to addition of 26W/m^2. The calculations below show the increment in volume flow rates (Q) that is required to maintain the conditions at 15:00h. The results for the daytime period are presented in Table-6.13.

Refer equation – 6.6

$$Q_v = 0.33xNxVx\Delta T$$

$$N = \frac{Q_v}{(0.33xVx\Delta T)}$$

Whereas;

N = additional air changes per hour

Q_v = additional heat loads

V = volumetric size of the hall (m^3)

ΔT = predicted temperature change

$$N = \frac{1800watts}{(0.33x310m^3x2k)}$$

$$N = 8.8/hour$$

Refer equation – 6.5

Q = volumetric flow rate of air

$$Q = \frac{NxVol}{3600} = \frac{31.8/h\,x\,310\text{m}^3}{3600}$$

Q = 2.7 m^3/s

Q = A (area of the inlet) x υ (air speed) x C_d (discharge coefficient)

$$\upsilon = \frac{Q}{AxC_d} = \frac{2.7}{4.83x0.6}$$

υ = 0.9m/s (at 15:00h)

Table 6.13: The air speed υ (m/s) and volume flow rates Q (m^3/s) required in the Hall of Columns

TIME	Predicted (ΔT)	Existing Q (m^3/s)	Required Q (m^3/s)	Required υ (m/s)
08:00	2.0	1.5	1.9	0.6
09:00	2.0	1.3	2.1	0.7
10:00	2.0	1.2	2.0	0.7
11:00	2.0	1.3	2.3	0.8
12:00	2.0	1.6	2.5	0.9
13:00	2.0	1.9	2.4	0.8
14:00	2.0	1.6	2.4	0.8
15:00	2.0	1.9	2.7	0.9
16:00	2.0	1.9	2.8	1.0
17:00	2.0	2.0	2.7	0.9
18:00	2.0	2.1	2.5	0.9

Additional 8.8 air changes per hour (ACH) are needed in order to evacuate the heat gains at 15:00h. This means an increment from the existing 23ACH to 31.8ACH. The required air speed (υ) and volume flow rates (Q) across the opening can be calculated from the new volume flow rate. Calculations of required air speeds and volume flow rates for 15:00h are shown above. Table-6.13 presents the hourly fluctuation air speeds and volume flow rates for the daytime period between 08:00h and 18:00h when the Hall of Columns is used as a meeting room.

The air velocity through the inlet to the Hall of Columns should range between 0.6 and 1.0m/s in order to retain the existing thermal environment (see Table-6.13). The air speeds at 15:00h need to increase from the existing 0.7m/s to 0.9m/s in order to eliminate the additional heat loads (see calculations above). In case that additional heat loads cannot be mitigated through additional flow rates, the possibility of lower air temperatures in the gardens is considered in the following calculations.

- Requirement for lower garden temperatures (T_{GG})

It has been suggested in previous sections that yard-to-yard airflow is mainly driven primarily by temperature differences. Hence, the flow rates across the Hall of Columns can be altered by changing the air temperature in the Main Patio or the Grand Garden. Previously, the temperature difference between the Grand Garden and Hall of Columns were used to calculate the convective cooling in the Hall of Columns. The calculations below consider the possibility of lower air temperatures in the Grand Garden. This approach takes into account the potential wet bulb temperatures (WBT) in the Grand Garden. The goal in this set of calculations is to remove the additional heat loads when 20 people (1.8kW) are added into the Hall of Columns (refer Table-6.12). The calculations for the required change in temperature in the Grand Garden at 15:00h are shown below. Table-6.14 shows the existing and required hourly fluctuation of daytime air temperatures (DBT) in the Hall of Columns and Grand Garden between 08:00h and 18:00h.

Refer equation – 6.4

$$Q_v = 0.33xNxVx\Delta T$$

$$\Delta T = {Q_v}/{(0.33xVxN)}$$

Whereas;

ΔT = required temperature change (k)

Q_v = additional heat loads (watts)

V = volumetric size of the hall (m^3)

N = existing air changes per hour (/h)

$$\Delta T = \frac{1800watts}{(0.33x310m^3x23/h)}$$

$$\Delta T = 0.8k$$

Table 6.14: The average of recorded air temperatures, wet bulb temperatures (WBT), and the temperatures difference required between the Grand Garden (GG) and Hall of Columns (T_{HC} - T_{GG}) from 08:00h to 18:00h.

TIME	Existing T_{GG} (°C)	Required $\Delta T = T_{HC} - T_{GG}$	Required T_{GG} (°C)	WBT (Grand Garden)
08:00	23.1	3.3	21.8	15.8
09:00	24	3.1	22.9	16.5
10:00	25.2	3.2	24.0	17.3
11:00	26.6	3.0	25.6	18.0
12:00	27.9	2.9	27.0	18.7
13:00	29.1	2.9	28.2	19.1
14:00	30.4	2.9	29.5	19.4
15:00	31.2	2.8	30.4	19.7
16:00	31.7	2.7	31.0	19.8
17:00	32.1	2.8	31.3	19.4
18:00	32.8	2.9	31.9	19.2

The data shows that very little variation in temperature in the Grand Garden is required to mitigate the additional heat loads. The temperature difference required to remove the additional heat loads range between 2.7K and 3.3K. A temperature difference of 2.8K is therefore required between the Hall of Columns and Grand Garden (T_{HC} -T_{GG}) at 15:00h in the presence of additional heat loads. This means, an additional difference of 0.8K is required above the existing difference of 2K. This is far below the WBT in the Grand Garden. These results show that a considerable amount of additional heat loads are removed by lowering the temperatures in the garden-courtyards through evaporative cooling and additional vegetation. The implication of these variations to thermal comfort is discussed in the next section.

6.5 Thermal Comfort in the Casa de Pilatos

The objective of this section is to evaluate the physiological implication of the environmental qualities observed in the field data. While the previous sections have presented the numerical analysis of the collected climatic data, this section does carry out the analysis of the thermal comfort in the Casa de Pilatos. This will enable the understanding of the fundamental qualities through which architecture has meet human physiological needs. Since the building is naturally ventilated, the adaptive comfort models are used as the criteria for evaluating the climatic conditions in the Casa de Pilatos. Adaptive comfort standard in ASHRAE standard 55 are used to analyze the conditions in the transitional spaces. The distinction between adaptive comfort and conventional thermal comfort models is also discussed.

The objective of this analysis is to widen the argument for adaptive comfort by taking lessons from a building which is fully dependent on nature. The analysis of hourly variation of daily recorded data is carried out by considering the thermal comfort requirements. Adaptive principles are used to analyze the relationship between the comfort temperatures and the temperatures in the transitional spaces. Lab based indices are not used because Casa de Pilatos is a free running building with courtyards and spaces where subjects are exposed to range of thermal conditions. The thermal response of the subjects is predicted using adaptive models of Nicol and Humphreys (2002) and Brager and de Dear (2001) in conjunction with other models.

A range of thermal sensations existing in the Casa de Pilatos is discussed. The building's thermal environment is discussed in five main sensations; hot, warm, neutral, cool, cold to represent some specific situations. Environmental and personal factors affecting the criteria for thermal comfort are also analyzed and evaluated. Environmental factors include air temperature (DBT), humidity (RH), air movement (velocity υ in m/s), and mean radiant temperature (MRT). This environmental data was collected by using data logging equipment. Personal factors include clothing (clo) and activity level or metabolic heat (met). Air quality or the feeling of freshness or stuffiness will not be considered in this approach. The discussion of the thermal comfort in the Casa de Pilatos considers the environmental impact of wide range of thermal conditions observed in the building.

This section focuses on thermal comfort in the transitional spaces (Hall of Columns and Praetor Chamber) between courtyards (see fig.6.49). It is conjectured that these spaces are strategically located to take advantage of convective cooling flows from the garden-courtyards. Psychrometric charts are used to present all the hourly recorded data. Psychrometric charts are also used to analyze the possibilities and limitations of natural ventilation and evaporative cooling. The analysis has also considered the criteria for location of window-seats in these transitional spaces.

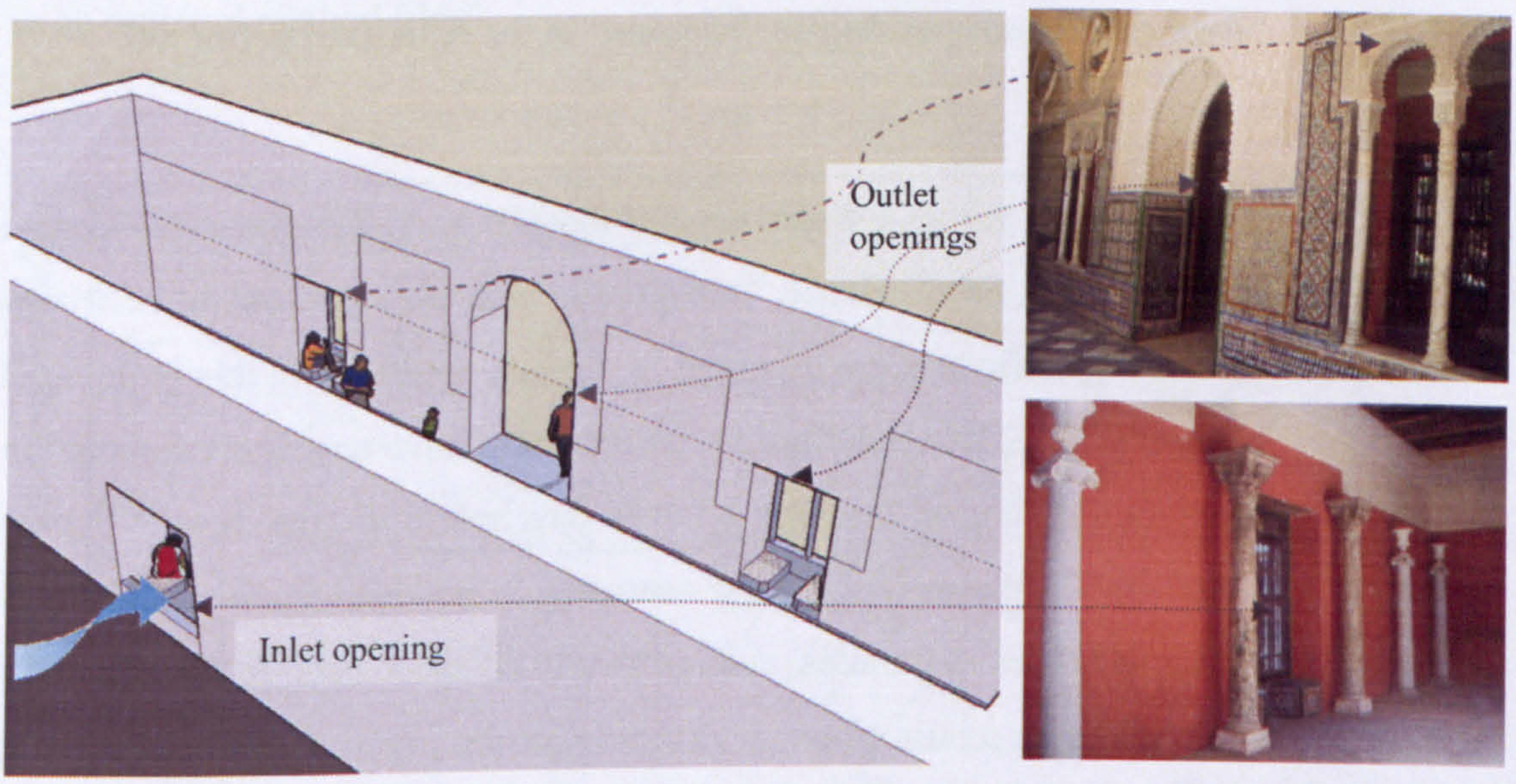


Fig. 6.49 the graphical image of the Hall of Columns (left), inlets to the Hall of Columns (top right), interior façade showing the window to the Grand Garden (bottom right)

6.5.1 Definition of thermal comfort

Unlike air conditioned buildings, the Casa de Pilatos is a free running building. Thermal comfort in naturally ventilated or free running buildings is guided by different principles. It can be deduced that thermal neutrality is not the design criteria for Casa de

Pilatos.Thermal satisfaction in this building is derived from the composition of the thermal environment and not a narrow range/set of thermal parameters promoted through PMV/PPD calculations. This is consistent with Nicol (2009) observation that there is no temperature at which everybody will feel comfortable.

The term 'thermal comfort' is widely promoted alongside a set of assumptions which are reflected in ASHRAE and ISO standards. ASHRAE's Standard 55 defines human thermal comfort as '*the state of mind that expresses satisfaction with the surrounding environment*'. The misinterpretation of ASHRAE's definition may have arisen from the mischaracterisation of the term '*surrounding environment*'. The observation by Spenser (2006) has shown that human thermal satisfaction goes beyond thermal neutrality. The environment in Casa de Pilatos does not insert boundaries or physical limitations on locale called '*surrounding environment*' in the ASHRAE definition.

The transition within a wide range of thermal environments in the Casa de Pilatos is an environmental event. Hence, '*satisfaction with the surrounding environment*' cannot be tied to a specific task environment or thermal neutrality in this building. The term '*state of mind*' in ASHRAE definition does not also have any direct association with body-air temperature balance or some specific psychological conditions. Clements-Croome ed. (1997 pp57) shows that human sensation is never maintained at a constant level, but rather oscillates in minutes, even in steady environments. In the Casa de Pilatos, time as duration of exposure plays a vital role in the comprehensive thermal experience and personal expression of satisfaction when the user is interacting with continuously changing environment.

ASHRAE 55 already incorporates adaptive comfort as part of thermal comfort criteria for naturally ventilated buildings (Brager and de Dear, 2001). However, the PPD (predicted percentage of dissatisfied) and PMV (predicted mean vote) models used in ISO and ASHRAE widely consider the steady state air conditioned buildings. The PPD-

PMV calculations are therefore limited in their application to adaptive comfort criteria as PPD-PMV calculations promote only a limited range of thermal sensation.

Work done by Nicol (2009) suggests that the standards based on comfort surveys are more reliable. Nicol and Humphreys (2002) show presents change in comfort temperature which tracks the monthly mean outdoor temperature (see fig.6.50). Comfort surveys were used by Brager and de Dear (2001) to qualify the criteria for adaptive comfort. Their analysis of 21,000 sets of raw data from 160 buildings has been used in ASHRAE 55 to demonstrate how the thermal comfort criteria for natural ventilation are consistently different from air conditioned buildings. The analysis is incorporated into Section 5.3 of ASHRAE's adaptive comfort standards (ACS). However, the argument about the scope of applicability of this standard has caused this section to be presented as an optional method (ibid).

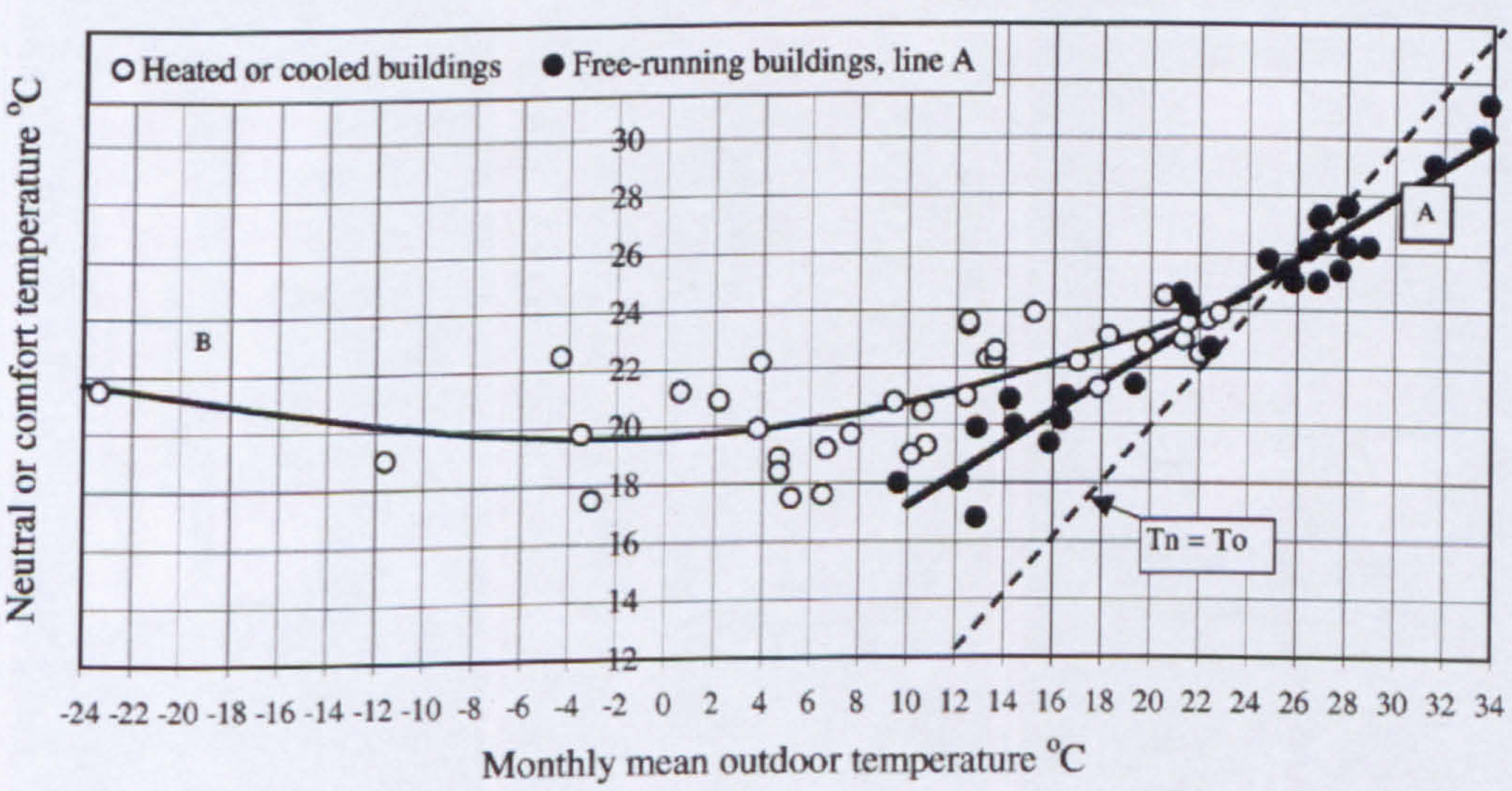


Fig. 6.50 The change in comfort temperature with monthly mean outdoor temperature; each point represents the mean value for one survey. Source: Nicol and Humphreys (2002)

In principle, most of the functional spaces in the Casa de Pilatos start a summer day as 'comfortably cool' which is acceptable in the morning and finish with 'comfortably warm' which is acceptable in the evening. In the daytime, between 11:00h and 17:00h, the temperature in some parts of the building would be categorised as 'hot' with temperature rising to as high as 48^{0}C in the Main Patio. The night-time conditions would be categorised as 'cold' as temperatures would fall to as low as 20^{0}C.

This work suggests that thermal comfort requires a holistic approach. Holistic approaches consider some human environmental factors beyond the standardised criteria for adaptive comfort. The heterogeneous environment of the Casa de Pilatos shows the merits of adaptive opportunities over ASHRAE and ISO standards. Casa de Pilatos was designed in a period when passive heating and cooling was the only available option; subsequent analysis of the thermal environment in this building will make an important contribution to the thermal comfort criteria for naturally ventilated buildings as a whole.

6.5.2 Thermal comfort in the transitional spaces

Transitional spaces are located between the courtyards in the Casa de Pilatos. The subjects in the transitional spaces (Hall of Columns and Praetor Chamber) are exposed to a range of thermal environments depended on their adaptive tendencies. This section evaluates the thermal comfort in the Hall of columns by using adaptive comfort models of Nicol and Humphreys (2002) and Brager and de Dear (2001). The impact of the thermal sensation of air flow for subjects seated or standing at the inlet window is also evaluated. Window-seat is the only built-in furniture in these spaces. These seats are built-in the window space to take advantage of the dimension and thermal mass of very thick building walls (see fig.6.51). It is suggested that the thermal comfort for subject in the transitional spaces is maintained by radiant heat from the building mass and convective cooling flows from the garden courtyards.

Fig. 6.51 Window-Seats in the Hall of Columns overlooking the Main Patio (left), overlooking the Grand Garden (middle), Window-Seats in the staircase overlooking the Grand Garden (right)

The window-seats are found in all windows in the Hall of Columns and Praetor Chamber. The window-seats in these halls do face both the Grand Garden and Main Patio. The Chapel lobby and the stair shaft leading to the upper floor also contain built in window-seats facing the Main Patio and Grand Garden respectively. In the Hall of Columns and the Praetor Chamber, the subjects seated at the inlet windows are exposed to a cool breeze from the garden-courtyards, while the subjects seated on the opposite side are exposed to radiant heat from the Main Patio and moderate speeds of air exiting the indoor space (see fig.6.52 and fig.6.53). This section uses mathematical models to determine the impact of the thermal condition in the Hall of Columns and window-seats on thermal comfort.

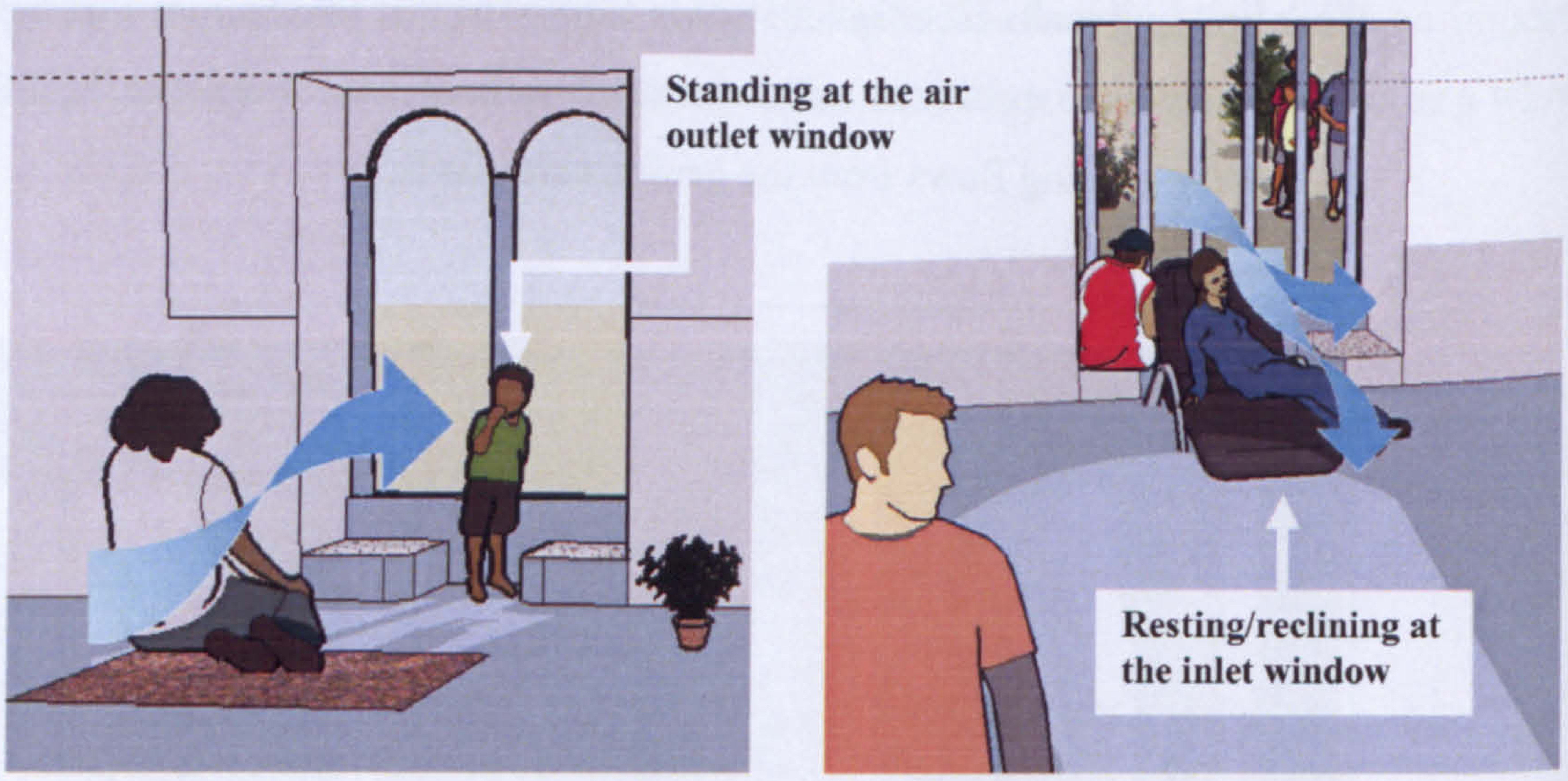


Fig. 6.52 Subjects at the window to the Main Patio (left), and Grand Garden (right)

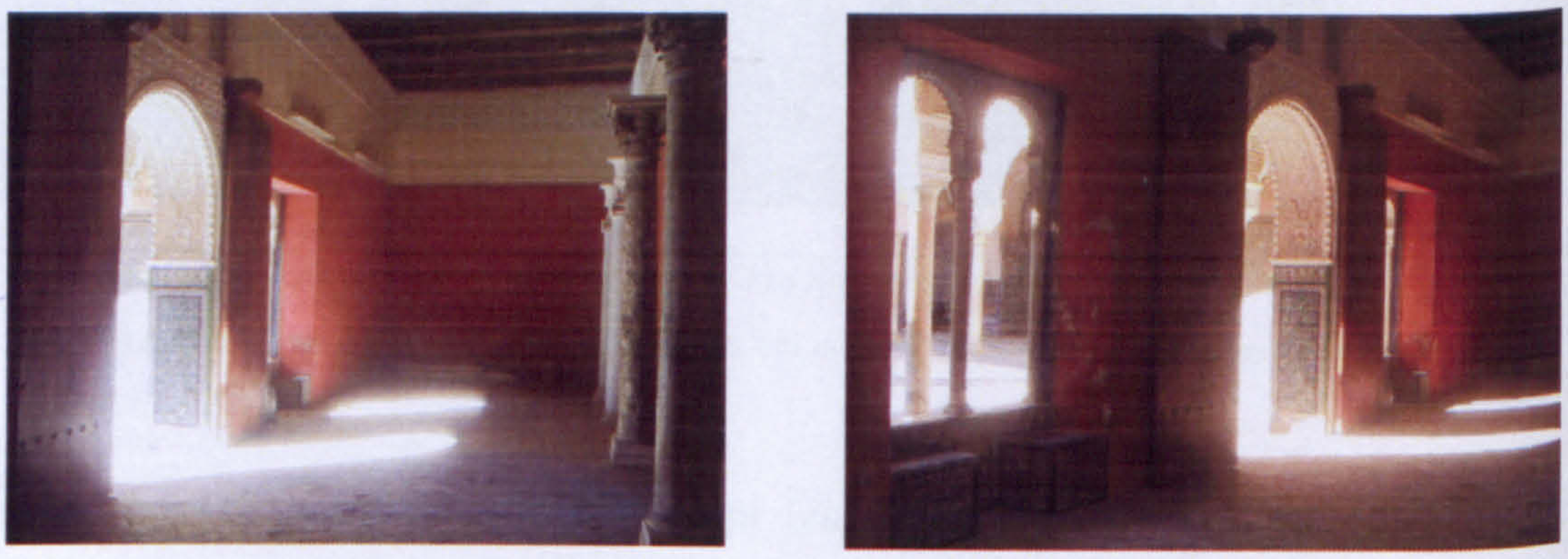


Fig. 6.53 Indoor photo of the 'Hall of Columns' facing the entry with radiation from the morning sun

Various mathematical models have been developed within research community in an effort to guide the understanding of the principles of adaptive comfort. This study uses the mathematical model by Nicol and Humprey (2002) to evaluate the thermal environment in the Casa de Pilatos. Their equation provides the comfort temperature (T_c) by using monthly mean outdoor temperatures (T_o). This results into a comfort temperature of 28.2^{0}C when the meteorological monthly mean outdoor temperature (T_o) of 27.3^{0}C (EnergyPlus Weather file) is used.

$T_c = 13.5 + 0.54T_o$ ....equation (6.7)

The average air temperature in the Hall of Columns at 11:00h in the morning is 26.5^{0}C. This is much lower than the adaptive comfort temperatures of 28.2^{0}C calculated from monthly mean outdoor temperature (refer equation-6.7). Conversely, by 13:00h, the DBT of 29.4^{0}C in the Hall of Columns is above the calculated comfort temperature of 28.2^{0}C. However, Nicol et al (2002) also observe that the acceptable range of conditions at any one time are in the region of +/– 2^{0}C. This adjusts the comfort temperature to 30.2^{0}C and extends the time when the thermal environment in the Hall of Columns is beyond the comfort temperature to 15:00h when the DBT is 31.2^{0}C.

Brager and de Dear (2001) provide a different equation in the new adaptive comfort standard for ASHRAE Standard 55 (see equation (6.8) below). The input for this equation is the recorded outdoor temperature. The calculation uses the outdoor average temperature of 39.1^{0}C recorded at the Roof-Top at 15:00h and results in a comfort temperature ($T_{comf.}$) of 29.9^{0}C at 15:00h.

$T_{comf} = 0.31xT_{a.out} + 17.8$ ...equation (6.8)

Although the calculated value falls within an acceptable range as suggested by Nicol et al (2002), the average temperatures in the Hall of Columns at 15:00h and 17:00h are 31.2^{0}C and 32.1^{0}C respectively well beyond the comfort limits (see fig.6.54).

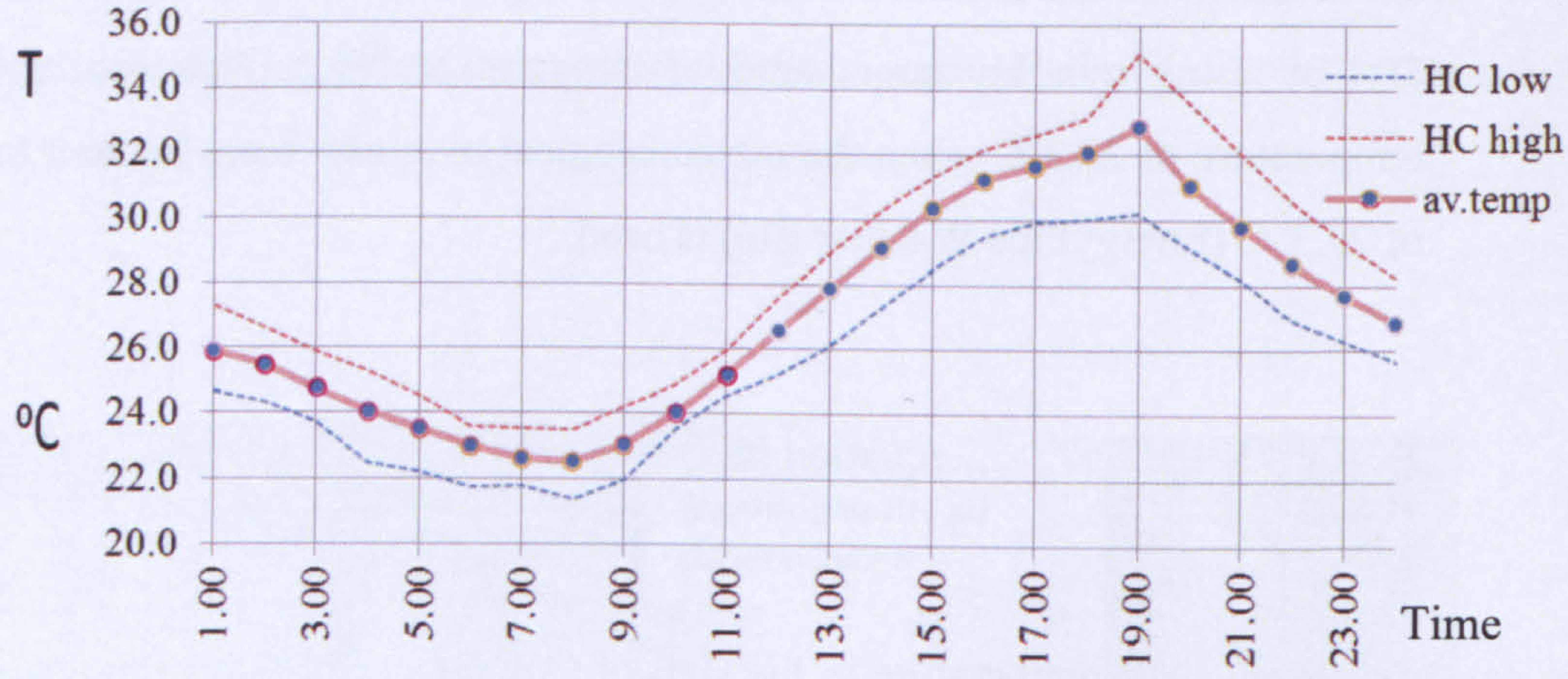


Fig. 6.54 hourly average temperatures recorded in the Hall of Columns (HC)

There is development of computer based mathematical models which include thermal comfort factors that are not easily integrated into psychrometric charts such as clothing level (clo) and metabolic rate (met). These models are useful for examination some adaptive actions taken by people to restore their comfort when there is a sense of discomfort. These tools give an opportunity to explore the relationship between parameters for thermal comfort and hence, enable the analysis of inputs from particular situations. The subject's reactions to parameters of interest can be explored.

The mathematical model by de-Dear (1999) has included the 'exposure time' among the personal parameters (see fig.6.55). This parameter is essential for the Casa de Pilatos where subjects are exposed to a range of temperatures and opportunity to adapt is widely available. Adaptive principles also assert that subjects are less likely to suffer discomfort in situations where there are opportunities to adapt.

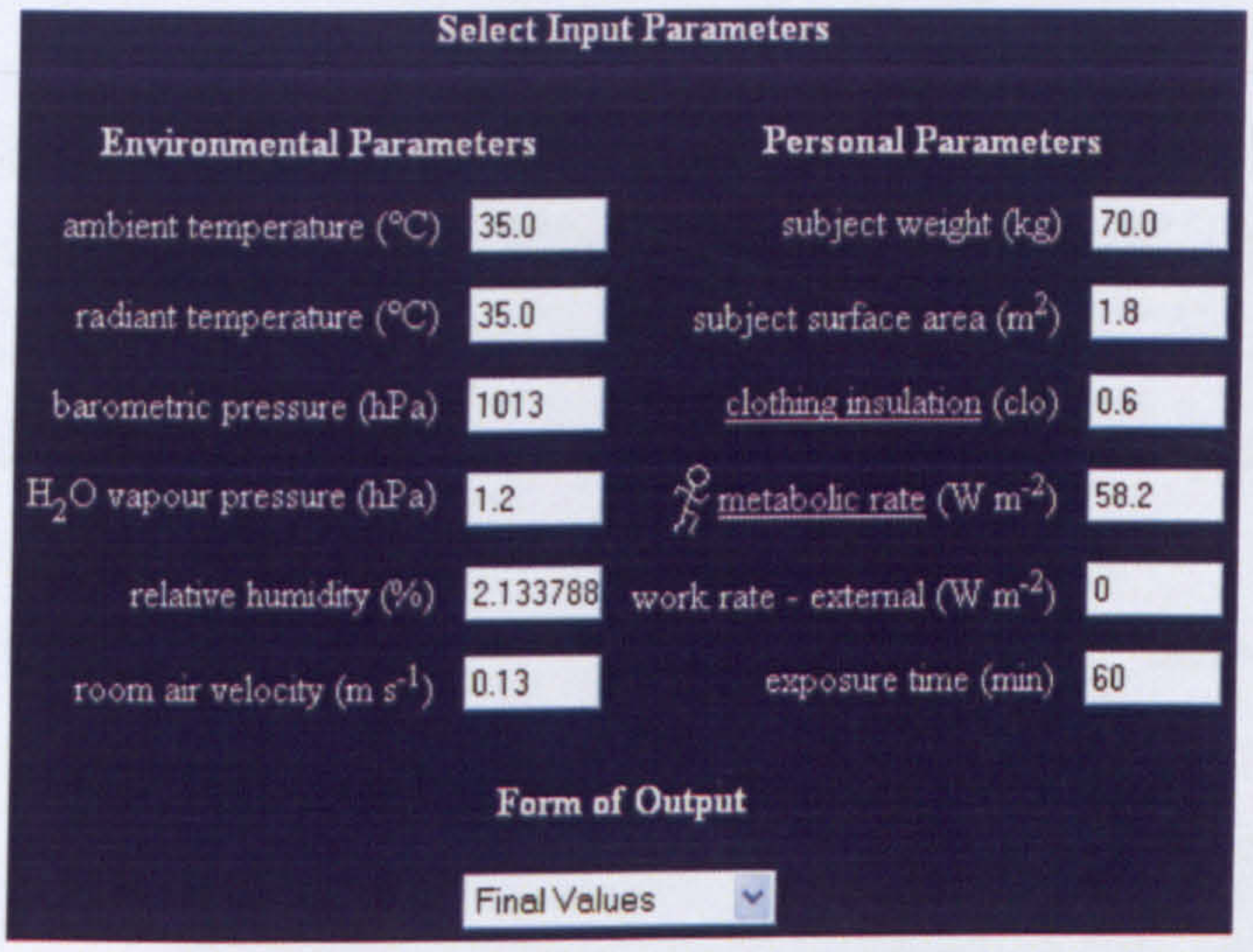


Fig. 6.55 Thermal comfort calculator, Source: Richard de Dear, Macquarie University, http://atmos.es.mq.edu.au, Sydney, 1999

The Comfort Calculator by Square-One is currently a common tool used by academic institutions to evaluate thermal comfort. The calculator used in this study is based on ISO7730-1993. It uses the aforementioned environmental and personal factors to predict thermal comfort (fig. 6.56). Thermal sensation in this tool is categorized into five conditions; cold, cool, neutral, warm, and hot. A scale has ranges from -3 'cold' to +3 'hot' with zero as neutral thermal sensation.

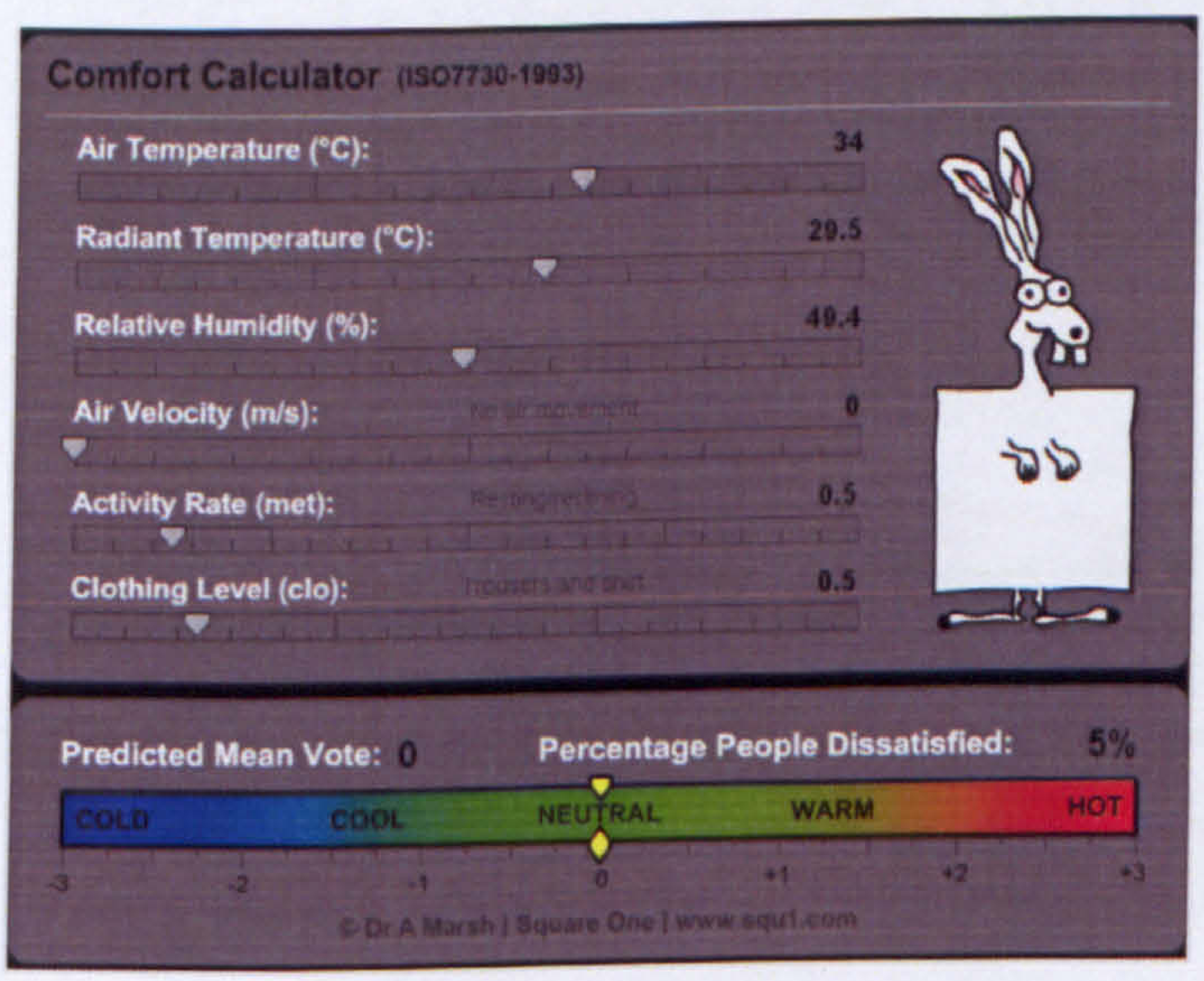


Fig. 6.56 Comfort calculator for the conditions at 1500h on the 16th August

The situations to be considered are presented in figures (fig.6.57 and fig.6.58) and the results are tabulated in Table 6.16 and Table 6.18. The analysis has considered the impact of changing air and radiant temperatures, while also taking into account the metabolic rates of subjects. Table 6.16 presents the results for stagnant condition (still air), while Table 6.18 considers a subject exposed to cooling sensation of airflow when seated on a window-seat.

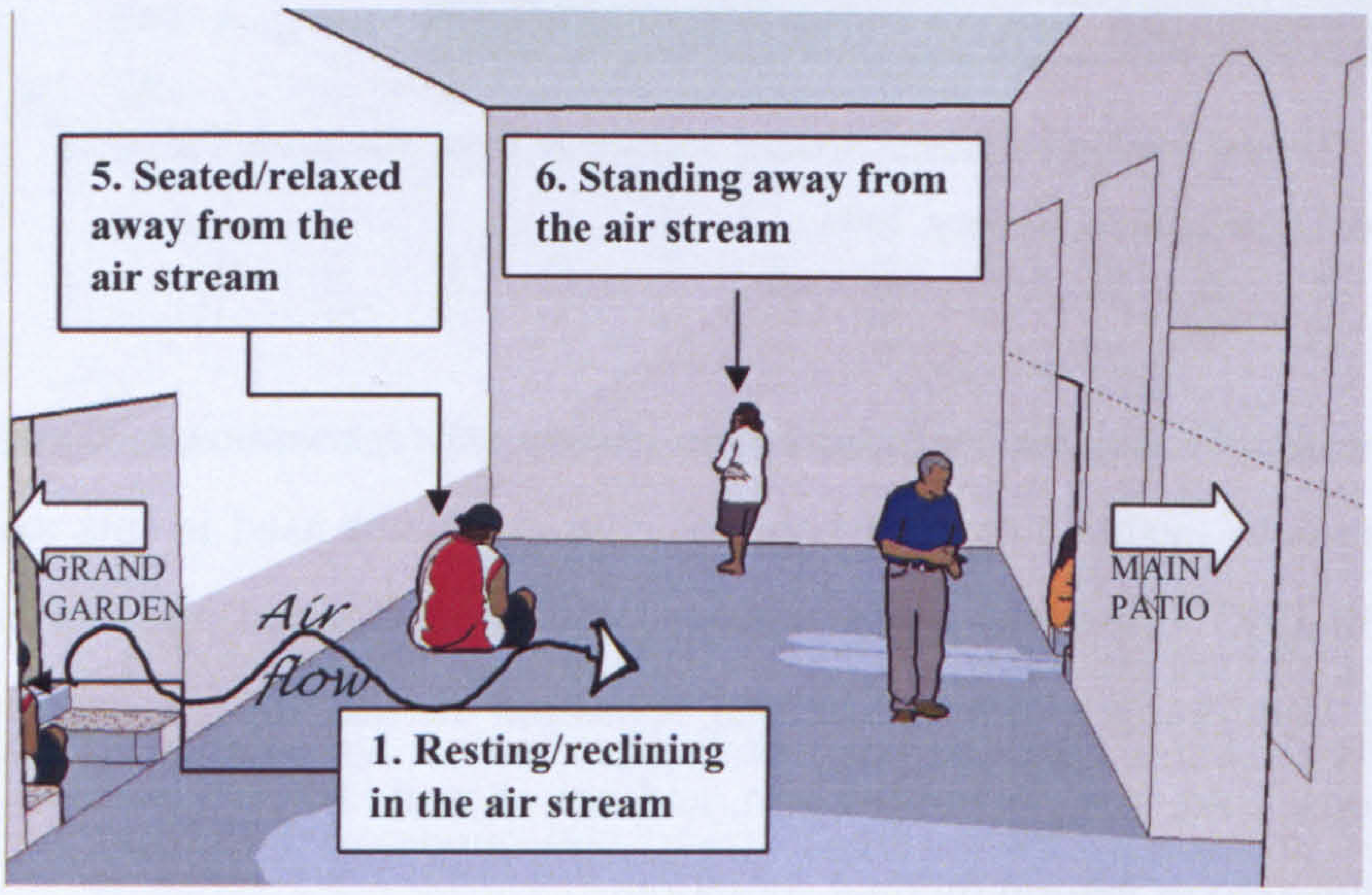


Fig. 6.57 the postures for various thermal sensation when inside the Hall of Columns

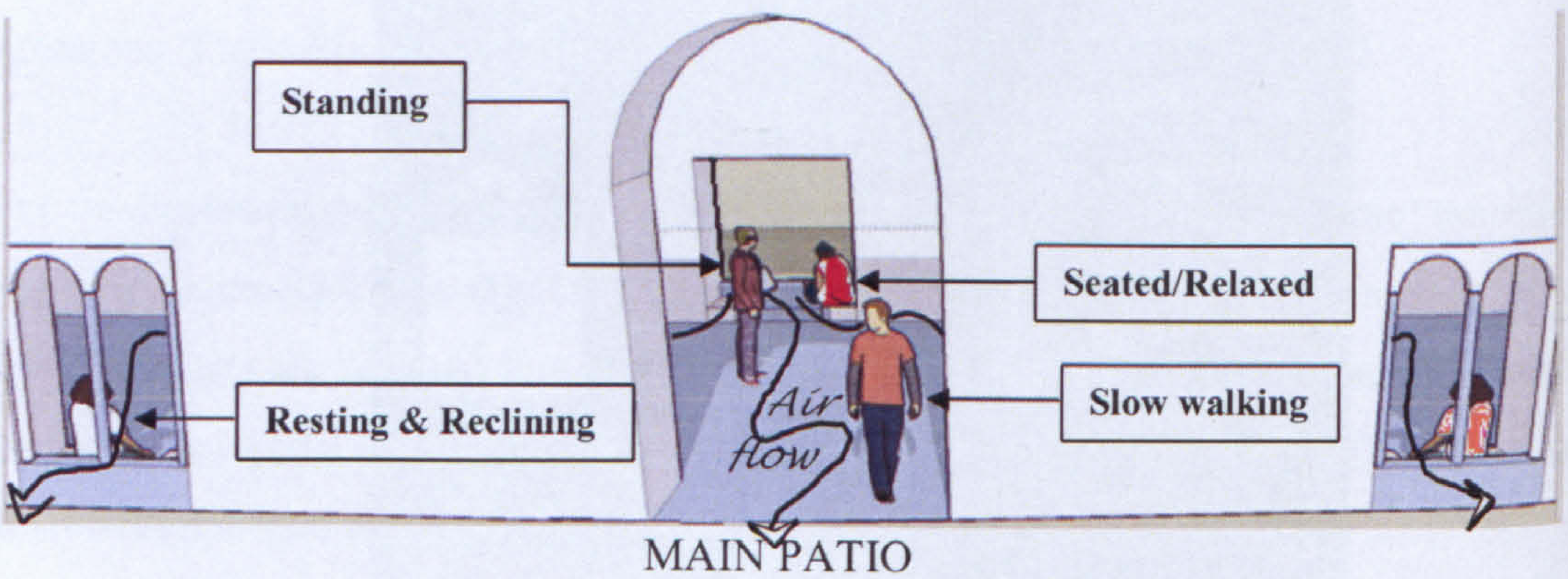


Fig. 6.58 the postures for various thermal sensation in the Hall of Columns

The air temperatures (DBT) and humidity (RH) used in these calculations are taken from field measurements. Mean radiant temperatures (MRT) are taken from the surface temperatures recorded in the Hall of Columns (refer Table 6.15). The analysis uses hourly averaged data (fig.6.54), and all cases consider a person wearing trousers and shirt (0.6clo). The data used is shown in Table 6.15, and results are displayed in Table 6.16.

1. Person resting/reclining in the air stream
2. Person seated/relaxed in the air stream
3. Person standing in the air stream
4. Person resting/reclining away from the air stream
5. Person seated relaxed away from air stream
6. Person standing away from air stream

Table 6.15: Summary of air and surface temperatures (^{0}C) recorded on the 16th Aug. in the Casa de Pilatos

	Roof Top	Hall of Columns		Praetor Chamber		Main Patio		Grand Garden		Small Garden	
time	air	air	surface	air	surface	air	surface	air	surface	air	surface
11:00	35.9	26.5	27.3	25.0	26.0	38.4	28.0	28.4	21.0	28.9	22.0
13:00	34.4	29.4	28.0	28.9	27.8	38.9	37.3	30.7	25.0	30.6	28.0
15:00	35.6	31.0	28.8	30.1	28.3	40.2	40.2	32.6	30.0	31.0	25.0
17:00	31.6	31.8	31.0	30.3	30.0	34.2	43.0	32.3	29.0	30.0	26.0

Table 6.16: Results from thermal comfort calculator (-3 'cold' 0 'neutral' +3 'hot'), the comfortable zone is not shaded. Note: the results have considered stagnant conditions and clothing at 0.4 – 0.7clo (trousers and shirt).

Activity Rate	Met	07:00h		09:00h		11:00h		13:00h		15:00h		17:00h		19:00h	
		22.5 °C	49.6 %	24.0 °C	44.6 %	26.6 °C	38.0 %	29.0 °C	31.0 %	31.0 °C	27.0 %	32.0 °C	22.6 %	31 °C	25.5 %
Seated/ relaxed	0.8-0.9	–1.5 → –1		–1→–0.5		–0.5 → 0		0 → +0.5		+0.5→+1		warm/hot +1.5→+3		warm +1→+1.5	
Sedentary activity	1.0-1.1	–0.5 → 0		0		+0.5		+1		warm +1.5		+2		+1.5	
Standing	1.2-1.5	0 → +0.5		+0.5→+1		+0.5→+1		warm/hot +1.5→+3		+1.5		+2		+1.5→+2	
Light activity	1.6-1.7	+0.5 → +1		+1		+1		+1.5		+1.5		+2		+2	
Medium activity	1.8-1.9	+1		+1		+1		+1.5		+2		+2		+2	
Slow walking	2.0-2.3	+1		+1		warm +1.5		+2		+2		+2		+2	

The shaded parts of Table 6.16 are set to demonstrate the impact of variation in thermal conditions. The acceptable level of activity in the Hall of Columns is represented by non-shaded part of Table 6.16. It demonstrates that activity must decrease with time in order for thermal conditions to be maintained when temperatures are rising. Conditions in the Hall of Columns do not allow comfortable 'walking' after 09:00h, while standing and medium activity are only possible until 11:00h. Sedentary activity can only be carried out until 13:00h. In the absence of airflow, the thermal conditions after 15:00h are relatively warmer. This situation coincides with the traditional siesta, or nap time, practiced from 15:00h to 18:00h, during Seville's summer period.

In this instance, it is important to consider the role of window-seat and the cooling sensation of airflow. The window-seats are useful in situations when it is only possible to be comfortable when the activity rate is reduced to seated/relaxed (0.8met) between 13:00h and 17:00h. In summer, increased air movement can provide an enhanced perception of thermal comfort. However, natural ventilation is discouraged in semi arid climates as temperatures of outside air can be extremely high. In the Casa de Pilatos, the garden-courtyards are used to enhance the thermal properties of air before spatial engagement. The equation provided by Szokolay (1998) is used to evaluate the impact of air movement on the subject seated on the window-seats (see Fig.6.59 and Table 6.16).

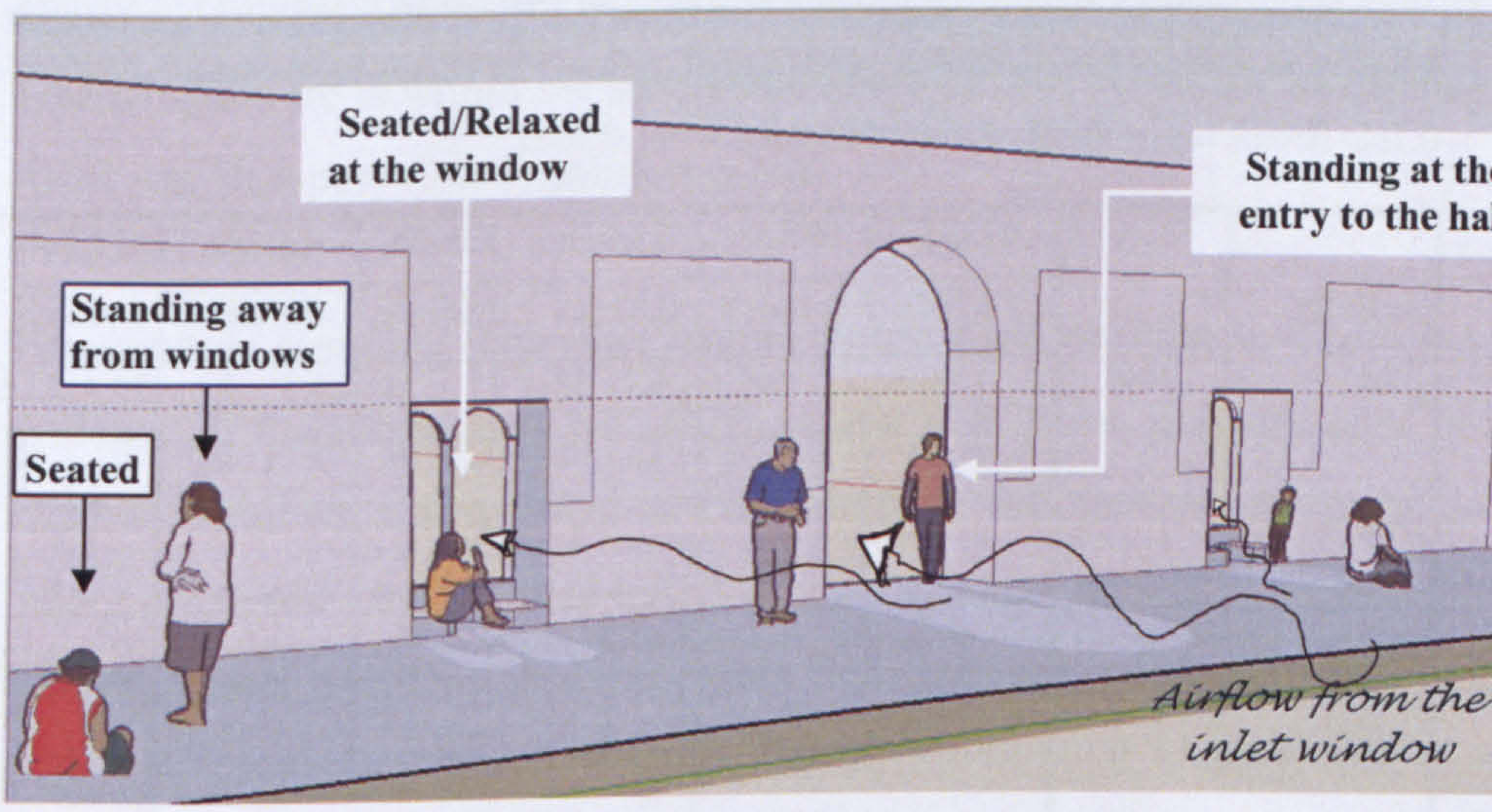


Fig. 6.59 Kinds of activity in the Hall of Columns or Praetor Chamber

Szokolay (1998) provides an equation for calculating the cooling sensation (CS) of airflow over exposed skin. In this equation 'υ' represents the mean air speed in meters per seconds, while the cooling sensation is in degree Celsius (^{0}C). Various activities are possible in these locations (see fig.6.59). Subjects could be standing, seated, or working near the window inlets. The results from Square-One Comfort Calculator using ISO7730-1993 (Table 6.16) are subjected to the field recorded air speeds. The impact of air movement to temperature difference (ΔT) is shown in Table 6.17. Table 6.18 presents the results after adjusting the DBT to account for air movement. Thermal sensation is thereafter predicted by using the Square-One Comfort Calculator.

$CS = 6(\upsilon - 0.2) - (\upsilon - 0.2)^2\ ^{\circ}C$ ...equation (6.9) Source: Szokolay (1998)

Table 6.17: Impact of air speeds on the DBT in the Hall of Columns

	07:00h	09:00h	11:00h	13:00h	15:00h	17:00h	19:00h
Volume flow rates (m^3/s)	2.2	2.2	2.5	2.6	2.9	2.9	2.1
ΔT	1.5k	1.5k	1.9k	2.0k	2.7k	2.6k	2.5k
Field Temp.	22.5 °C	24 °C	26.6 °C	29 °C	31.0 °C	32.0 °C	31.0 °C
Adjusted Temp.	21.0 °C	22.5 °C	24.7 °C	27 °C	28.3 °C	29.4 °C	28.5 °C

Table 6.18: Thermal comfort on with the impact of air movement in the Hall of Columns; Note: DBT is adjusted to account for the cooling sensation of airflow; the results have considered the clothing at 0.5 – 0.7clo (trousers and shirt); the comfort zone is not shaded.

Activity Rate	Met	07:00h	09:00h	11:00h	13:00h	15:00h	17:00h	19:00h
		0.47m/s	0.46m/s	0.53m/s	0.56m/s	0.69m/s	0.67m/s	0.66m/s
		21 °C, 49.6 %	22.5 °C, 44.6 %	24.7 °C, 38 %	27 °C, 31 %	28.3 °C, 27 %	29.4 °C, 22.6 %	28.5 °C, 25.5 %
Seated/ relaxed	0.8-0.9	–1.5	–1.5→–1	–1→–0.5	–0.5→0	0 →+0.5	+1	+0.5 → +1
Sedentary activity	1.0-1.1	–1 → –0.5	–0.5	0	+0.5	+1	warm/hot +1.5	warm +1.5
Standing	1.2-1.5	0	0 → +0.5	+0.5→+1	+1	1 →+1.5	+1.5	+1.5
Light activity	1.6-1.7	0→ +0.5	+0.5	+1	+1→+1.5	warm +1.5	+2	+1.5
Medium activity	1.8-1.9	+0.5	+1	+1	warm/hot +1.5	+1.5	+2	+1.5→ +2
Slow walking	2.0-2.3	+1	+1	warm +1.5	+1.5→+2	+1.5 →+2	+2	+2

Thermal comfort in the transitional spaces is influenced by user activity, body posture and microclimate in various spots in the room. Table 6.18 shows that thermal comfort among subjects who are undertaking '*sedentary activity*' or '*standing*' in an environment with air movement can be achieved until 15:00h. The subjects who are '*seated and relaxed*' at these inlets may not require an afternoon rest 'siesta', as comfort is maintained throughout the day. At 13:00h, the subject '*standing*' at the air inlet window will be comfortable unlike the person standing in different positions within the Hall of Columns. At 17:00h, the subjects will only be comfortable when 'seated/relaxed' at the air inlet window.

The results show that wind velocity is a necessary requirement to restore comfort when temperatures and relative humidity are outside the comfort zone. A temperature difference of as high as 2.7k was realized from the cooling sensation of airflow. The hourly average temperatures which were as high as 32.1^{0}C at 17:00h fall to below 30^{0}C. This temperature is within the acceptable range of 28.2 ^{0}C +/–2K as calculated using the Nicol and Humprey (2002) comfort model.

The window-seats are important feature in the Casa de Pilatos. The window-seats are evidence of the mechanism by which natural ventilation is maintained in the Casa de Pilatos. Windows act as inlets of cool air from the garden-courtyards and outlets of indoor air. Seats are integrated in the window space to help subjects to exploit the direct inflow of cool air. This study suggests that different window-seats perform different roles throughout the year. The usefulness of a particular window-seat changes hourly and from season to season. Simple acts of habitation were practiced during the field study in order to better understand how window-seats affect thermal comfort; these confirmed airflow through the orifice and the accompanying cooling sensation. The boundaries of the study are such that – the observations are limited to the window-seats facing the garden-courtyards only during the summer.

It is apparent that the window-seats facing the garden-courtyards are most efficient during the day time period for the duration of the summer season. The window-seats facing the Main-Patio are useful at the beginning of the day when temperatures are low or in other seasons when temperatures are moderate. The surface temperature of a tiled seat is much cooler and subjects are also benefiting from thermal conduction. It is confirmed that cooling sensation of airflow is part of the criteria for comfort in the multiple courtyards of Casa de Pilatos.

6.5.3 The psychrometric boundaries of field data

Psychrometric charts are used to present the physical and thermal properties of moist air in a graphical form. The fieldwork hourly data of air temperatures (DBT) and relative humidity (RH) for all locations are plotted in individual psychrometric charts (Fig.6.60 to Fig.6.66). The potential and limitations of evaporative cooling and ventilation are discussed. The demarcated boundaries of evaporative cooling and ventilation are adopted from Alvarez (ed.) (1991 pp156). The boundaries of ventilation zone consider air velocity of 1m/s from Givoni's thermal stress index (Alvarez (ed.), 1991 pp156).

The comfort zone is not shown in these psychrometric chart because any definite comfort perimeter outline is based on arbitrary assumptions. According to Olgyay (1992 pp17), the comfort does not have real boundaries. Some studies consider the conditions closer to sunstroke or heat stroke and freezing point as the upper and lower temperature limit for human existence (ibid). The presented boundaries of evaporative cooling and ventilation strategies are only demarcating the perimeter outline where corrective measures necessary to restore the feeling of comfort are possible. The extent by which these parameters can be varied is dependent on the physiological needs of the subjects at any point in time.

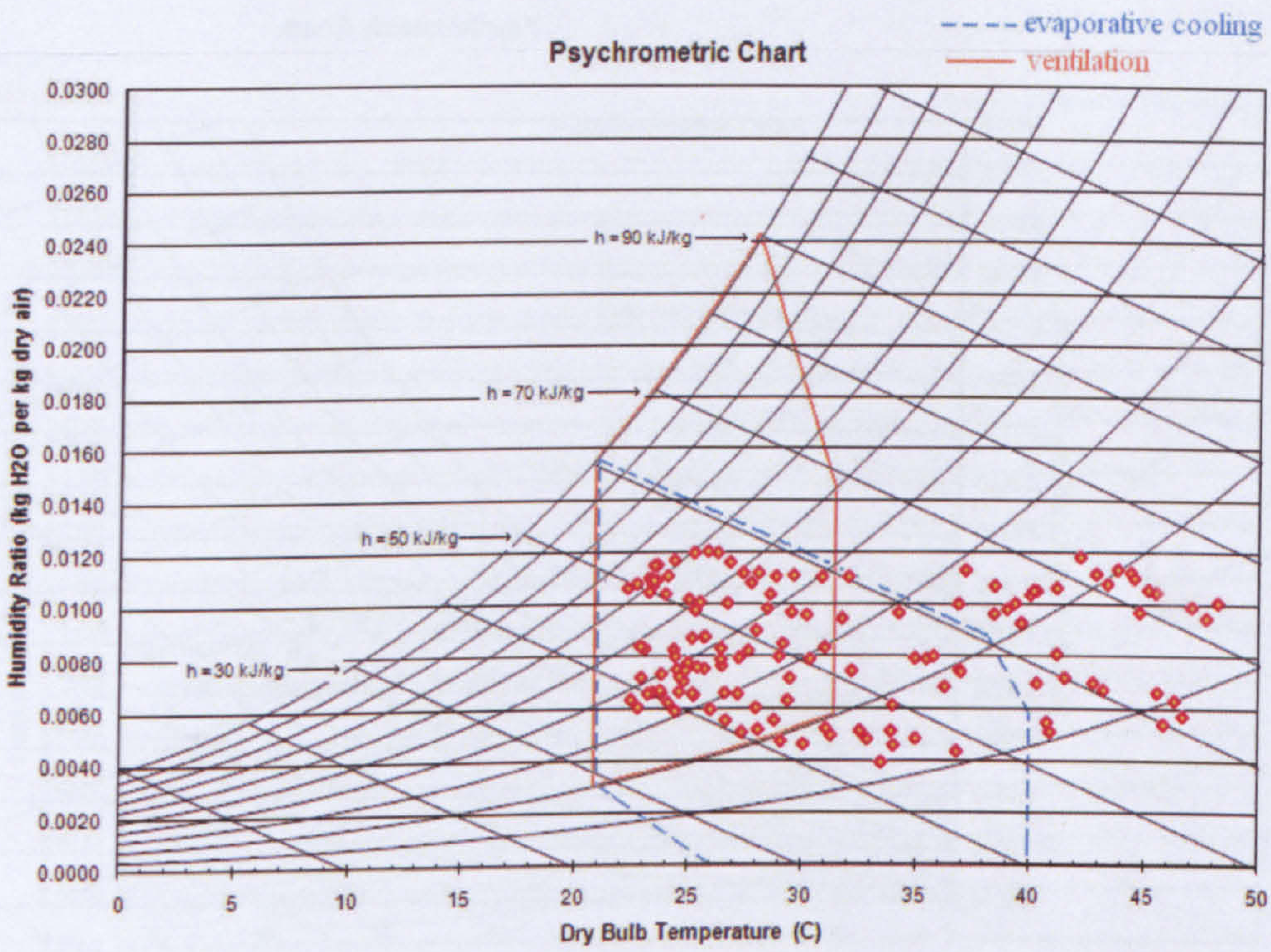


Fig. 6.60 The layout of the daily data recorded in the Main Patio (MP) from 12^{th} – 19^{th} Aug.

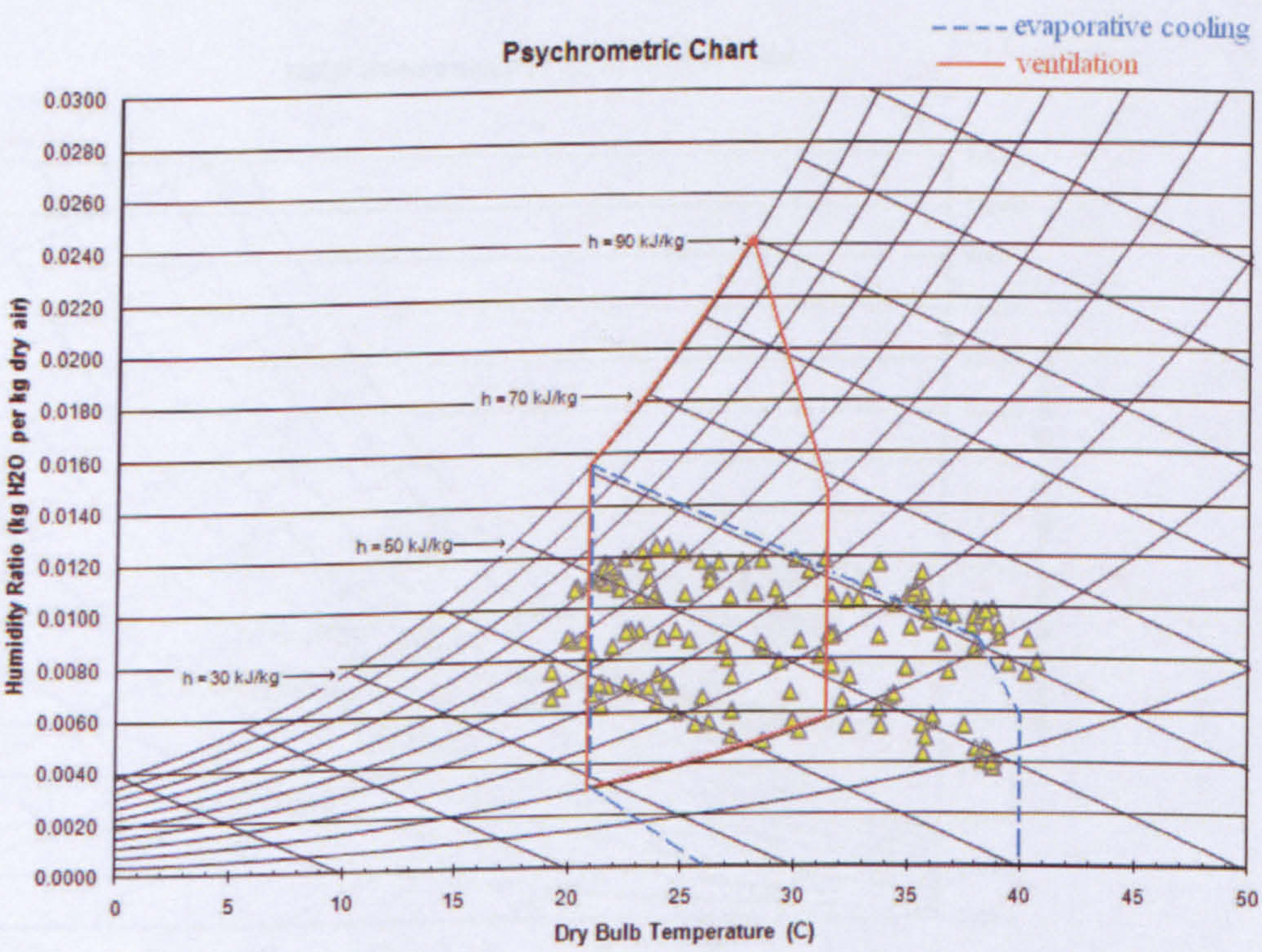


Fig. 6.61 The layout of the daily data recorded in the Roof Top (RT) from 12^{th} – 19^{th} Aug.

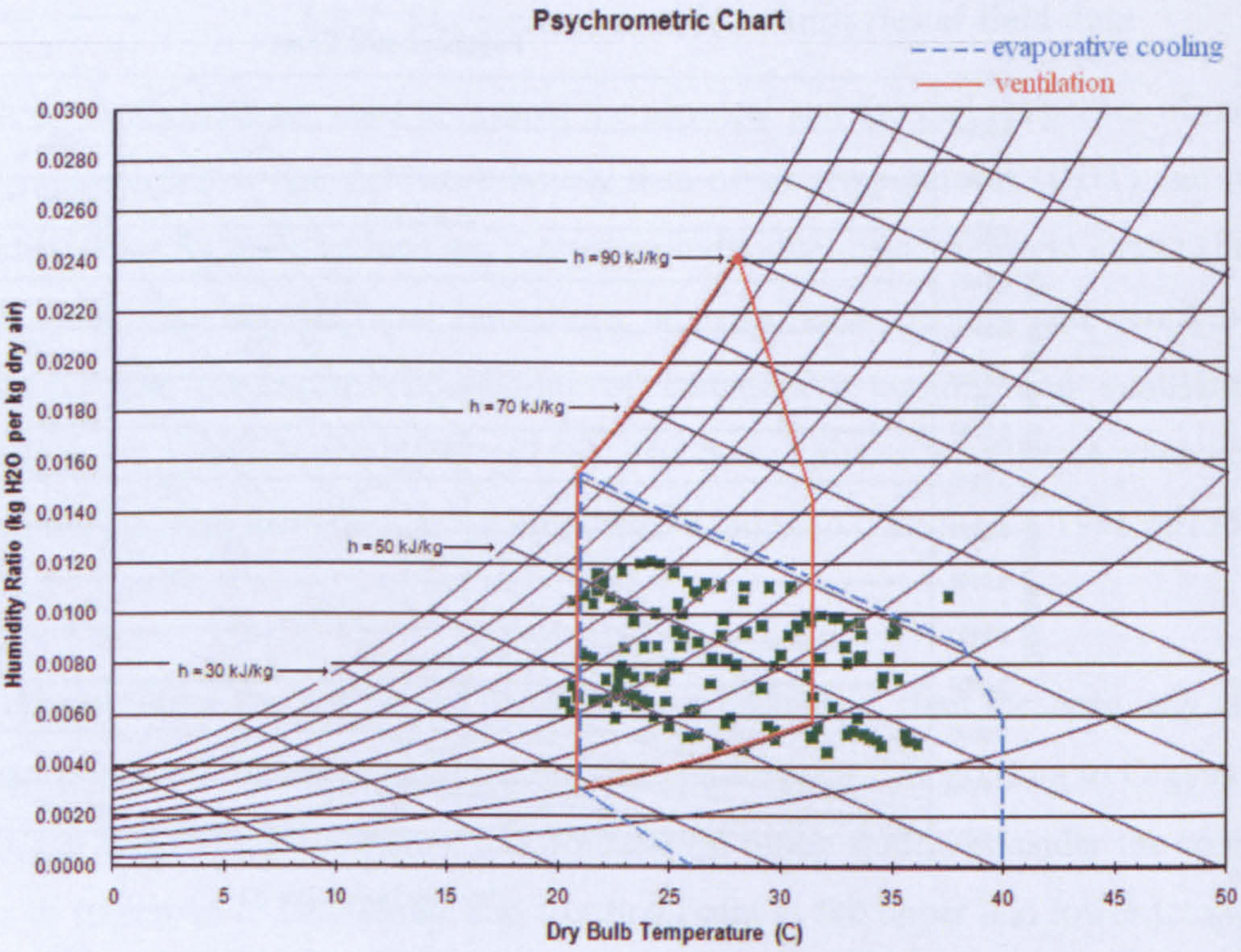


Fig. 6.62 The layout of the daily data recorded in the Grand Garden (GG) from 12th – 19th Aug.

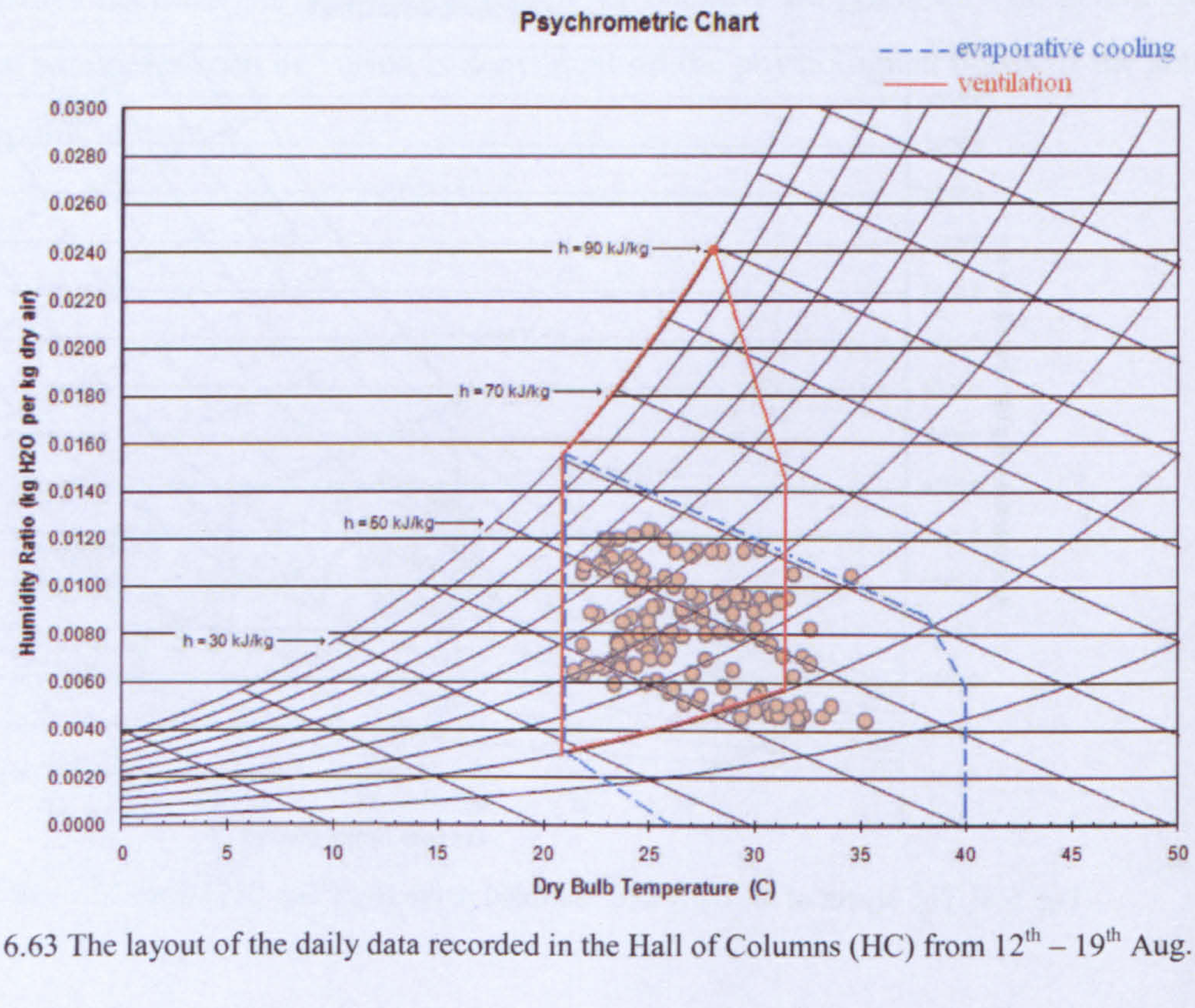


Fig. 6.63 The layout of the daily data recorded in the Hall of Columns (HC) from 12th – 19th Aug.

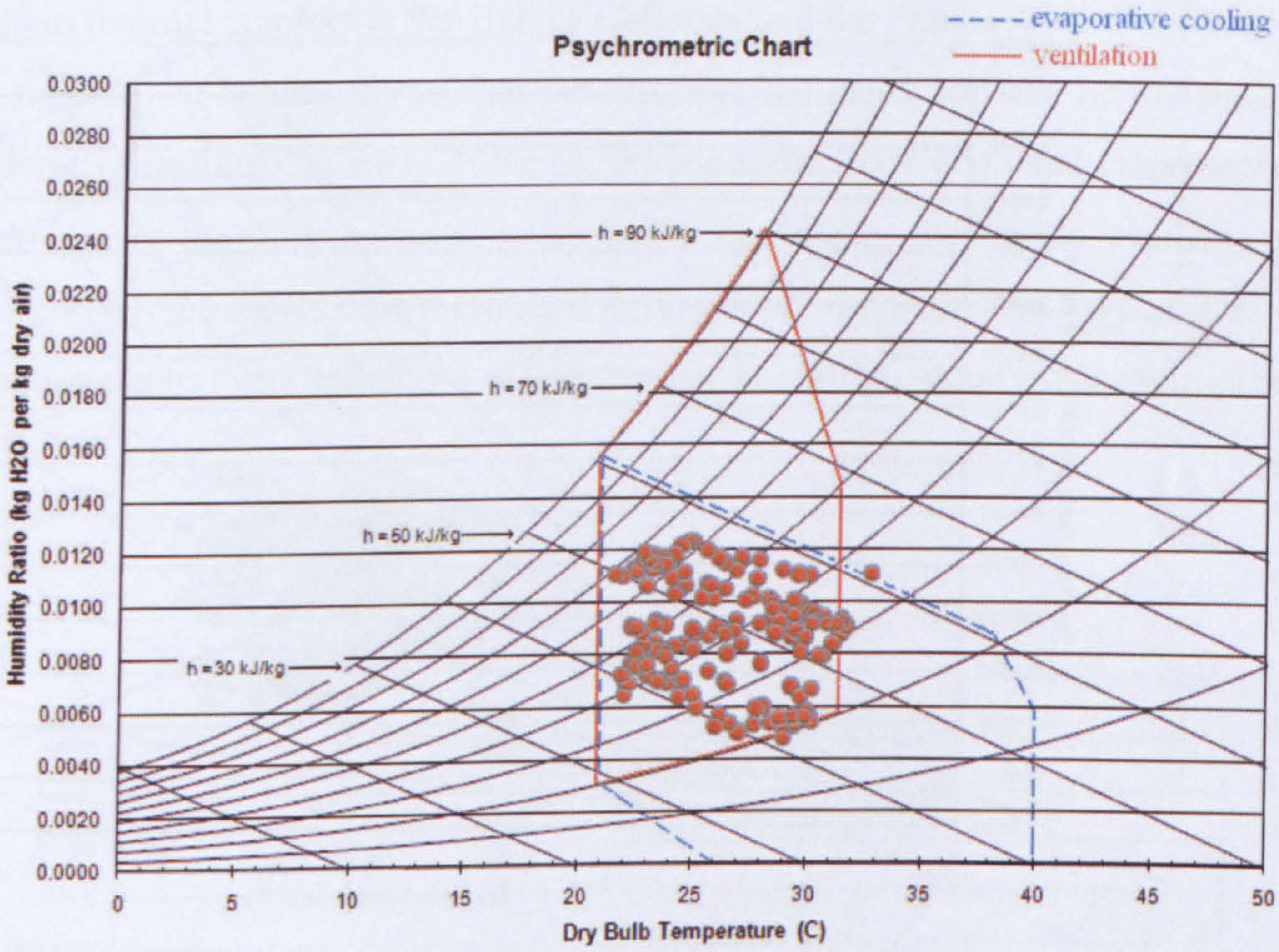


Fig. 6.64 The layout of the daily data recorded in the Praetor Chamber (PC) from 12th – 19th Aug.

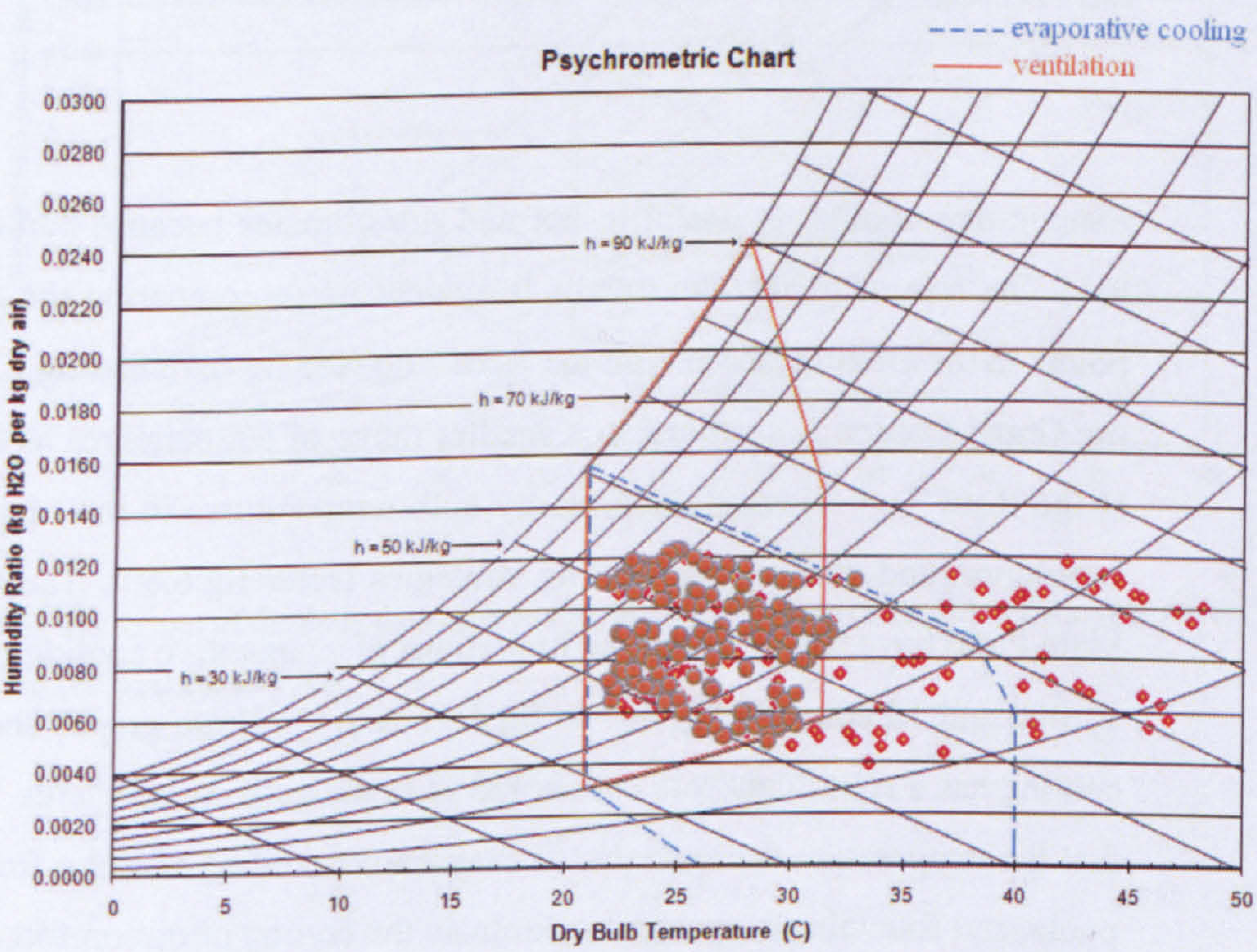


Fig. 6.65 The layout of the daily data recorded in the Main Patio (MP) and Praetor Chamber (PC) from 12th – 19th Aug.

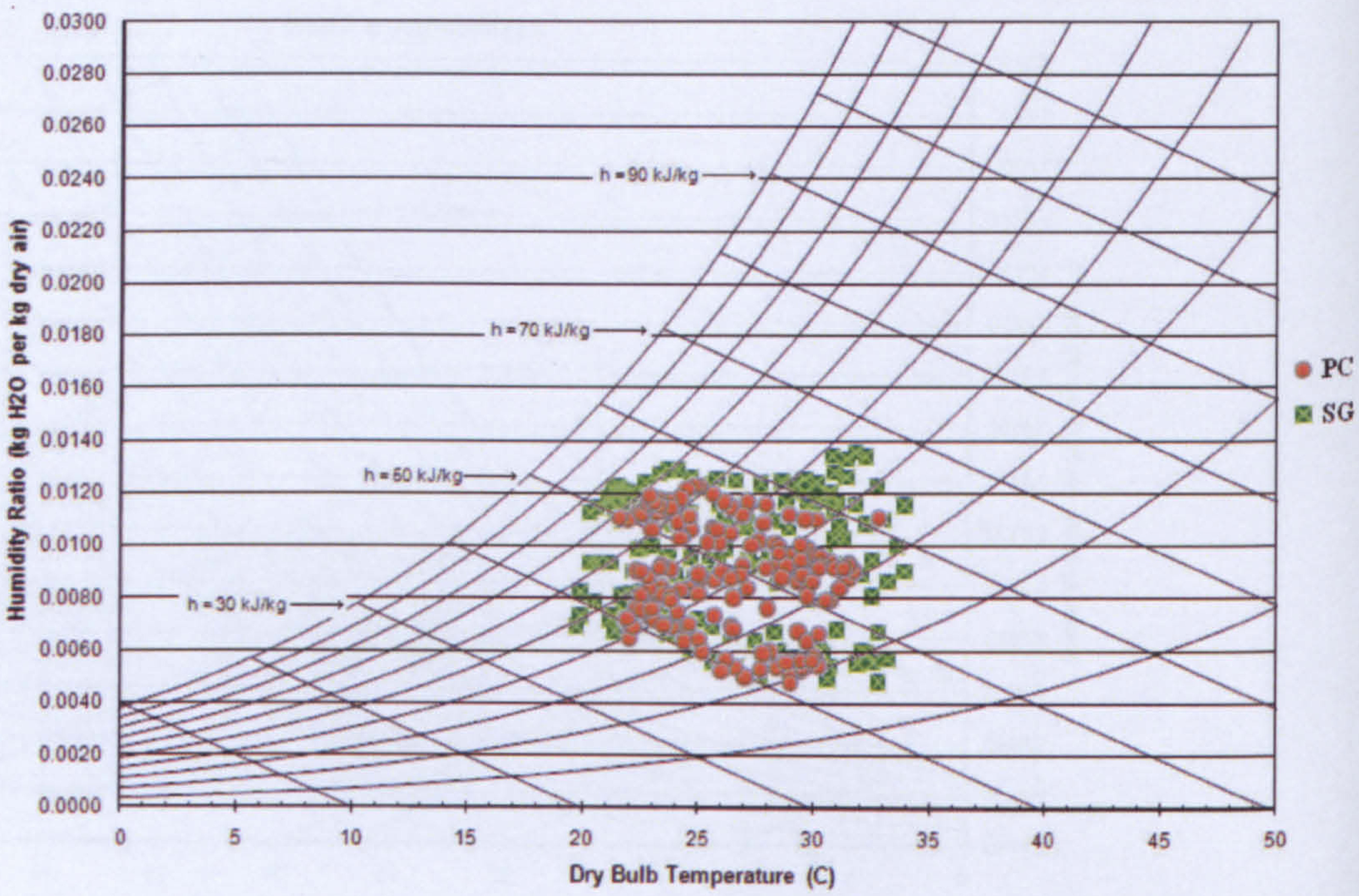


Fig. 6.66 The layout of the daily data recorded in the Praetor Chamber (PC) and Small Garden (SG) from 12th – 19th Aug.

Evaporative cooling is useful in hot and dry climates because humidity is sufficiently low. The role of garden-courtyards is evident when comparing the distribution of data points in the Grand Garden with the Roof Top (see fig.6.61 and fig.6.62). The air within the Grand Garden is confined to a smaller range of temperatures as compared to the air at the Roof Top. Most of daytime dry bulb temperatures in the Main Patio are beyond ventilation and evaporative cooling strategies (refer fig.6.60). The temperatures in the Main Patio have risen beyond the limitations of evaporative cooling particularly between 13:00h and 18:00h (see fig.6.67 to fig.6.77 below). These graphs show that evaporative cooling has a significant role on low DBTs in the garden-courtyards. It can be suggested that the temperature decrease due to evaporative cooling of water from trees, vegetation, pools, and fountains is enough to eliminate the feeling of discomfort among the subjects.

It has been shown that air movement (up to 1m/s) and evaporative cooling can be used to attain thermal comfort in the Hall of Columns and the Praetor Chamber (refer fig.6.63 and fig.6.66). It is also shown that the DBTs at the Roof Top can be lowered through evaporative cooling (fig.6.61). If the conditions at the Roof Top would represent outdoor conditions in the neighborhood, evaporative cooling is the option available to open spaces which are outside the multiple-courtyards environment. The psychrometric charts show that natural ventilation is a viable strategy in multiple-courtyards environments.

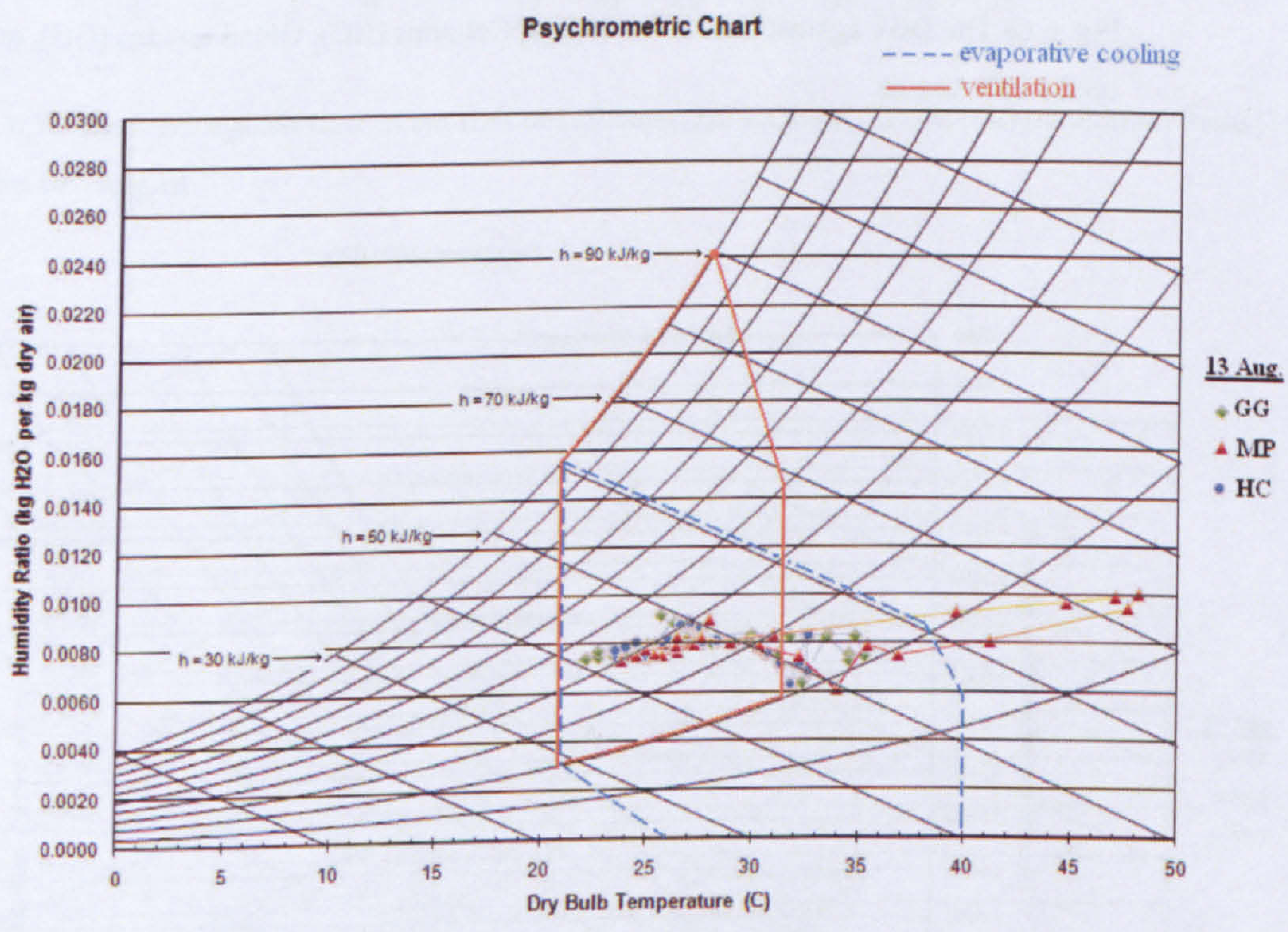


Fig. 6.67 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 13th Aug.

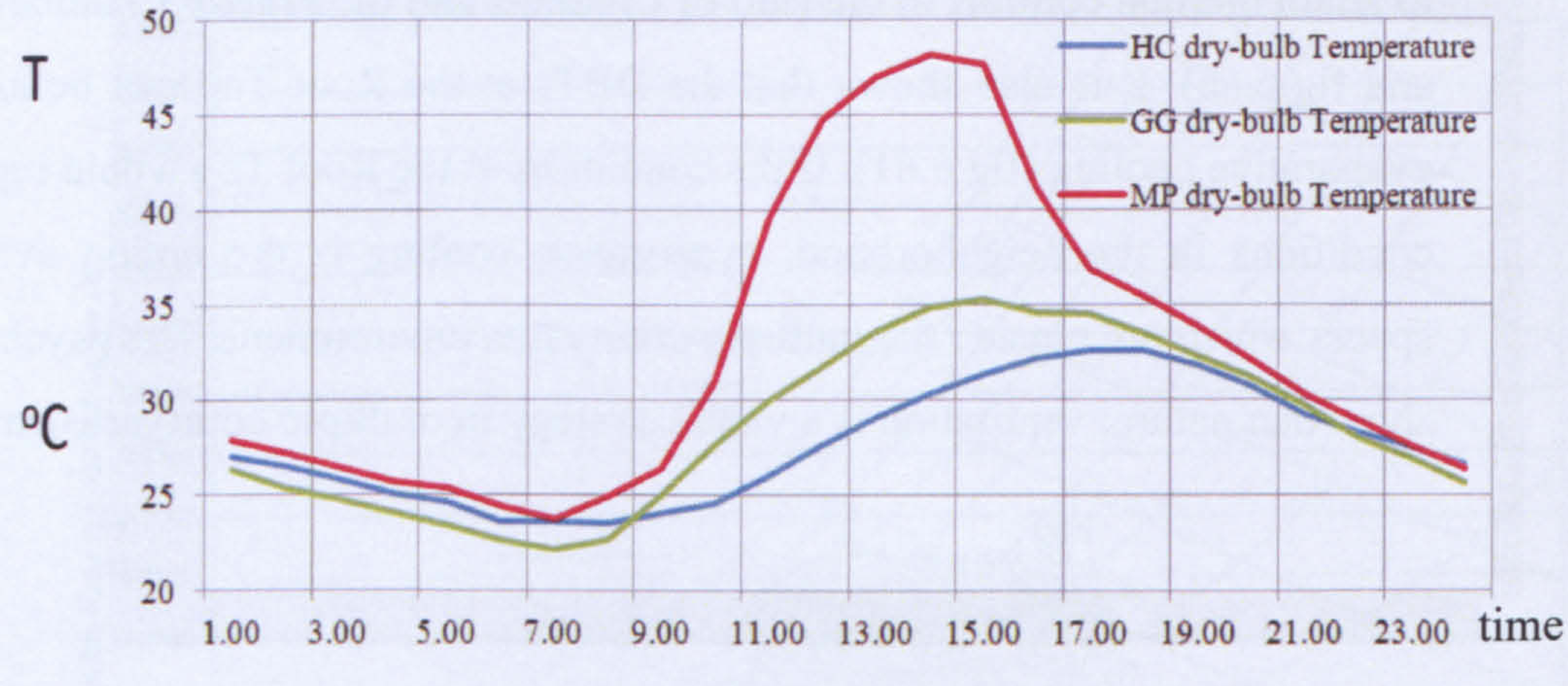


Fig. 6.68 The DBT against time in the Hall of Columns (HC), Grand Garden (GG), and Main Patio (MP) on the 13th August

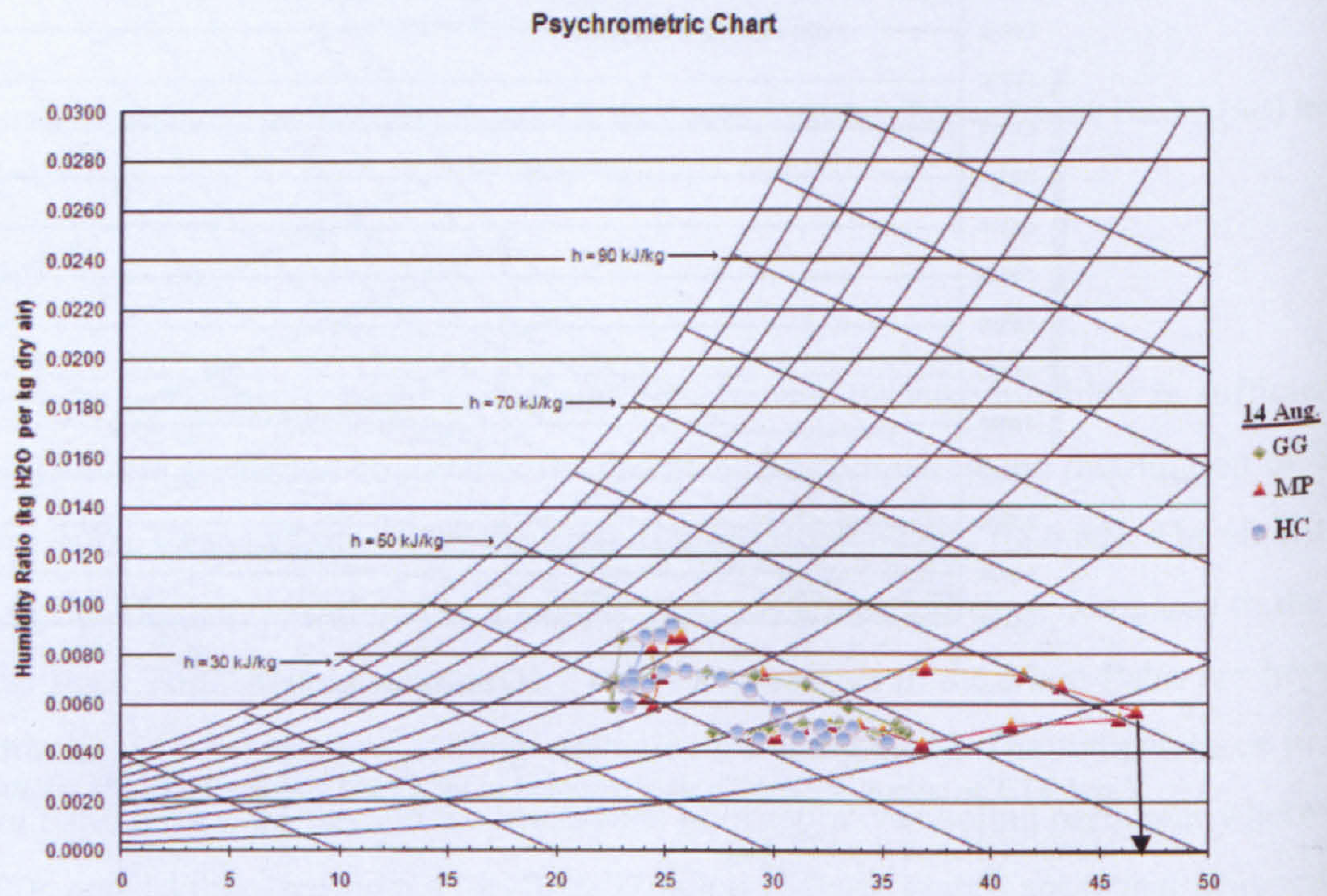


Fig. 6.69 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 14th Aug.

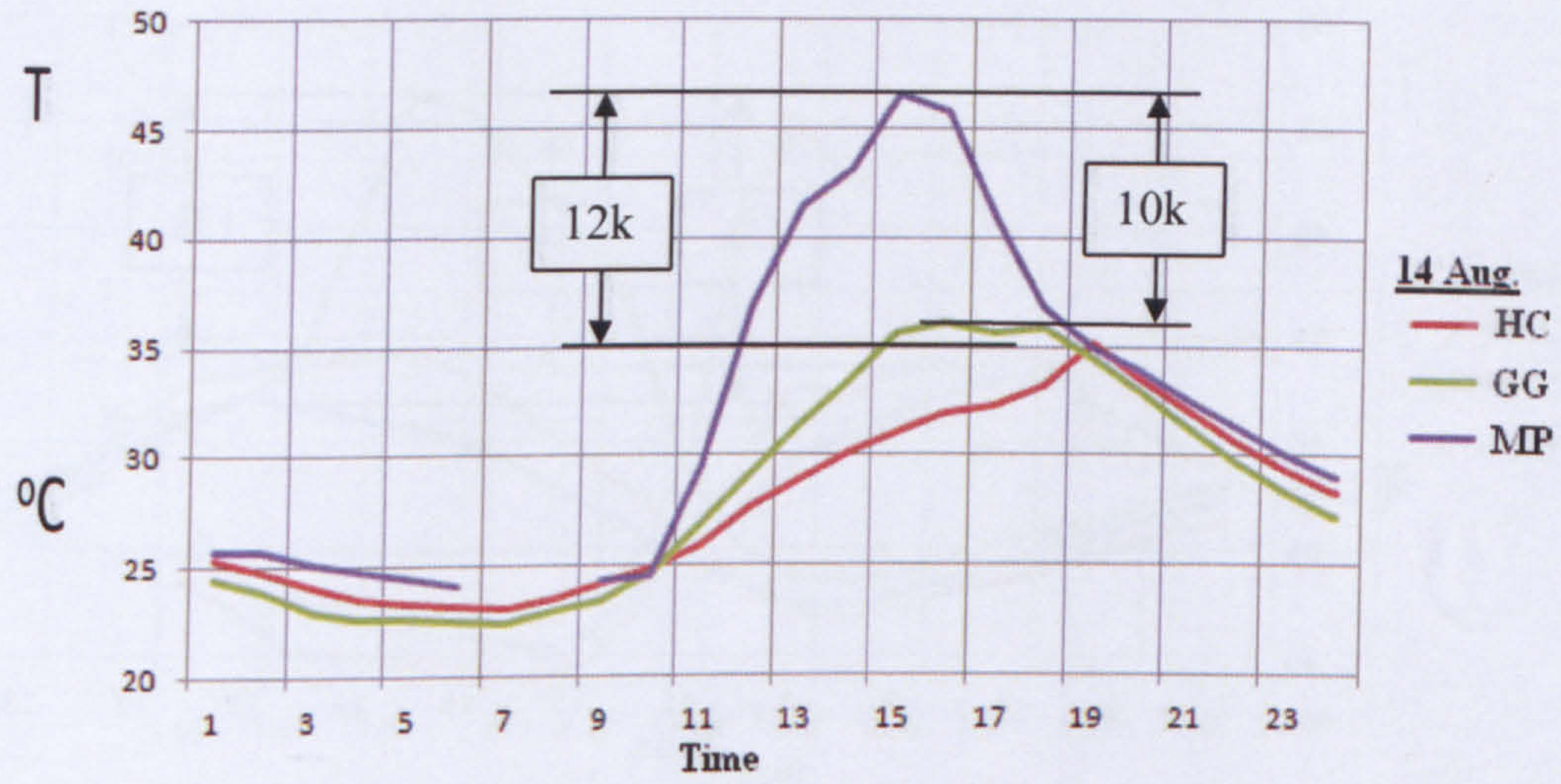


Fig. 6.70 The DBT against time in the Hall of Columns (HC), Grand Garden (GG), and Main Patio (MP) on the 14th August

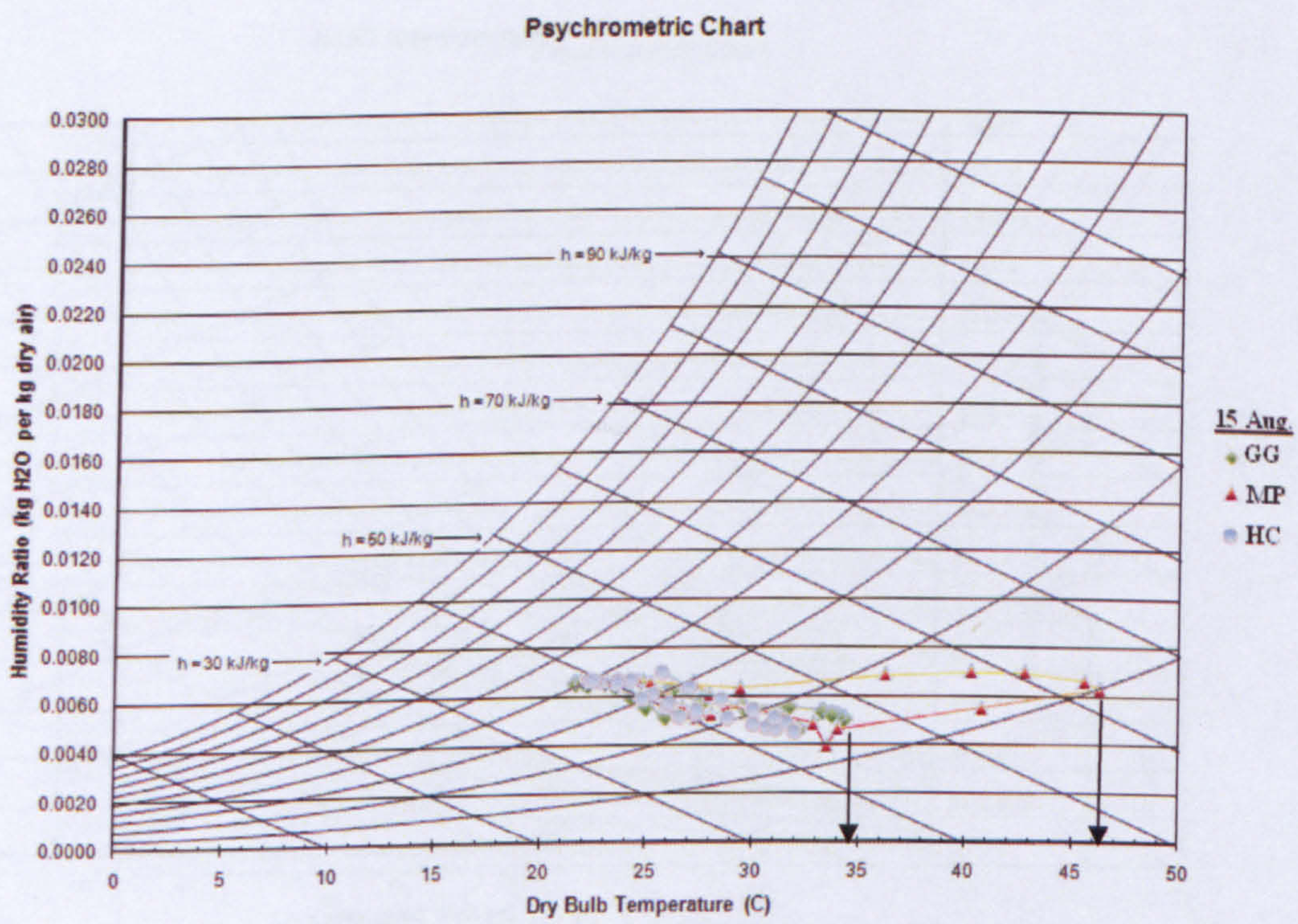


Fig. 6.71 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 15th Aug.

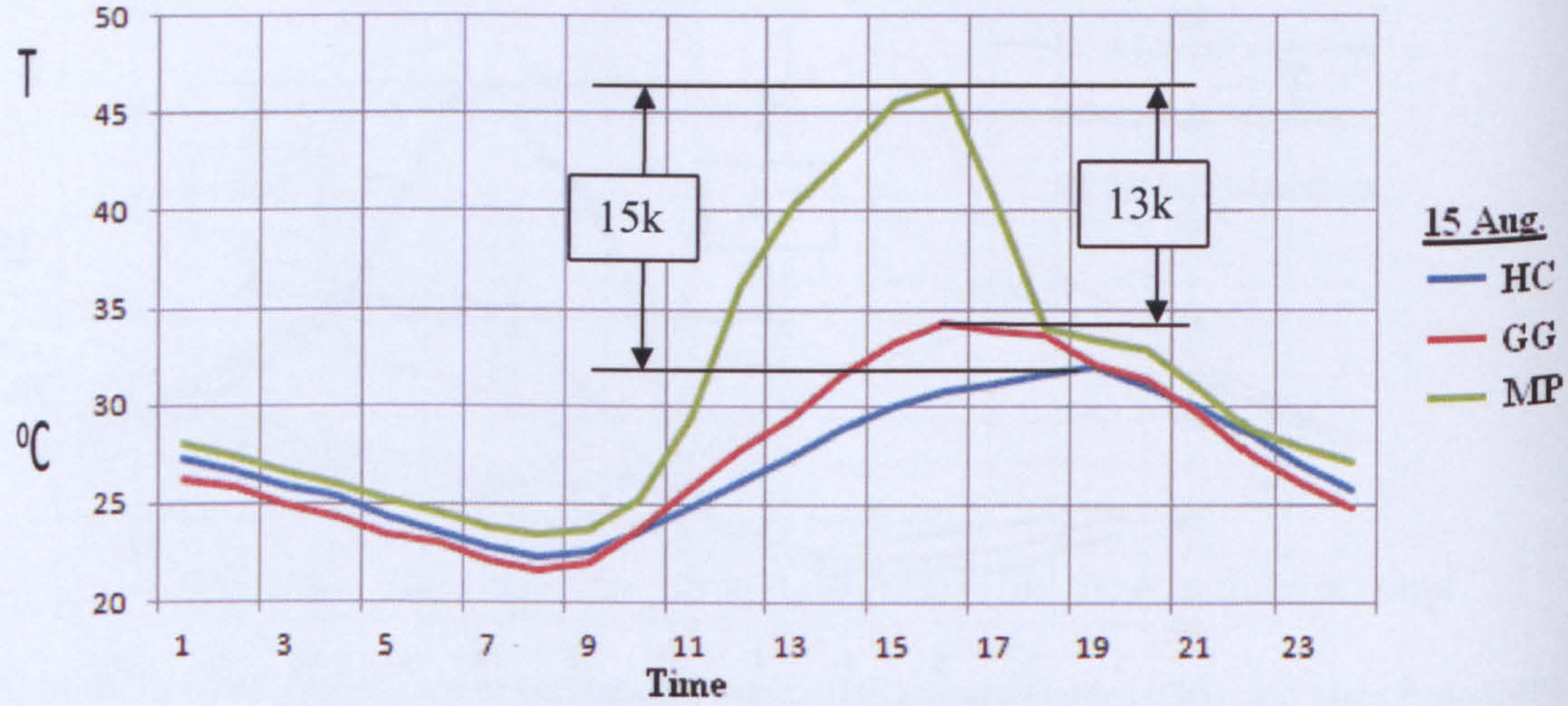


Fig. 6.72 The DBT against time in the Hall of Columns (HC), Grand Garden (GG), and Main Patio (MP) on the 15th August

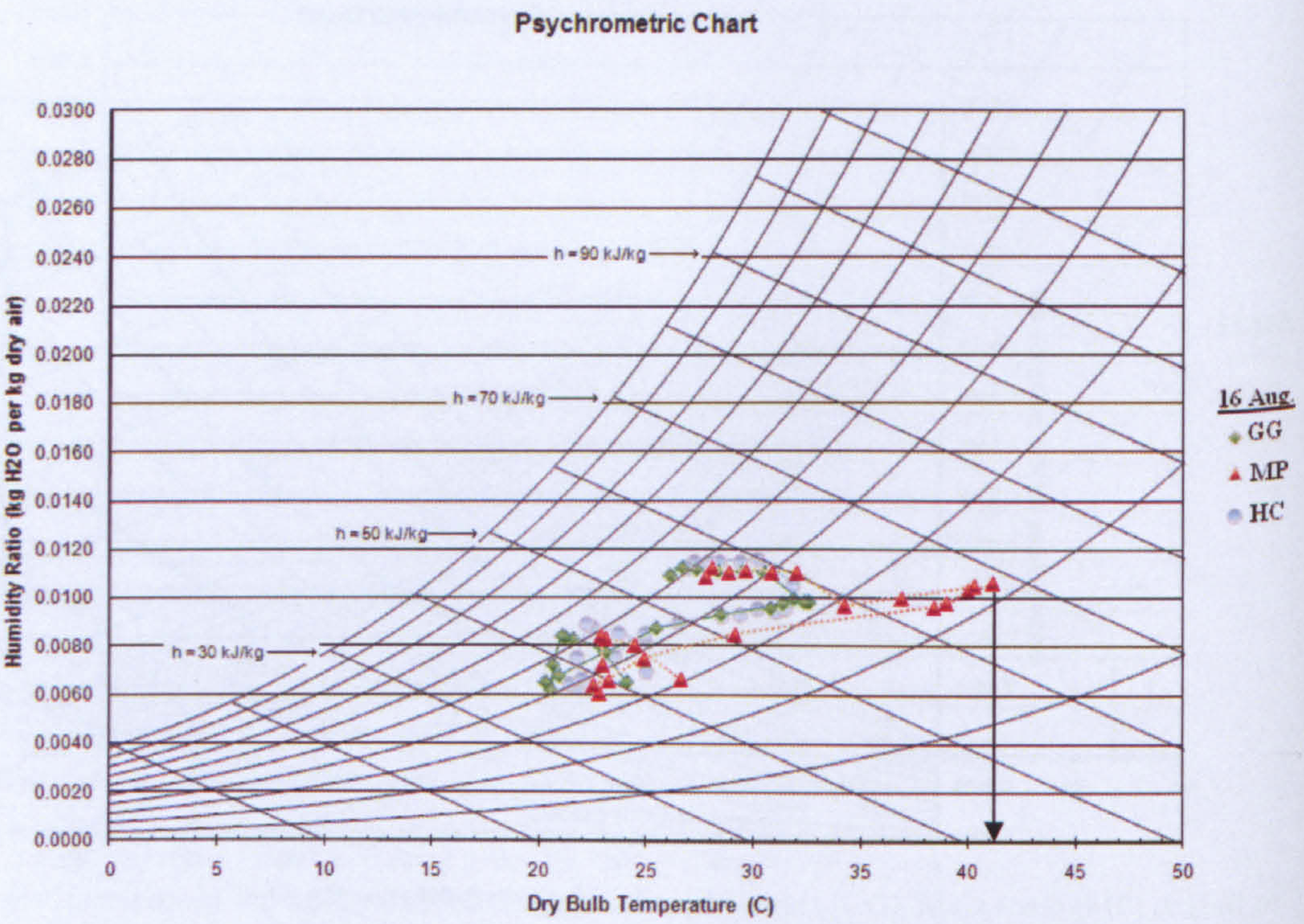


Fig. 6.73 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 16th Aug.

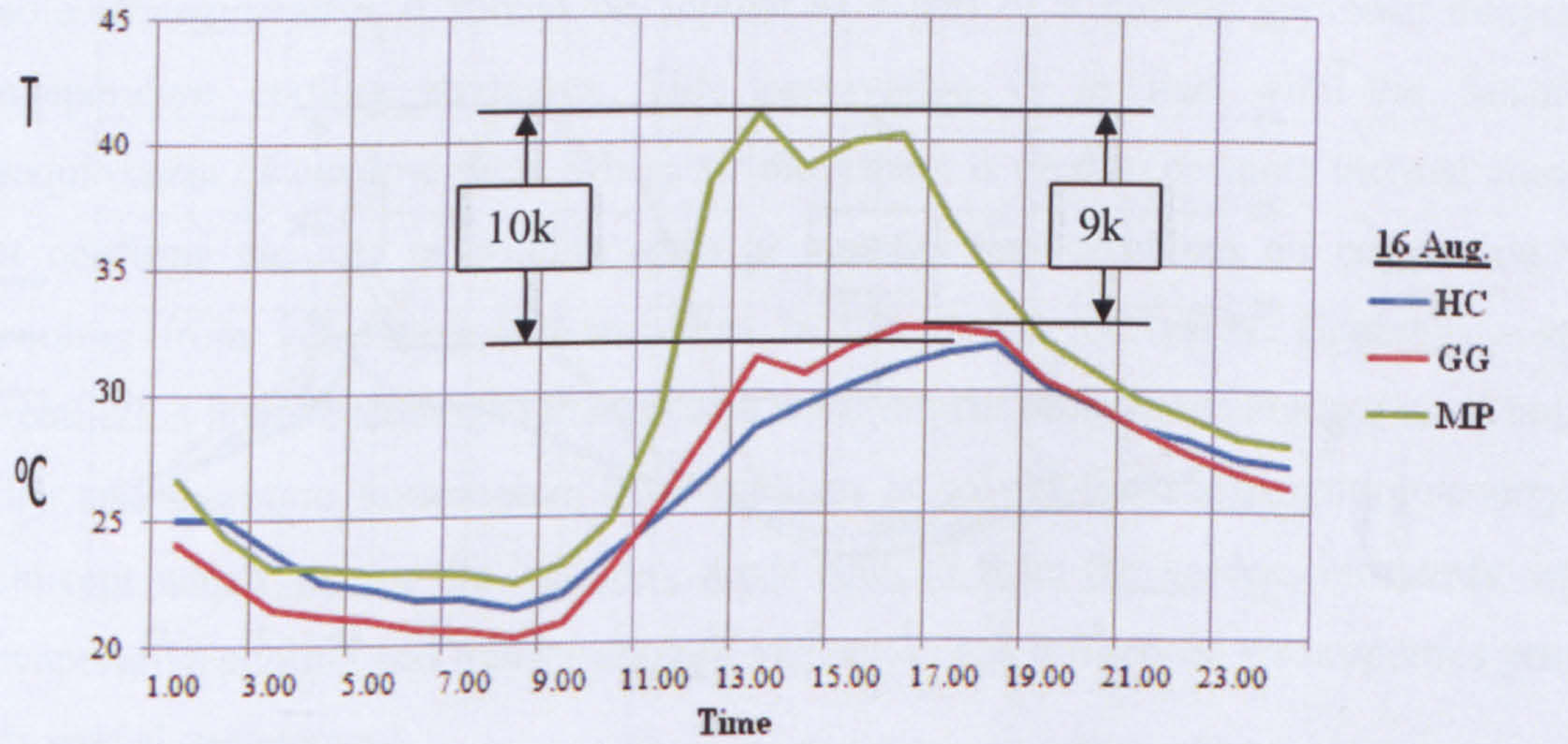


Fig. 6.74 The DBT against time in the Hall of Columns (HC), Grand Garden (GG), and Main Patio (MP) on the 16th August

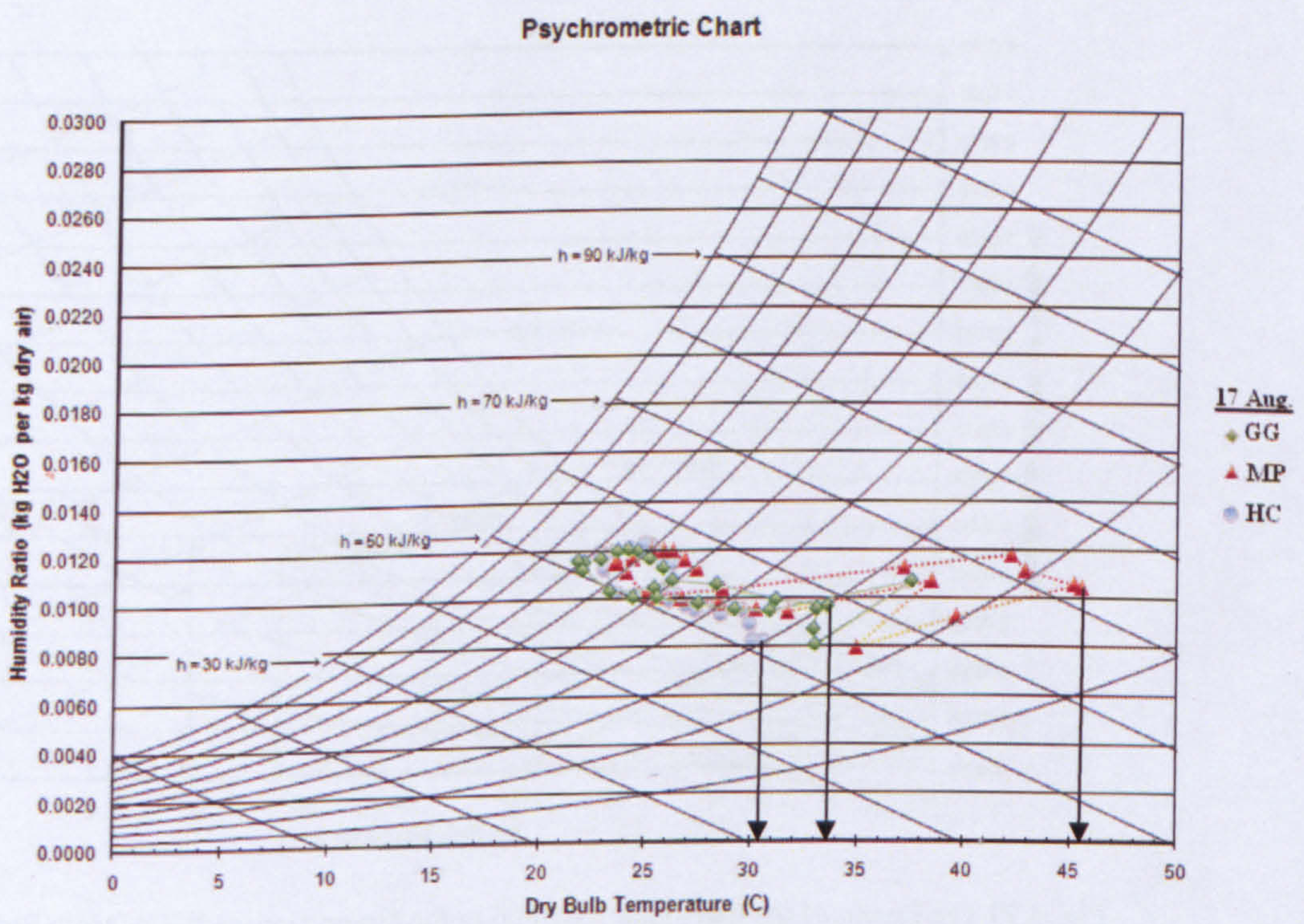


Fig. 6.75 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 17th Aug.

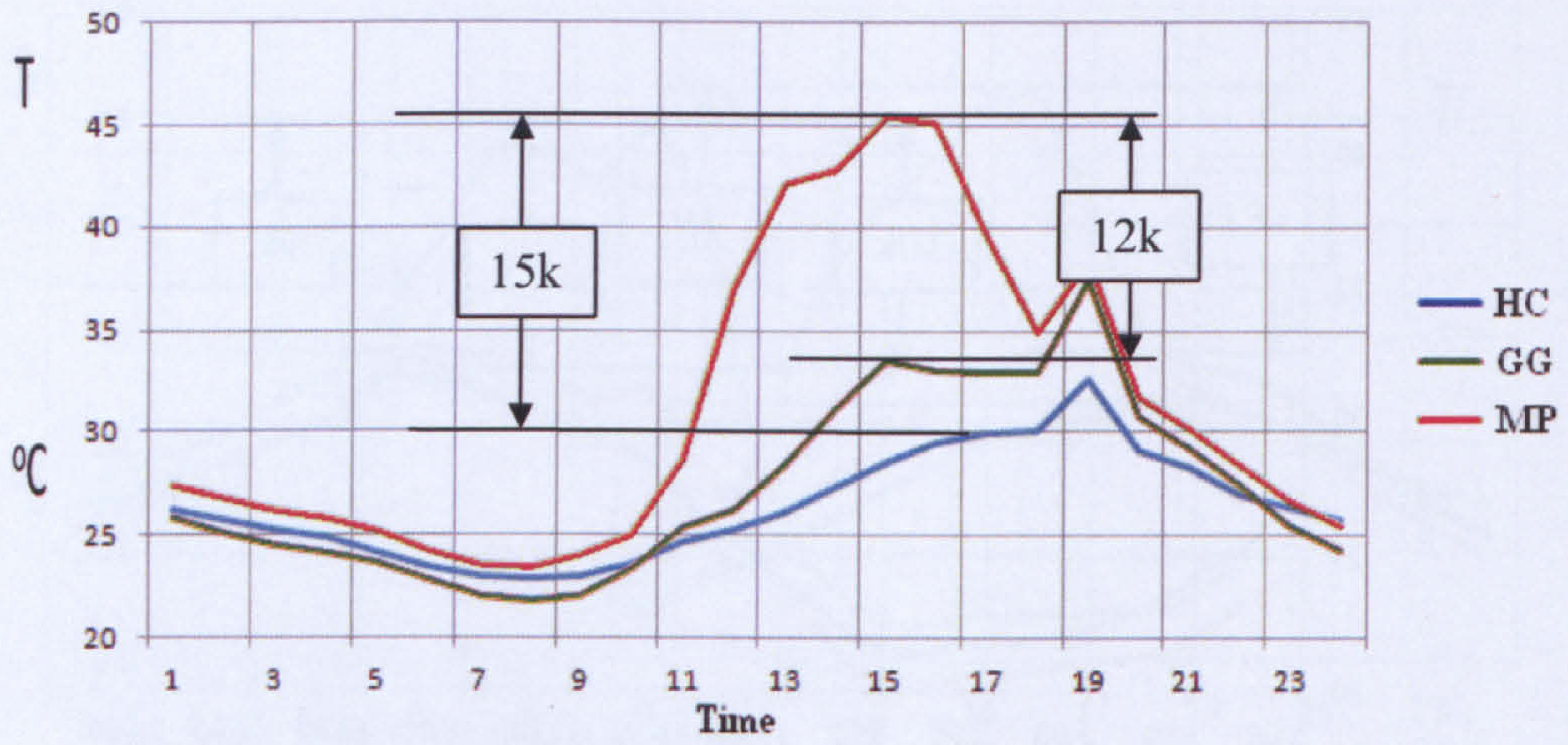


Fig. 6.76 The DBT against time in the Hall of Columns (HC), Grand Garden (GG), and Main Patio (MP) on the 18th August

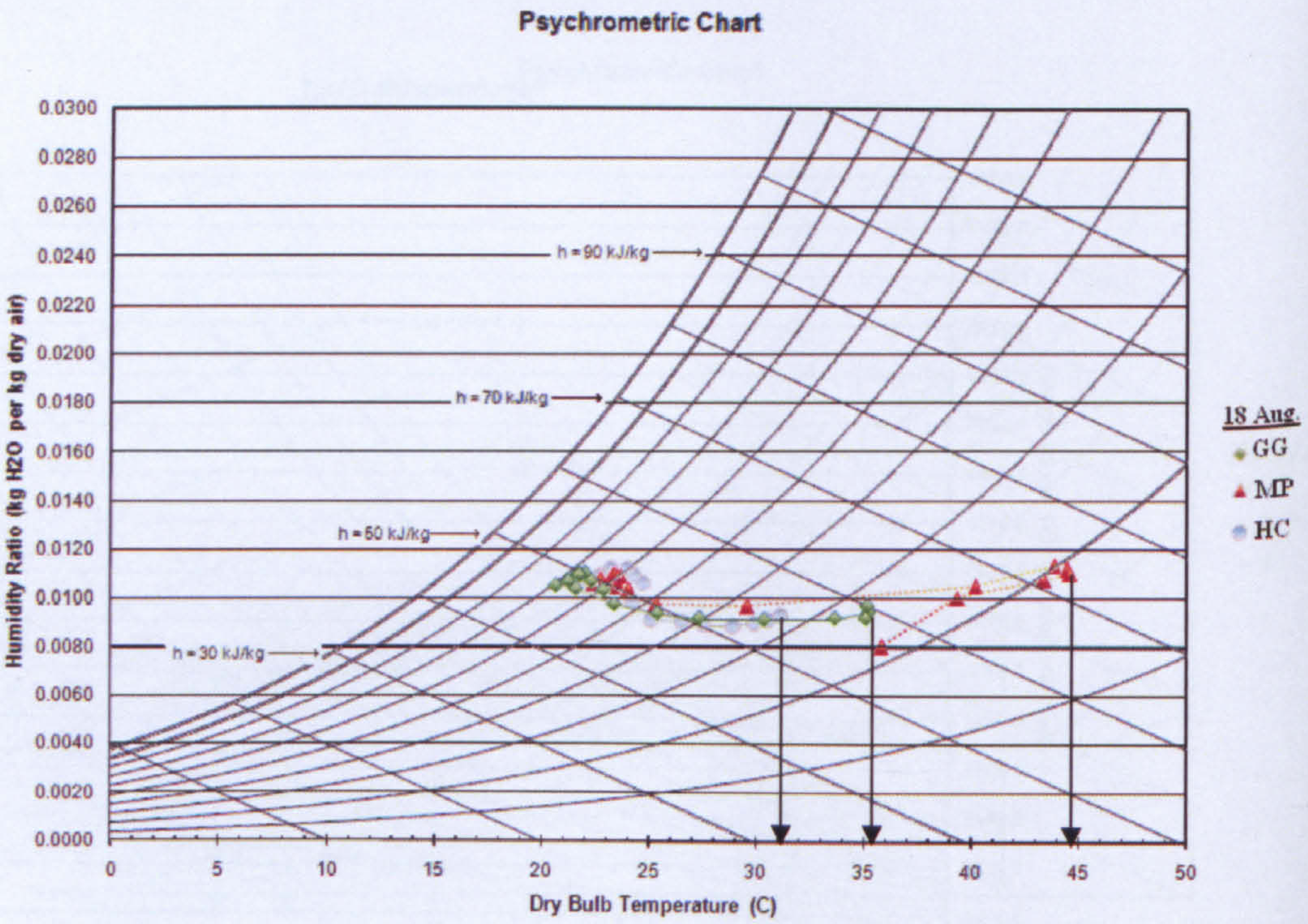


Fig. 6.77 The layout of the daily data recorded in the Grand Garden (GG), Main Patio (MP) & Hall of Columns (HC) on the 18th Aug.

These psychrometric charts have shown that natural ventilation cannot be applied as the sole strategy; rather it should be applied as a part of a holistic approach integrating evaporative cooling strategies. This observation is in line with the functional requirement of window-seats, where air movement is used to promote thermal comfort. It confirms the role of window-seats as strategy that combines air convection with cooling from vegetation and fountains in the garden-courtyards. Generally, natural ventilation is not encouraged in semi arid environment because the outdoor air is hot and dry and therefore undesirable. This problem is solved by using multiple-courtyards concept which insures the incoming air is sourced from the garden-courtyards, where evaporative cooling and transpiration of vegetation has influenced air properties prior to its spatial engagement.

6.5.4 Adaptive comfort versus PMV/PPD calculations

Previous discussion establishes that the thermal environment in the Casa de Pilatos changes daily and across seasons. This approach is contrary to contemporary approaches which have restrained the natural human tendencies into static or steady thermal environments. Parsons Ken (2008) has characterised steady state as environments with temperatures of <1K peak to peak or <2K per hour. This characterisation does not consider desirable thermal variants. Thermal stimulus is part of architectural aesthetics (Heschong, 1979), and humans have a natural desire for thermal contrast (Spenser 2006). Casa de Pilatos is non-steady state thermal environment; the building has very distinctive transients among its thermal environments.

Holistic approach in the design of the Casa de Pilatos produces a range of thermal experiences. It seems possible that the desirable thermal environment is at times outside the temperature range that is acceptable by adaptive comfort limits within ASHRAE 55 and ISO 7730. Although ASHRAE 55 criteria for adaptive comfort accepts the context wherein the indoor thermal conditions track the variable outdoor conditions, Casa de Pilatos instead provides a range of conditions which without consideration of time and duration of exposure are categorised as extreme and outside the comfort limits presented by adaptive comfort criteria.

Naturally, there are fluctuations in the general environment, just like the constant variation in human body activity. When confronted with a perceptual question such as, 'how do you feel now?' the answer might be 'good/bad' and not 'hot/cold' as a PMV model would dictate. When asked whether the environment is acceptable or tolerable; the answer will reflect time, duration of exposure, and adaptive opportunity in the immediate environment. The evaluation of affection 'how do you find it (e.g. comfortable)?' or preference 'how would you prefer to be (e.g. warmer)?' are also influenced by adaptive opportunities. These contrasts are part of the scenario represented by the Casa de Pilatos.

ASHRAE & ISO standards consider the spaces in the built environment in isolation from each other, and the user is tied into a specific task environment. In the Casa de Pilatos, there is characteristic interdependency among the spaces. For instance, there is direct access from the room with a fountain 'cool & moist' to the 'warm & dry' Chapel's lobby. In modern terms, Parsons Ken (2008) argues that an overshoot in sensation would occur with a step change of above 2K per hour. In the Casa de Pilatos there exists a variation of up to 15K and 40%RH across spaces in the daytime. This is characterised in some instances with very elaborate step change as you move from an interior space (Hall of Columns & Praetor Chamber) to an arcade (+/-3K) or from an arcade into the Main Patio (at least +/-7K). The data shows that Casa de Pilatos is designed to have at least 10K difference across the spaces in the summer daytime from 11:00h to 18:00h.

PMV-PPD is the main criterion used to define the thermal comfort in ISO code. ISO generally predicts the thermal sensation and degree of discomfort (thermal dissatisfaction) of subjects using the calculation of PMV and PPD. PMV calculations inherently provide some standardized neutral environment to a group of people, unlike the Casa de Pilatos which is inherently exhibiting a wide range of thermal conditions. Parsons Ken (2008) argues that with a step change of above 2K per hour, PMV would be too high, and 30 minutes would be needed to reach a steady state as ideal thermal condition. The experience at the Casa de Pilatos show that the variations in temperature as you migrate from one space to another is an environmental event. The Casa de Pilatos adopts a holistic approach in the sense that its design produces a range of seamlessly connected thermal environments.

6.6 Discussion of the Results

Daytime DBTs in the Grand Garden and Small Garden are influenced by changing solar altitude. The recorded data shows that the air temperatures in the middle of Grand Garden rise above the air temperatures at the inlet of the Hall of Columns by 11:00h in the morning. Due to solar altitude, solar radiation reaches the middle of the Grand Garden by 11:00h (refer fig.6.7 and fig.6.9). The temperatures in the middle of the Grand Garden rise to 30^{0}C by around 12:00h noon (refer fig.6.10). The temperatures that are recorded in the Hall of Columns have remained around 30^{0}C until 14:00h in the afternoon. There is a delay of two hours (12:00h to 14:00h) for the temperatures on the shaded end of the Grand Garden (T_{HC}) to rise to the level of the temperatures in the middle of the Grand Garden (refer fig.6.10). The disparity is caused by the absence of vegetation in some parts of Grand Garden (refer fig.6.16). Likewise, solar radiation has more access in the Main Patio due to absence of vegetation. As a result, the daytime temperatures in the Main Patio are rising faster than the temperatures in the Grand Garden and Small Garden.

Although solar radiation does not move air through space, the location of irradiated surfaces changes, and hence relocate the driving force for thermal buoyancy within courtyards. The absence of vegetation coverage in some parts of the Grand Garden and Small Garden is linked to increased temperatures with changing solar altitude. Influx of much cooler air at the inlet to the Hall of Columns and Praetor Chamber is related to intense vegetation and absence of solar radiation at the near end of the Grand Garden. Although the physical space has remained stationary in the daytime; the location of radiant surfaces has changed with time; this happens as the solar altitude changes with time and suggests that the potential flow characteristics are also influenced by the changing location of irradiated surfaces.

Field data shows that evaporative cooling reduces air temperatures in the garden-courtyards. This is evident in the temperature difference (up to 18K) between the garden-courtyards and Main Patio. Lower air temperatures are recorded in the Grand

Garden and Small Garden as compared to the Roof Top and Main Patio (refer fig.6.13). With openings on either side, the Hall of Columns and Praetor Chamber provide a connection between the garden-courtyards and the Main Patio. Psychrometric chart also shows significant potential for further evaporative cooling in the garden-courtyards.

It is shown that lower night time temperatures remove heat from the building mass and reduce cooling loads in the following day. The impact of building mass is evident in three hours delay observed between the DBT taken at the Roof Top and Praetor Chamber (refer fig.6.17). It is observed that after 12:00 noon, the impact of building mass is useful because the recorded air temperatures are higher than indoor surface temperatures. By 13:00h, radiant cooling is estimated at around 0.64kW (8.7W/m^2) (see Table 6.5). The surfaces in the Hall of Columns contribute up to 2.45kW (36.2W/m^2) in radiant cooling by 15:00h (see Table 6.6). Radiant cooling falls to 1.7kW (24.6W/m^2) by 17:00h in the afternoon (see Table 6.7). At this time, the outdoor air temperatures 'Roof-Top' starts to fall too.

The field data indicates that temperature differences between the courtyards have a major role on the distinctive flow patterns. There is a wide difference in temperature between the Main Patio and garden-courtyards. And as such the temperatures in the Grand Garden rise on average by only 4k between 12:00h and 16:00h as opposed to the temperatures in the Main Patio which increase by 14k (refer fig.6.25). A difference of at least 10k is sustained across courtyards between 13:00h and 17:00h. The difference in the thermal properties of the air in the garden-courtyards and Main Patio indicates major influence on the convective flow of the air. It is suggested that thermal convection is a result of the variation of thermal condition between courtyards, which happens when the air in the Main Patio becomes less dense and rises; the immediate cooler air from the garden-courtyards then moves through transitional spaces to replace it. Cool air is then heated and the process continues, forming convection current.

Buoyancy-driven flows between the inlet and outlet openings in the Hall of Columns (refer fig.6.27) are calculated from temperature differences between the Grand Garden and Main Patio. These are compared with field recorded volume flow rates. Buoyancy effect has produced volume flow rates of between $0.8m^3/s$ and $2.8m^3/s$ (refer fig.6.28) between 08:00h and 18:00h. Low volume flow rates are reached at 08:00h in the morning, while higher volume flow rates are attained between 12:00h and 14:00h in the afternoon. The calculated value for air flow rates at 15:00h suggests an air velocity (υ) of 0.5m/s. The field recorded air velocity through the Hall of Columns and Praetor Chamber ranges between 0.4m/s and 1m/s at 15:00h.

It is suggested that the air movement is induced through the Hall of Columns and Praetor Chamber with warm air going out through the sky window in the Main Patio. Field data is used to calculate the stack force between the inlet in the Hall of Columns and outlet in the Main Patio. Stack effect has produced volume flow rates of between $1.3m^3/s$ and $4.6m^3/s$ between 08:00h and 18:00h. The theoretical volume flow rates are thereafter plotted against temperature differences (ΔT) (see fig.6.30). Field data has fallen beyond the theoterical boundaries in some instance (refer fig.6.31). There is nearly equal number of data points falling both below and above the buoyancy and stack effect boundaries respectively, suggesting random error from spot measurements. These are moments when either high volume flow rates are achieved at narrow temperature differences or low volume flow rates are attained when the temperature differences is big. It is suggested that inconsistency between the theoretical and field recorded flow rates is linked to fluctuations in the local wind regime.

Wind develops varying surface pressures across the envelope of the Casa de Pilatos adding to the hydrostatic pressure. The potential variable magnitude and direction of wind poses a greater challenge in the analysis of field data. The data recorded at the Roof-Top shows a constant fluctuation with hourly averaged wind speeds ranging between 0.3 and 1.7m/s. Lower wind speeds of highly variable nature are recorded on the Roof Top calling into question the meteorological data (compare Table 6-10 and fig.6.32). In order to determine the driver for air velocity, the air velocity data collected in the Praetor Chamber is separated between periods of low (0 – 4) K and high (10-18) K temperature difference between the Small Garden and Main Patio. Volume flow rates in the Praetor Chamber are then separated between the two temperature ranges and plotted against the wind speeds recorded at the Roof Top. The results show no correlation between the wind speeds recorded at the Roof Top and the air velocity recorded in the Praetor Chamber (see fig.6.38 and fig.6.39), indicating that there is no obvious correlation with wind speed.

The impact of urban layout on inflows to the Casa de Pilatos is predicted by using the general relationship between the wind velocity υ, within the canyon, and above-roof free stream wind speed U provided by Santamouris (ed.2001). Santamouris (ed.2001 pp36) measurement of wind speed in canyons observes that, although the wind speed above the canyon and meteorological station may reach values up to 5m/s and 6m/s respectively, the air speed within canyons never exceeds 1m/s. This observation is critical for analysis of the data collected in the Casa de Pilatos wind speeds which are below 1m/s have no influence on natural displacement flows. This is confirmed in fig.6.38 and fig.6.39 where at least 75% of data plots below the wind speed of 1m/s. It is suggested that since the air speed on the street canyon does not exceed 1m/s, buoyancy is the dominant force for air velocity through the transitional spaces in the Casa de Pilatos.

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The primary challenge in the application of natural ventilation is summertime temperatures. The daily variation of temperatures between the Hall of Columns and Grand Garden ($T_{HC} - T_{GG}$) is used to calculate convective cooling. Calculations show that cooling is possible because the specific humidity is sufficiently low and the enthalpy of air from the garden-courtyards is significantly lower than the enthalpy of air in the Hall of Columns (72 kJ/kg at 15:00h) and the Main Patio (59.5 kJ/kg). A considerable part of the enthalpy difference is due to variation of air temperature. The results in Table-6.11 use the temperature difference of 2K between the Grand Garden and Hall of Columns. This temperature difference produces convective cooling energy of between

2.7kW (39.2W/m^2) at 08:00h and 4.9kW (71.4 W/m^2) at 16:00h. However, it is likely that the airflows through the Hall of Columns are driven by much bigger temperature difference. The implication of additional heat loads is determined because fieldwork was undertaken in unoccupied spaces. The data shows that very little variation in temperature in the Grand Garden is required to mitigate the additional heat loads. The temperature difference required to remove the additional heat loads range between 2.7K and 3.3K.

In summertime, the cooling potential of natural ventilation is also limited by occupancy expectation of thermal comfort. Thermal comfort is evaluated by using adaptive models. The mathematical models which are employed are not precision models for estimating thermal comfort in built environment; however, they are useful in the evaluation of the implication of variation in the climatic conditions. The models were taken from field surveys done by Nicol and Humprey (2002) and Brager and de Dear (2001). The results from the equation by Brager and de Dear (2001) provide a comfort temperature of 30^{0}C. This means the new adaptive comfort standard for ASHRAE Standard 55 is consistent with the conditions recorded in the Hall of Columns and Praetor Chamber.

In an environment with a large range of microclimatic conditions, duration of exposure is part of the criteria for thermal comfort. The breeze at the window-seats in the Halls of Columns, Praetor Chamber and staircase is refreshing after experiencing the hot and still Main Patio. People identify places for themselves within a built environment, as time moves on. Users of this building are able to reinvent their space in parallel with the variable microclimates experienced throughout the year.

There is a dramatic impact from the current urban environment on the thermal conditions in the Casa de Pilatos. Cars which did not exist 400 years ago now generate heat and pollution, overwhelming the ancient passive cooling techniques, and making air conditioning unavoidable in some parts of the building. Number of people visiting a building is at times higher than intended users. Thatcher et al (2005) has shown the connection between the argument for steady state thermal environments and the requirement of the systems delivered from the global economy. Some spaces in this building have to meet arguably new functional requirements of computers, printers and scanners to meet contemporary economy needs. Security issues have necessitated unexpected confines as tourism has replaced the inhabitants of the building. Additionally, global environmental changes may prove to have a significant contribution to overheating in the summer time as the ozone layer continues to be depleted.

6.7 Conclusion

This chapter has presented the analysis of field data and determined passive cooling strategies and drivers for yard-to-yard airflows in the Casa de Pilatos. The amount of convective cooling attributed to the airflow through the transitional spaces and implication of additional heat loads is calculated. Lastly, the criteria for thermal comfort are evaluated by using adaptive comfort models provided by Nicol and Humprey (2002) and Brager and de Dear (2001). The aim of this analysis is to determine the drivers for convective cooling flows through the transitional spaces in the multiple-courtyards strategy.

Various cooling strategies are employed in the Casa de Pilatos. The walls in the transitional spaces contribute up to 2.5kW (36W/m^2) in radiant cooling. The absence of vegetation coverage is linked to high temperatures in some parts of the garden-courtyards. Psychometric chart shows the possibility for potentially low temperature (17 – 23 ^{0}C) through evaporative cooling in the garden-courtyards. The analysis shows that although solar radiation does not move air through space, the location of irradiated surfaces changes, and hence relocate the driving force for thermal buoyancy within courtyards.

Field temperature difference between the garden-courtyards and main patio are used to determine the volume flow rates (Q) through the transitional spaces. The theoretical calculation of buoyancy between the inlet and outlet in the transitional space has shown potential volume flow rates of 0.8 – 2.8 m^3/s between 08:00h and 18:00h. The calculation of stack forces between the inlet in the transitional space and the aperture in the main patio has shown potential volume flow rates of 1.3 – 4.6 m3/s between 08:00h and 18:00h. The plot of these results against field recorded volume flow rates confirms that buoyancy is the likely driver for airflow through the transitional spaces.

The field data has shown that cooling is attained because the specific humidity of the airflows from the garden-courtyards is sufficiently low and its enthalpy is relatively low. The difference in enthalpy of 12.5kj/kg is observed between the garden-courtyard and main patio at 15:00h. The field data has shown that multiple-courtyard phenomenon is a robust strategy accommodating a wide variation in heat loads.

Subject response to thermal environments recorded in the building are analysed and possible response to the cooling sensation of airflow is determined. Air movement through the transitional spaces has reduced discomfort by up to 2.7k. It is concluded that the thermal comfort in multiple-courtyard buildings cannot be calculated from models based on PMV or PPD. The environmental diversity provided in these buildings confirms the human desire for variable thermal qualities. Field investigation suggest that thermal comfort in multiple-courtyards buildings depends less on climate and more on how building and occupants interacts.

The results suggest that the multiple-courtyard designs were not created arbitrarily, but they are optimised according to their thermal qualities and yard-to-yard flow rates. Next chapter uses CFD calculation to demonstrate the impact of temperature difference between the garden-courtyards and paved courtyards.

CHAPTER SEVEN: THEORETICAL MODEL

7.1 Introduction

The aim of this chapter is to use a theoretical model to investigate the flow patterns and air velocity through the transitional spaces. The term 'theoretical model' and 'numerical model' are used in this chapter to represent a detailed computer calculation that allows for multi-dimensional (non-uniform) heat flow. Computational fluids dynamics (CFD) is a powerful predictive technique that can realistically describe natural ventilation flow (Howell and Potts 2002). Numerical analysis provides the most precise results and is always a permissible alternative to physical investigation (BRE443, 2006). Fluent software used in this study, is widely circulated and used among professionals. The CFD code embedded in Fluent software is used to investigate the flow patterns due to temperature differences between courtyards.

The nature of environment in the Casa de Pilatos has necessitated the use of three dimensional modelling (see fig.7.1). Airflows in deep courtyards within dense urban environments are primarily driven by buoyancy and natural displacement flows (Coronel and Alvarez, 2000). This theoretical model uses a steady state case to explore the impact of particular boundary conditions, with only the most important features being reflected. The results of this theoretical analysis are expected to reflect air velocity values from field work.

The simulation model considers a steady state environment in order to simulate natural convection flows with only heat transfers taken into account. Wind forces are not taken into account in order to reduce the number of equations being solved and memory consumed by computer. Solar radiation is represented by field values for fluxes of heat from the respective boundary walls. Evaporative cooling and evapotranspiration processes are not taken into account. The heat transfer model uses convective heat transfer information (embedded in Fluent) and surface fluxes of heat calculated from field surface temperatures as boundary condition for CFD simulation.

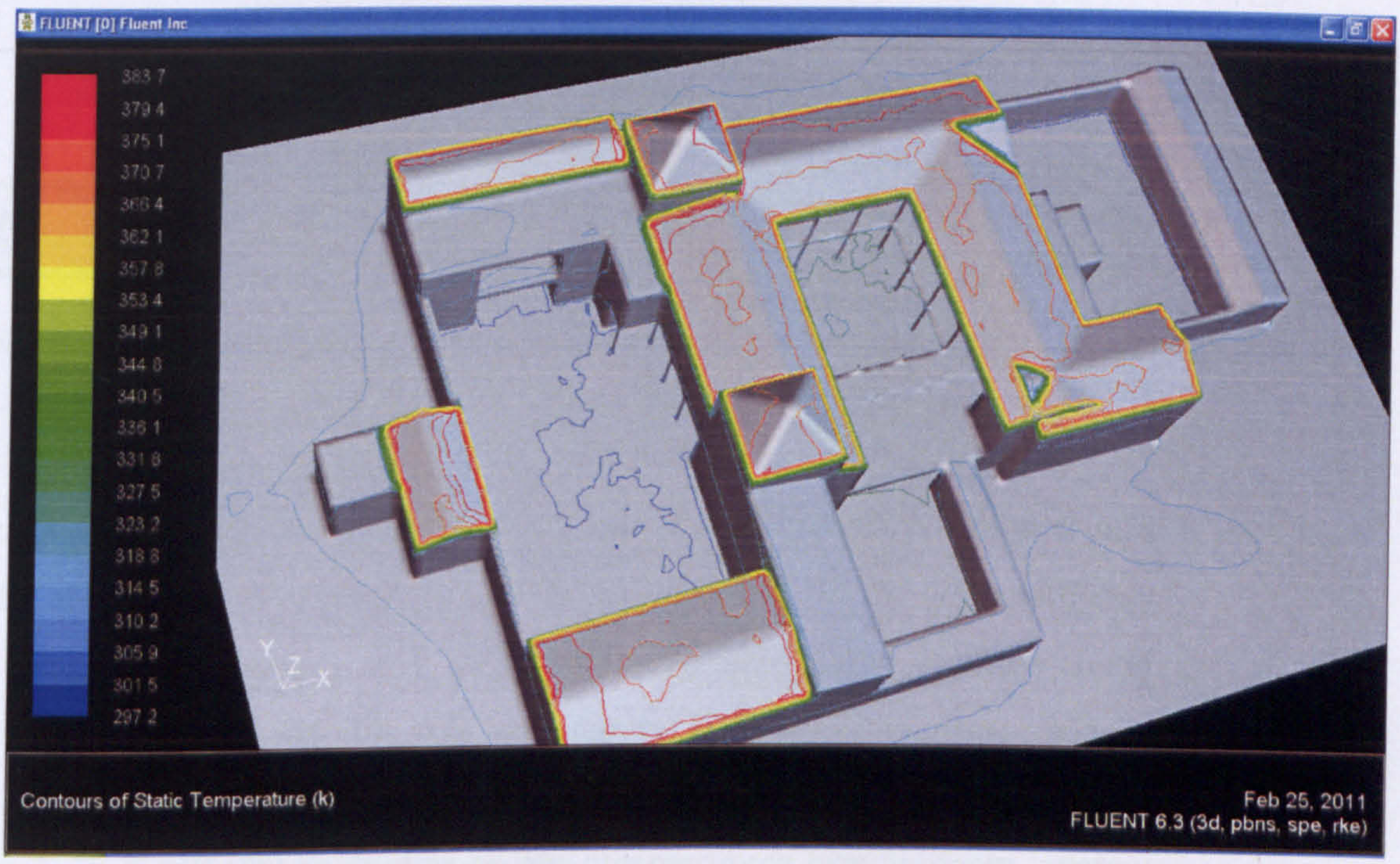

Fig. 7.1 The theoretical model used in these calculations

7.2 Problem Description

The problem to be considered is shown schematically in Fig. 7.2. Surface temperatures used in this calculation are taken during fieldwork by using infrared thermometer (Raytek® - MiniTemp™). The lower surface temperatures were recorded in the garden-courtyards due to shading and transpiration from vegetation. The Main-Patio or central courtyard recorded higher temperatures because its surfaces were exposed to direct solar radiation. This work has set material properties and boundary conditions observed during field studies, and then examined the generated airflow and temperature fields. It is projected that buoyancy flows would develop from thermally-induced density gradients. The objective of thermal modelling is to compute the impact of the fluxes of heat from boundary walls, by using discrete ordinance (DO) radiation model embedded in Fluent 6.3.26 software. DO model is used for solving transport equations for radiative heat transfer in Fluent software.

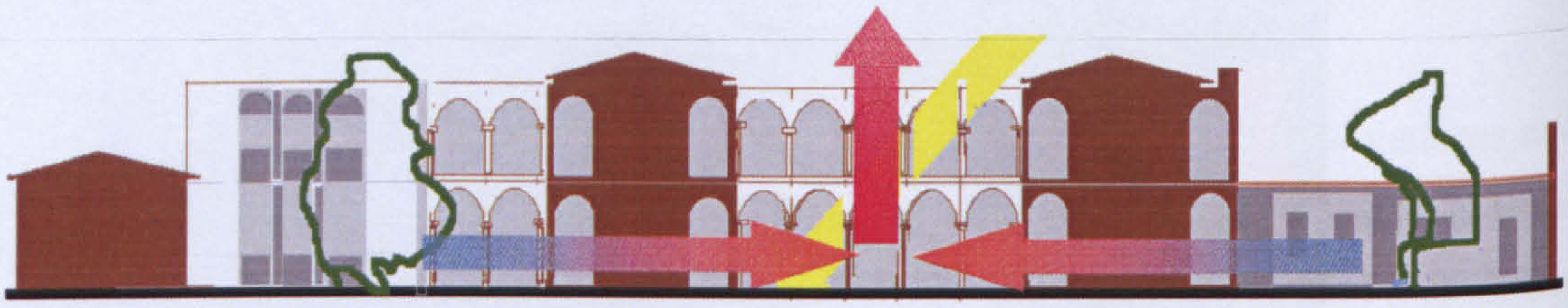

Fig. 7.2 Thermodynamics of buoyancy flows and the suggested pattern of air movement in the Casa de Pilatos

The complexity of the environment in and around plant canopies force some gross simplifications on the boundary conditions in the garden-courtyards. Heat flux from plants surfaces is simplified into heat flux from a single plane. This simplifies the problem sufficiently that it is tractable but that still valid and valuable conclusions can be made concerning the airflow patterns. According to Jones (1992), heat flux from well watered plants in arid environments can be as high as 680 Wm^{-2}. This study calculates heat flux from surface temperatures taken during field studies.

7.3 The geometry

The size of the domain constructed for theoretical investigation is 150x100x40 metres in length, width, and height (see fig.7.3). The geometry of Casa de Pilatos is modeled at the size of 100 X 70 metres. The geometry has considered the building form, height, and the size of courtyards. The size and geometry of the transitional spaces and their respective inlet and outlet openings are also modelled.

The Hall of Columns is located between the Grand Garden and Main-Patio. The Praetor Chamber rests between the Small Garden and Main-Patio. Both rooms have got single opening connecting them to their respective gardens and three openings (entry door and two windows) facing the Main-Patio. The size of the Hall of Column is 16 x 4 metres, while the Praetor Chamber is 22 x 6 metres. The ceiling height used in both spaces is around 4.5 metres.

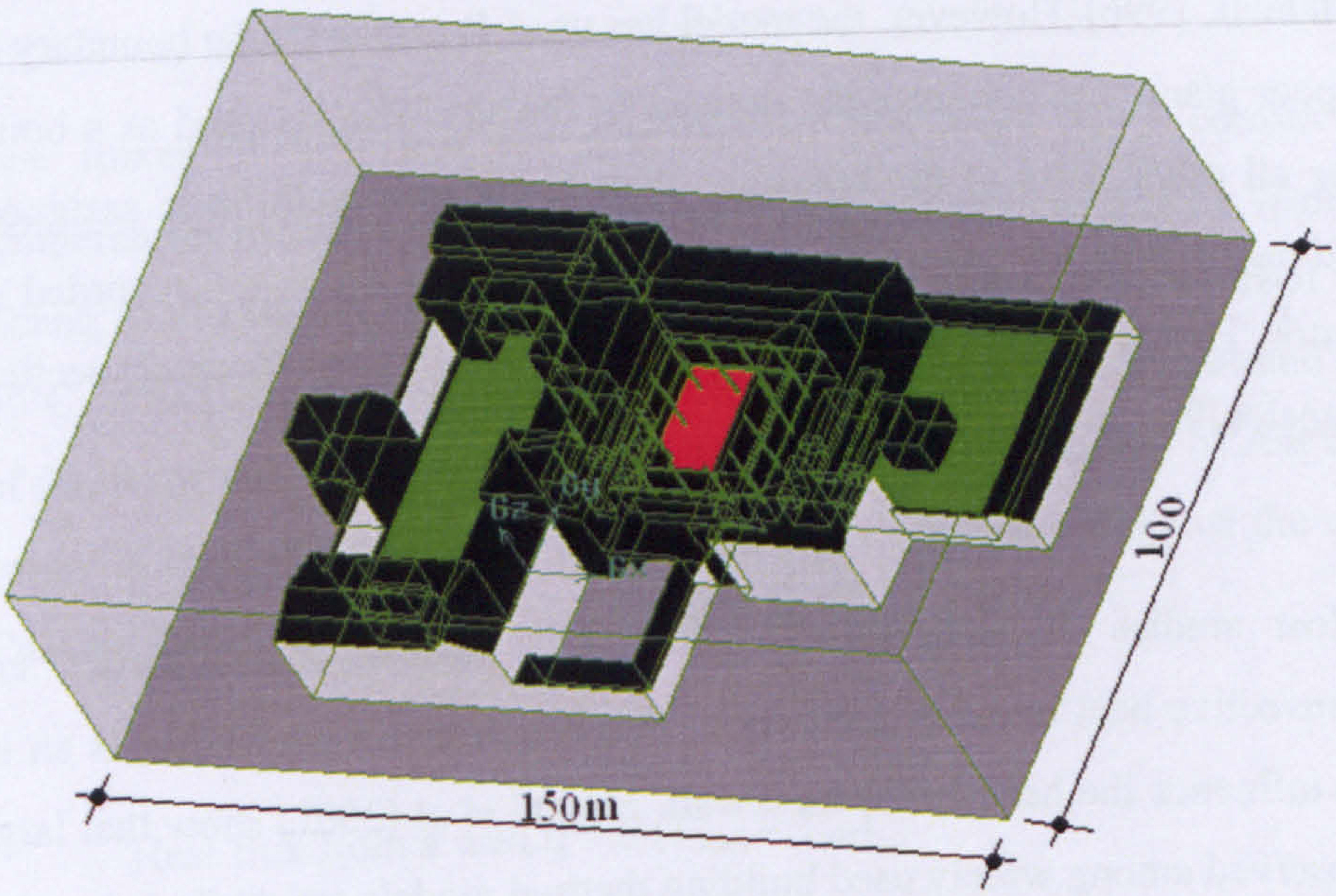

Fig. 7.3 Domain for geometry of the Casa de Pilatos

7.4 Meshing strategy

This section gives an indication of mesh sizes used in CFD calculation. Mesh creation is an important part of CFD calculation. The smaller the mesh the more detailed the results and more computer power is needed to run simulations. A balance is needed to ensure that the size of the mesh does not compromise the value of the results. The TGrid type of Tet/Hybrid elements were used for meshing due to the complexity of the geometry. The 3D domain has a total of 1,362,000 tetrahedral cells. The biggest mesh size or spacing is 1.1 metres. The mesh size is adjusted for grid sensitivity tests. The quality of the mesh was examined. In the scale of zero to one with one representing the worst quality, the general quality of the mesh *EquiAngle Skew* and *Aspect Ratio* of this model are below 0.4 scales.

7.5 Boundary settings

Pressure Inlet boundary conditions are used to define free boundary of an external flow in all four vertical planes in the computational domain. Pressure inlet boundary condition is recommended for problems that involves buoyancy-driven flows (Fluent

Manual, 1996). However, the model has used *Pressure Outlet* boundary condition on the upper plane that connects the domain to the sky. *Wall* is used as a boundary condition for all other parts of the building. Wall boundary condition is assigned with different fluxes of heat depending on surface temperatures that were recorded during the field work. Heat Flux conditions are specified through the '*Thermal*' section of the '*Wall*' panel within Fluent software.

Most studies do conclusively show that airflow characteristics are sensitive to convective heat transfer coefficient. The heat transfer coefficient is an important factor to influence the heat flux from a wall. Emmel et al (2007) show that large discrepancies observed among widely used building thermal models are attributed to the values of heat transfer coefficient. According to Marcelo et al (2006), when wind velocity is lower than 2 m/s the difference between surface and air temperatures would have a significant impact on the thermal environment. Zhang et al (2004) has conducted an experiment for a masonry wall in hot climate to determine the relationship between the wind speed (m/s) and the heat transfer coefficient h (W/m^2K). The results are tallied with results from mathematical equation to conclude the heat transfer coefficient of around 12 $W/m^2.K$ for steady state condition and 13 $W/m^2.K$ for air speed of 0.5m/s (see fig.7.4).

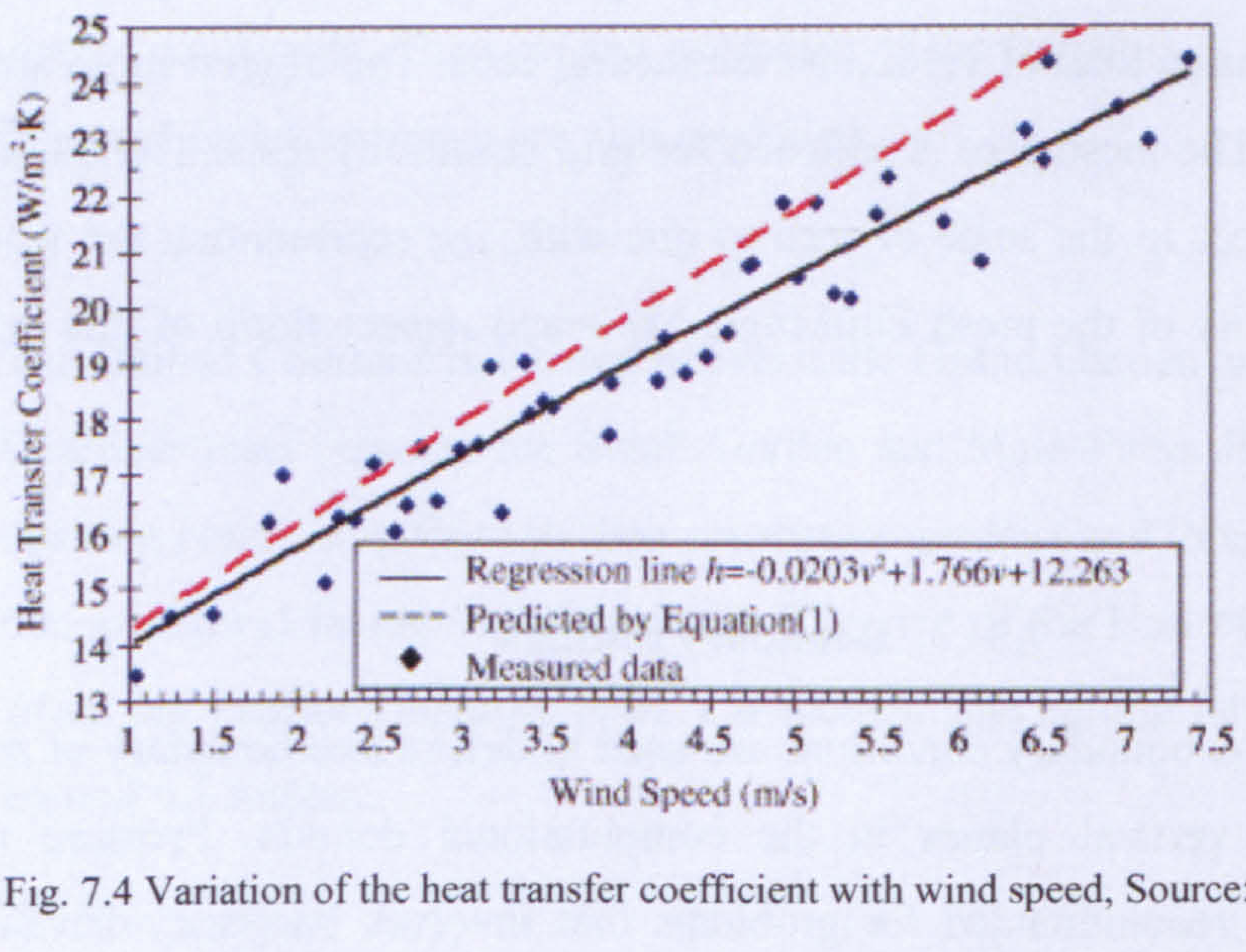

Fig. 7.4 Variation of the heat transfer coefficient with wind speed, Source: Zhang et al (2004)

The fluxes of heat that are specified in this work have considered the surface temperatures recorded at 15:00h and heat transfer coefficient of 13 $W/m^2.K$ suggested in Zhang et al (2004). The average air temperature recorded at the roof top at 15:00h is 40^0C. The Ecotect weather tool record shows the maximum direct and diffuse radiation of $900W/m^2$ and $100W/m^2$ respectively at 15:00h in the month of August. The equation below is used to calculate fluxes of heat from boundary walls of the courtyards in the Casa de Pilatos. The results are presented in Table 7.1.

Heat flux from a wall $q = h\,(T_{wall} - T_{air})$

q = heat flux (W/m^2)

T_{wall} = wall temperature (K)

T_{air} = air temperature (K)

h = convective heat transfer coefficient → masonry wall = $13W/m^2K$

The hottest month and time have been chosen for this simulation. The case details are summarized here;

- Seville (Latitude 37.40^0N, Longitude 5.9^0E)
- Time Zone GMT+1
- Day of Year 226 16th August
- Time of Day 1500 3pm
- Maximum radiation; direct 900 W/m sq., diffuse 100 W/m sq.

Main-Patio:

- Heat flux (W/m^2) from a wall q = h (Twall – Tair)
- Twall = surface temperature in main patio (refer fig.1) = (273+50)K = 323 K

- T_{air} = average air temperature in main patio (refer fig.2) = (273+44)K = 317K
- h = convective heat transfer coefficient → masonry wall =13W/m^{2}K (Zhang et al)
- q = 13W/m^{2}K (323 – 318)K = 78 W/m^2

Flux of heat from the main patio at around 50^{0}C when the air is 44^{0}C is **78 W/m^2.**

Roof:

- Heat flux (W/m^2)from a wall q = h (Twall – Tair)
- Twall = surface temperature of ceramic roofing tiles = (273+60)K = 333K
- Tair = average ambient air temperature (refer fig.2) = (273+38.7)K = 311.7K
- h = convective heat transfer coefficient → ceramic clay tiles = 19W/m^{2}K
- q = 19W/m^{2}K (333 – 311.7)K = 405 W/m^2

Flux of heat from the roof at around 75^{0}C when the ambient air is 38.7^{0}C is **405 W/m^2.**

The boundary settings for garden-courtyards:

Although this theoretical modelling does not simulate evapotranspiration, the impact of transpiration is estimated in watts per metre square (W/m^2). The benefits from transpiration are estimated from the percentage of the ground that is covered with vegetation. The total fluxes from the garden courtyard take account of both vegetation canopies and soil underneath. The resultant temperature is named as T_{garden} in this calculation below. The calculations consider Kustas and Norman (1999) model for partitioning the fluxes of heat between the vegetation canopies and the soil underneath. Kustas and Norman (1999) model the turbulent fluxes of sensible and latent heat from canopies and soil show that soil evaporation represents a third of vegetation canopy's transpiration, due to advection of a significant amount of sensible heat from soil to vegetation canopy. The equation below is used to calculate fluxes of heat from garden-courtyards in the Casa de Pilatos. The results are presented in Table 7.1.

- Heat flux (W/m^2) from vegetation surface $q = h\,(T_{garden} - T_{air})$
- T_{garden} = surface temperature in the garden-courtyards (refer fig.7.1 and fig.6.14) = (273+27) K = 300 K
- T_{air} = average air temperature in garden-courtyards = (273+32.6) K = 305.6K
- h = convective heat transfer coefficient → vegetation =23W/m²K for sensible heat and 42W/m²K for latent heat (Kustas and Norman 1999)
- for sensible heat $q = 23W/m^2K\,(300 - 305.6)K = 128.8\ W/m^2$
- for latent heat $q = 42W/m^2K\,(300 - 305.6)K = -235.2\ W/m^2$

Flux of heat from the green-courtyard at around 27^0C when the air is 32.6^0C is – 106.4 W/m^2.

Table 7.1: A summary of boundary conditions and their specification

No.	Boundary condition	Element	Specification
1	Pressure Inlet	All four vertical sides of the domain	313K
2	Pressure Outlet	Upper horizontal plain of the domain	313K
3	WALLS	Grand Garden	– 106.4 W/m^2
		Small Garden	– 106.4 W/m^2
		Main-Patio	78 W/m^2
		Roof	405 W/m^2
		Inside Hall of Columns & Praetor Chamber	10 W/m^2
		Shaded facades of the courtyards	10 W/m^2
		Un-shaded facades of the courtyards	78 W/m^2

7.6 Setting up the theoretical model

The choice of model for thermal radiation is important for correct prediction of the temperature stratification within space. According to Fluent Manual (1996), the density based solver takes more effort and troubleshooting in controlling convergence. The simulations in this work have incorporated Discrete Ordinance DO model to account for the effect of heat transfer due to thermal radiation. Other radiation models in fluent i.e. Rosseland, P-1, DTRM, and S2S have either lacked extra transport equations for radiation, or limited in the absorption coefficient they can accept. The DO model is used with heat flux boundary conditions defined at walls, such that the defined heat flux is treated as the sum of the convective and radiative heat transfer. Air is set to operate under gravity (- 9.8 m/s^2) and the operating pressure is set to 101325 pascals. Air is considered as incompressible-ideal-gas. Realizable k-epsilon model is the turbulence model which is used for these calculations. The use of DO radiation model, will both solve additional transport equations, and bring additional residuals for radiation.

7.7 The results

The results for the boundary conditions at 3pm taken from field recorded surface temperatures in August are shown in fig.7.5 – 7.8. The analysis is done over a cross section of three courtyards (see fig.7.5). Airflow is observed to be moving in a particular direction. There is air movement from the garden-courtyards to the Main-Patio. There is an almost stagnant condition in the garden-courtyards (see fig.7.6). With less than 0.1m/s movement of air in the garden-courtyards, airspeeds of up to 0.9m/s are realized at the inlets to the transitional spaces (see fig.7.7). The theoretical model has also confirmed the magnitude and direction of airflow. The results are consistent with the average air velocity of 0.7m/s recorded during field studies (refer field data in fig.5.35 and Table 5.4 in chapter 5).

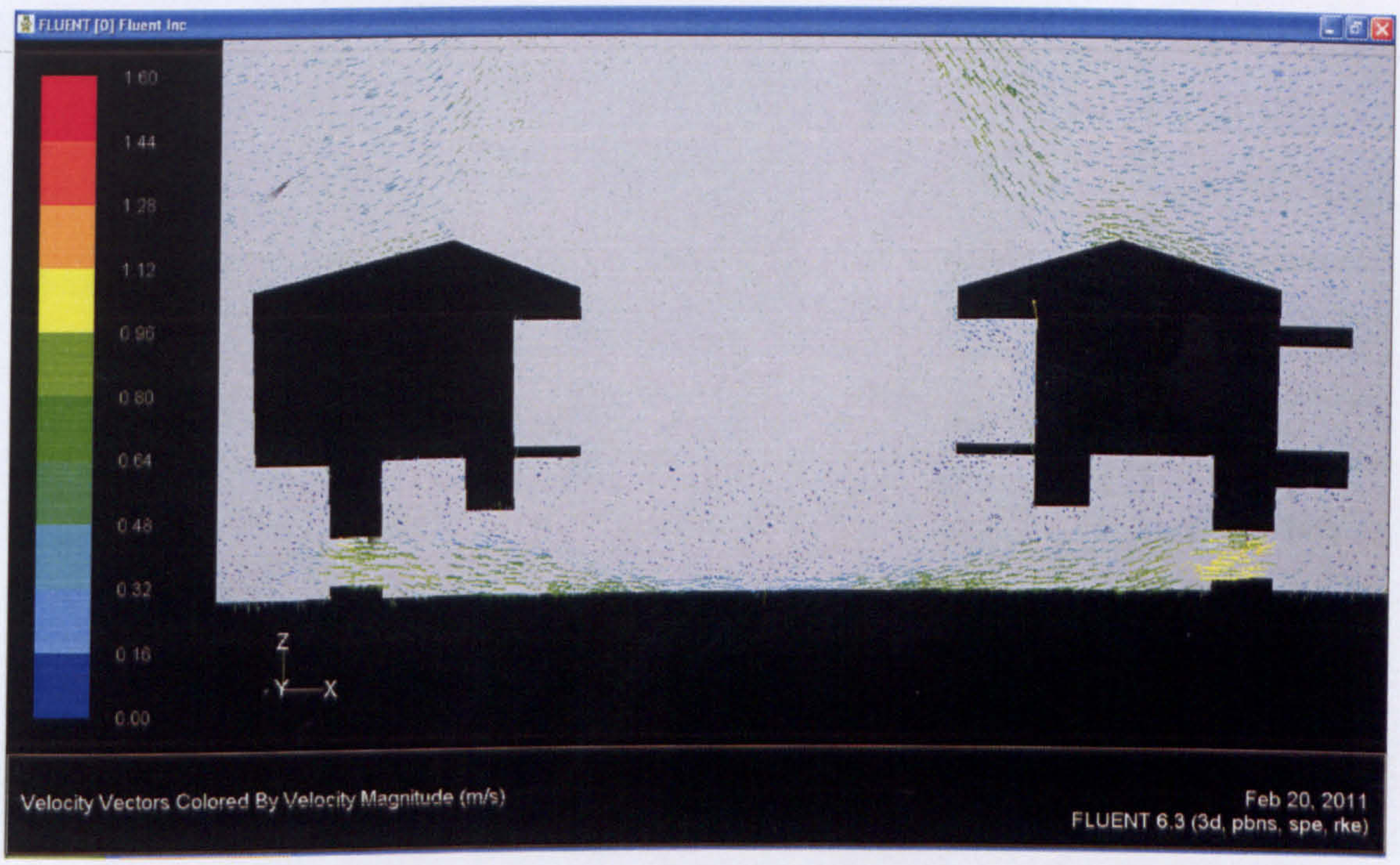

Fig. 7.5 A cross section through the transitional spaces showing the velocity vectors

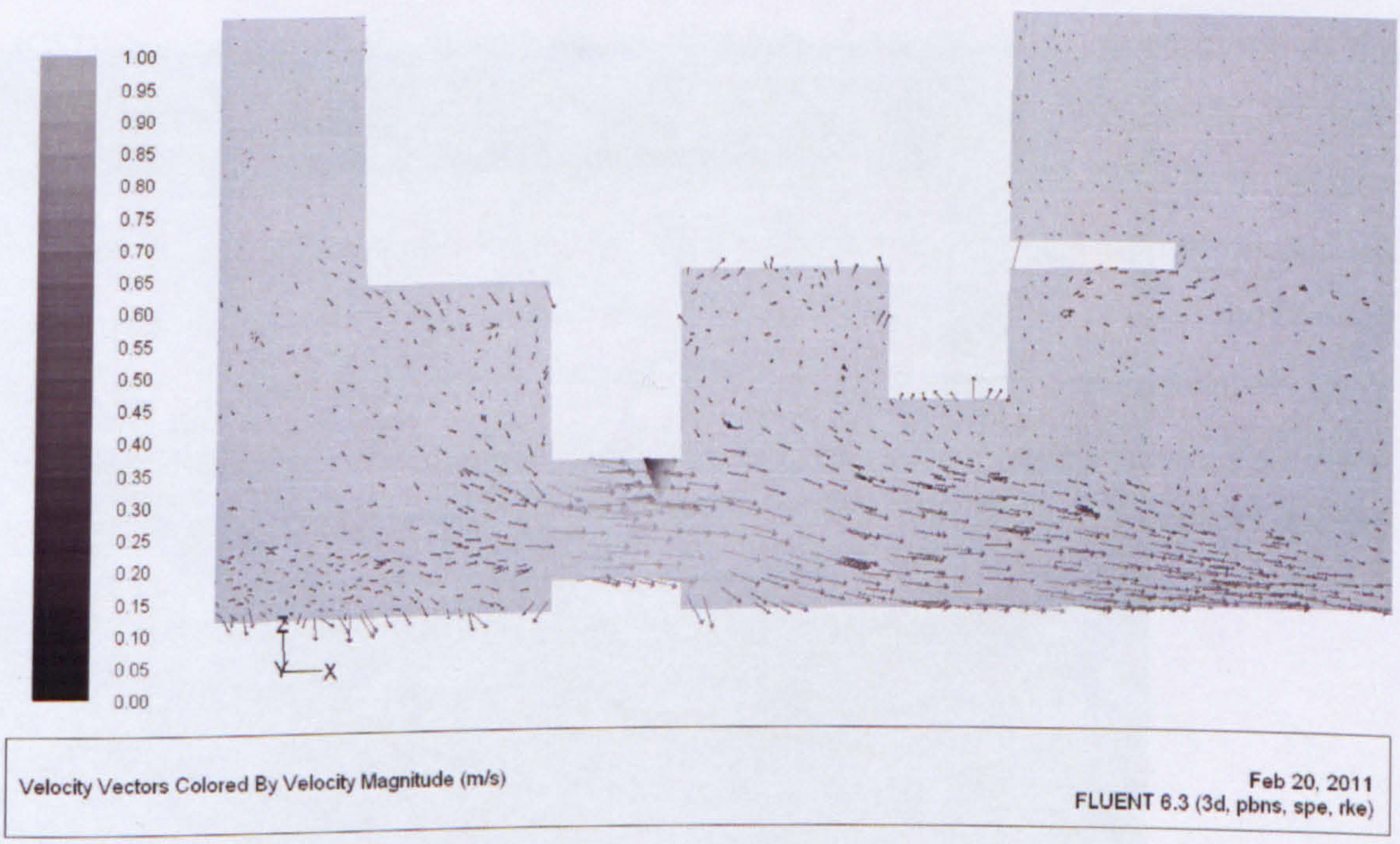

Fig. 7.6 A cross section through the Hall of Columns showing the velocity vectors

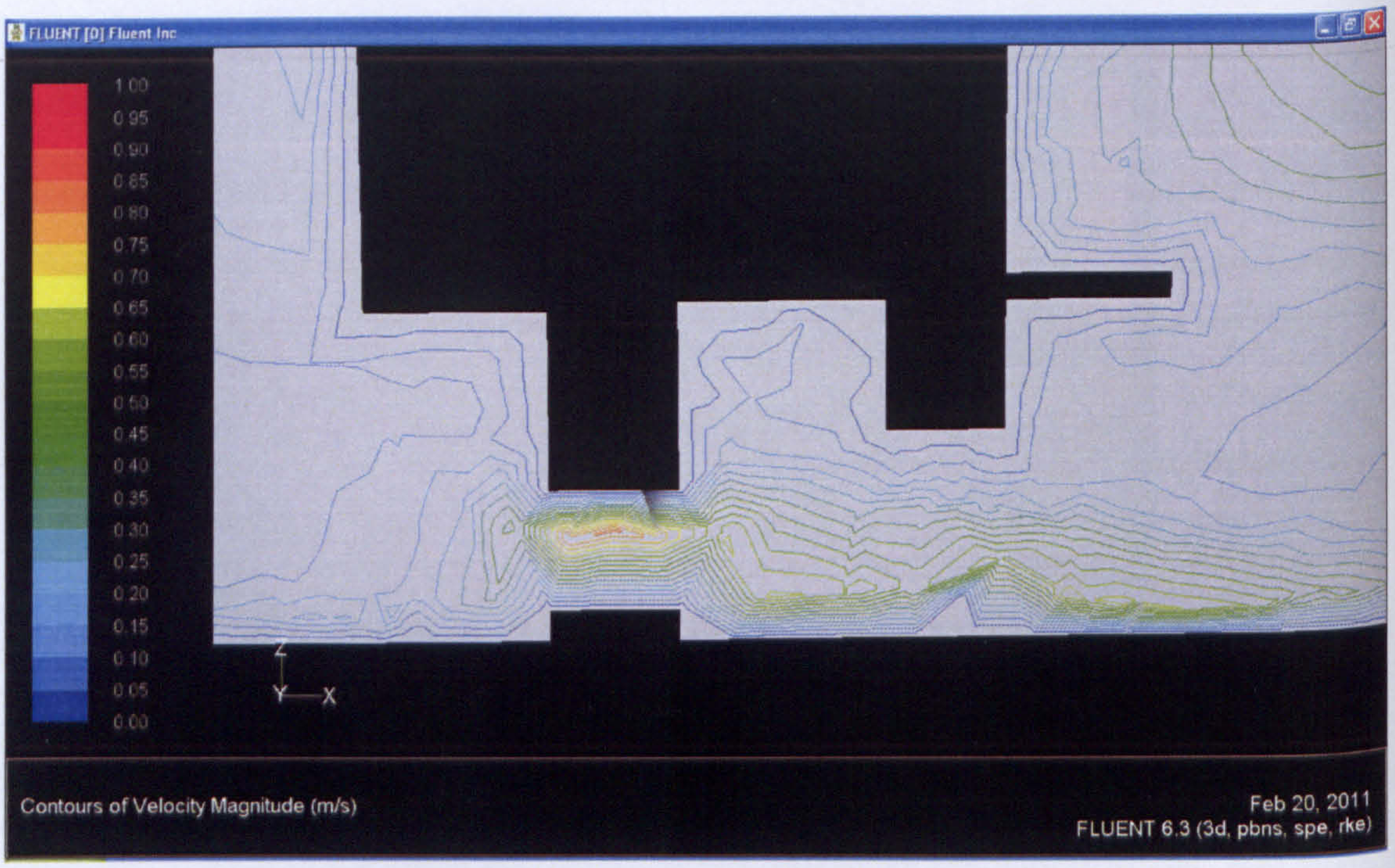

Fig. 7.7 Contours showing air velocity in a cross section of the inlet to the Hall of Columns

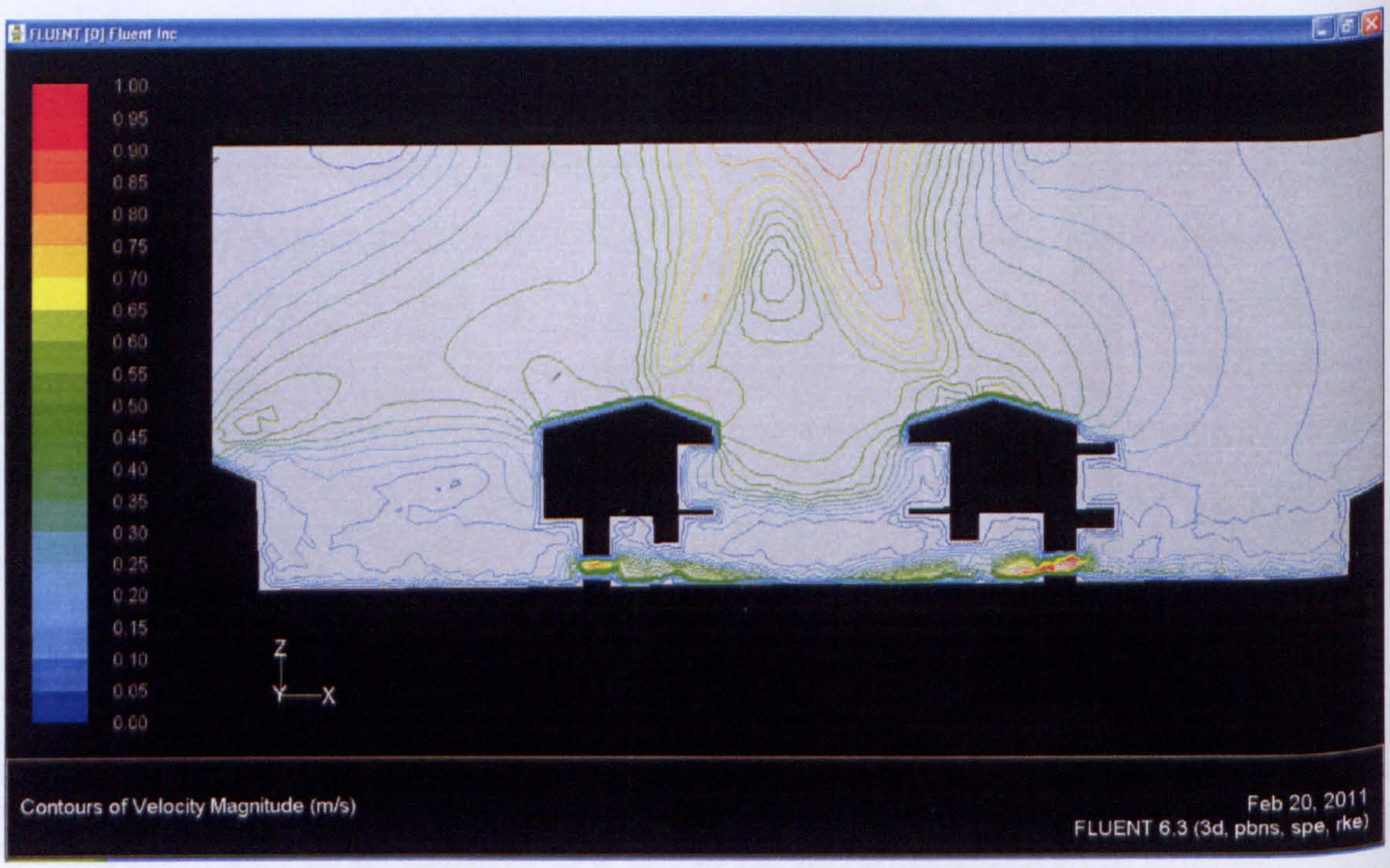

Fig. 7.8 Contours showing airflow patterns and velocity in all courtyards

Conclusion

The fluxes of heat from building surfaces were used for thermal modelling in order to validate the natural convection process. The numerical modeling techniques in Fluent 6.3 code confirmed the airflow pattern observed during the field measurements. Theoretical investigation has shown air velocity of between 0.6 and 0.9m/s through openings into intermediate spaces due to natural displacement of air from the garden-courtyards to the Main Patio. The comparison of predicted velocities with the measured velocities at 3pm presented similar results. The average air velocity of 0.7m/s is recorded during field studies. The field recorded magnitude of the airflow is presented in fig.5.35 and Table 5.4 in chapter five. There is an agreement between the theoretical and observed magnitude and direction of airflow.

The degree of environmental control achieved by this concept is quite dramatic, as has been demonstrated through theoretical simulations. Computational fluid Dynamics (CFD) has confirmed the magnitude and direction of natural displacement flows in the Casa de Pilatos. Discrete Ordinance (DO) radiation model has accounted for heat transfer due to thermal radiation, and realizable k-epsilon model is used for turbulence modelling. The simulations have also shown the sensitivity of building context to environmental variables and particularly the impact of the fluxes of heat emitted by surfaces or radiant flux density (Wm^{-2}). Although these computer simulations were complex, and large numbers of variables were used to construct them, they have nevertheless provided a particularly powerful tool for verification of hypotheses and the quantitative description of the underlying phenomenon.

CHAPTER EIGHT: SUMMARY AND CONCLUSIONS

8.1 Introduction

This thesis is set out to verify the conjecture made by Hassan Fathy (1986) that the multiple-courtyard buildings in semi arid climates were purposely designed to promote convective cooling through the spaces between the courtyards. Despite the anecdotal evidence provided by Fathy (1986), empirical and numerical studies have never been conducted to confirm the impact of temperature difference between two adjacent courtyards on convective cooling through transitional spaces in semi-arid climates. To verify this phenomenon, this thesis is organized in eight chapters. The introduction, aims and objectives were presented in chapter one. The principles underlying the multiple-courtyard buildings were presented in chapter two and chapter three has presented the precedents which suggest this principle. Chapter four has presented the building and context for physical investigation. Field work is presented in chapter five. Chapter six and seven have presented the analysis of fieldwork data and results from theoretical modelling respectively. This chapter presents the summary and conclusions from this thesis.

The summary and conclusions in this chapter are presented in five subsections. The first part presents the hypothesis, historical precedents and principles. The second part reiterates the field investigation and methodology. The third part presents the summary of results. The fourth part presents the conclusions and contribution to knowledge. And lastly, the fifth part presents the limitations of this study.

8.2 Hypothesis, historical precedents and principles

The hypothesis of this thesis is that multiple-courtyard buildings are designed to make use of temperature difference between courtyards to promote convective cooling through transitional spaces. These transitional spaces had titles such as *Takhtabush* and *Liwan* in the Arabic culture; and *Tablinum* in a Roman Domus. Three precedents have been taken from areas ranging from the Middle East through Northern Africa and Italy. These precedents include the Al-Suhaymi House of Cairo, Egypt; Roman Domus of Pompeii, Italy; and Beit Ghazaleh House, Syria.

Al-Suhaymi House of Cairo in Egypt has a prominent transitional space named 'Takhtabūsh' located between its two courtyards. This space rests between the arcaded garden-courtyard and grey paved courtyard. It stands between the public and private areas of the courtyard. Visitors were invited to this space and important meetings were held there. On the fore side of the Takhtabūsh is a private garden-courtyard (green) while a larger drier courtyard area (grey) is public and located behind this space. It is believed that the *mashrabiyya* screens behind the Takhtabūsh were used to maintain the flow of air while providing privacy between the two courtyards. It is conjectured that the grey-courtyard was purposely paved almost entirely in stone for incident solar radiation to create a much warmer environment. It is suggested that the temperature difference between the courtyards promotes air movement through the Takhtabūsh (refer section 3.2).

The Roman domus of Pompeii in Italy has a prominent transitional space named 'Tablinum' located between the atrium and colonnaded peristyle -courtyard 'garden'. The atrium served as the entry lobby, while the garden-courtyard of the Roman Domus provides light, and air, and gave users a refreshing and cooling effect in very hot weather. While an atrium is designed for reception of clients waiting to meet the patron, the Tablinum is used to display owner's status and meet guests on social occasions. The Tablinum was one of the most richly decorated rooms in the Roman Domus. The space has a similar position as the Takhtabūsh, and it is believed to have functioned in a similar way, acting as a conduit for air moving from the cooler garden courtyard to the atrium. It is predicted that air in the relatively warmer atrium would be rising by buoyancy, for cool air from the garden-courtyard to be driven through the Tablinum (refer section 3.3).

Beit Ghazaleh House of Aleppo in Syria has a transitional space named 'Liwan' located between the front main courtyard and rear garden-courtyard 'peristyle-courtyard'. The house is entered through the main courtyard which is more exposed to solar radiation than other parts of the building. The peristyle courtyard is packed with vegetation and water fountain to keep it cool. It's relatively smaller peristyle courtyard is naturally shaded and has limited access to solar radiation. Liwan is used as an open summer sitting room. Similar to other multiple-courtyards buildings, it is most likely that Liwan space in this building has gone through irresponsible alteration. It is conjectured that the temperature difference between the shaded and cool private peristyle-courtyard, and the warm and exposed front courtyards is meant to promote convective flow of cool air and influence the climatic condition in the *Liwan* (refer section 3.4).

The three precedents presented above have suggested that design of multiple-courtyard buildings is set up to promote convective cooling through the transitional spaces. It has been shown that this fine living space is mainly set along the main axis connecting courtyards as a transitional space with splendid design and link to both courtyards. The environmental case for this concept has considered the empirical traditions, bio-climatic strategies, design concept, pragmatics and apobetics (further elaborated in chapter two).

Empirical traditions refer to the practices where building knowledge is accumulated by trial and error and then handed down to generations. Hence, the knowledge became familiar to the native builders who have always participated in the design process. Historic builders had to use experience gained from the environment they have lived and interacted with. They had to master this environment over a period of time to know the inherent patterns of nature. Unlike contemporary buildings which seem to consider a narrow range of climatic conditions, historical building practices seem to consider a wider range of thermal environments. Multiple-courtyard buildings employed the ancient empirical traditions where knowledge is attained by the way of accumulated tradition of building design. Although the precedents are taken from empirical traditions in different contexts, they have employed similar bio-climatic features, with all buildings dependent upon physical and botanical processes (refer section 2.2).

Bio-climatic features involve a set of elements which were used to generate a desirable building climate. The features adopted in historic multiple-courtyard buildings were determined by the possibilities and capabilities of their traditional building techniques. They were also influenced by building design and ambient microclimate. The bio-climatic features in multiple-courtyard buildings employed vegetation (the use of evapo-transpiration); fountains and ponds (for evaporative cooling); thick walls (for thermal mass); and paved surfaces (for solar radiation to provide radiant heat for temperature differences). The bio-climatic features in the courtyards and transitional spaces had to be well thought out particularly from the conceptual stage. Multiple-courtyard environments suggest that a set of bio-climatic features were used to form a design concept (refer section 2.3).

Design concept refers to a unified set of bio-climatic features aimed at delivering the required environmental conditions. In the multiple-courtyard buildings referred to in this thesis, the environmental design concept combines garden-courtyards with grey-courtyards to promote specific environmental qualities and particularly convective cooling through the transitional spaces. The grey-courtyard is exposed to solar radiation and therefore warmer, while the garden-courtyard is shaded and supplied with vegetation and fountains to provide cooler environment. The house and garden, for all intents and purposes are one, convective cooling being a key feature in the multiple-courtyards design. It is believed that the objective of this design concept is to enhance the environmental conditions in the functional space between the grey warm-courtyard and cool garden-courtyard. However, the impact of the design concept was influenced by the sophistication of implementation (pragmatics) (refer section 2.4).

Pragmatics refers to the responses that are desired of the user. Any architectural design is bound to have functional requirements. The expected and implemented user responses were a part of pragmatics. Pragmatics focuses on the designer's actions and actions which are expected on the built environment. Multiple-courtyard entity was designed to respond to a variety of different functions or conditions to match the design concept. The building combines some responses to various climatic patterns (i.e., sleeping on the ground and upper floor in the summer and winter respectively) and user responses (i.e., shutters and openings to admit sun in winter and provides shade from solar heat during summer). It is believed that the multiple-courtyard buildings were primarily determined by pragmatic considerations of climate. However, design considerations are not limited to the pragmatics of climate, but must be carefully related to an understanding of the limitation of human adaptability to thermal environment '*apobetics*' (refer section 2.5).

The term '*apobetics*' is the teleological aspect referring to the relationship between design purpose and end utility (Gitt, 2001). Just as the way media industry collapses as soon as it starts to disseminate information without due regards of the recipient, the designs of historic multiple courtyard buildings were a dialogue and not a monologue. This is important because it is believed that multiple-courtyard environments make an allowance for user responses that are not derived from the builders. A spatial journey in such a building gives user the choice of diverse environments. It is suggested that because the thermal environment in multiple-courtyard buildings were intentional and had an unambiguously formulated purpose, field experience is the valuable approach of this kind of investigation (refer section 2.6).

Field investigation considered the fact that three precedents have suggested that multiple-courtyard concept was set up to promote convective cooling through the transitional spaces between courtyards. The environmental case for multiple-courtyards design is made by reviewing traditional building practices. The five aspects examination of empirical traditions, bio-climatic features, design concept, pragmatics and apobetics in these buildings was used to suggest the environmental case for multiple-courtyard buildings. The next section is going to present the fieldwork and methodology used to investigate this phenomenon.

8.3 Field investigation and methodology

Fieldwork was carried out in order to confirm the hypothesis. This section summarizes the field investigation and methodology that is used to conduct this study. The studies by Nicol (1983) and Brager & de Dear (2001) are used to justify field investigation over other research methods. These scholars have shown that that this research methodology would provide data which is more reliable than laboratory based studies. This section starts by giving a reason for the choice of site and reading to be taken. Then it shows how the collected data can meet objectives such as the determination of drivers for airflow, convective cooling and thermal comfort. The impact of urban layout and local wind patterns are also considered. Field study is carried out through physical investigation and installation of monitoring equipment. The field investigation took place in the summer of 2008. Further details on the physical investigation at the Casa de Pilatos are presented in *chapter five.*

This thesis is based on a single-case study of the Casa de Pilatos located in the historic part of Seville in the Southern Spain. The Casa de Pilatos is an exemplary multiple-courtyard building which has been well maintained. Its fabric and layout has been the same since it was built. It was chosen because it is a typical of many of the multiple-courtyard buildings. The history of this building started in 711AD when the Moorish 'Muslim' conquest of Spain brought some techniques to deal with extreme summer heat. It is believed that hot and dry summer seasons in the Southern of Spain 'Andalucia', set the path for Moorish garden-palaces with ingenious arrangements of materials, vegetation, and water features for building climate. Further details are presented in chapter four. Climatic data were taken in six difference locations in the building in the summer period between 10th and 20th August 2008.

The readings for DBT (^{0}C) and RH (%) were taken in six locations in the Casa de Pilatos because the feeling of comfort or discomfort does primarily rely on these parameters. The readings for air velocity were taken at the inlet to the transitional spaces in order to confirm the magnitude of airflow and to determine convective cooling energy. The readings for DBT (^{0}C) and RH (%) were taken in three courtyards (Grand Garden, Small Garden, and Main Patio), two transitional spaces (Hall of Columns, and Praetor Chamber), and house roof. The wind speed readings were taken at the roof top in order to determine the impact of local wind patterns. Spot measurement of surface temperatures were taken to help estimate the impact of the radiant energy from vegetation and building surfaces. The amount of data and fieldwork duration was limited by available equipment and resources respectively. The choice of instruments for recording DBT, RH, and air velocity was based on their ability to provide a continuous record of data, which is summarized into mean hourly data. Further details are presented in *chapter five.*

The enthalpy of the air in the garden-courtyards is analyzed so as to determine the possibility for cooling. Field data are used in conjunction with mathematical models to determine the amount of convective cooling taking place in the transitional spaces. Free cooling is possible when the specific humidity of incoming air is sufficiently lower and the enthalpy of the outside air is lower than the ambient enthalpy. The exposure to direct solar radiation would raise the enthalpy of air in the Main Patio as compared to the garden courtyard. Shading and evapotranspiration from vegetation would result in garden-courtyards with sufficiently lower enthalpy. Free cooling in the intermediate 'transitional' spaces is available because air with low temperature is driven through by multiple-courtyard strategy.

Convective cooling energy attributed to airflows through the transitional spaces is calculated. These calculations are based on field measurements of the area of inlet, volumetric size of transitional spaces, air velocity, and interior and exterior temperatures. The calculation of volume flow rates has considered the area of the opening, air velocity and discharge coefficient. These are used in conjunction with temperature differences to determine the convective cooling energy in kilowatt (kW) and watts per meter square (W/m^2). These values are also used to determine the impact of multiple-courtyards strategy and the means of mitigating additional gains. Additional heat loads are applied to the transitional spaces because fieldwork was undertaken in unoccupied spaces. Results are used to predict the applicability of this technique to a contemporary natural ventilated building. The next section summarizes results from chapter 6.4.4 of this thesis.

Field data are used in adaptive comfort models to evaluate the thermal conditions in transitional spaces. The adaptive comfort models by Nicol and Humphreys (2002) and Brager and de Dear (2001) are adopted in order to evaluate field's DBT, RH and air velocity and predict subjects' response to various thermal environments in the transitional spaces. The impact of air movement on the subject seated on the window-seats is evaluated by analyzing thermal sensation for different postures and locations in the transitional space. Psychrometric charts have illustrated the potential and limitations of evaporative cooling and ventilation for each location where readings were taken. The outcome is presented in chapter 6.5.

Field data are used to determine the drivers for airflow through the Hall of Columns and Praetor Chamber. This is done by evaluating the impact of natural displacement through buoyancy 'stack forces'. Internal and external air temperature in these calculations is represented by the temperatures in the Main Patio and garden-courtyards respectively. The Main Patio and surrounding spaces are considered as single space because they are connected by openings that are much larger than openings in their respective external envelope. The magnitude of these forces is calculated and tabulated (Table 6.8 and 6.9) in order to make a correlation between the field recorded volume flow rates and those derived from temperature differences between the Grand Garden and Main Patio.

To gather greater insight into the building's flow field computational fluid dynamics software was used. CFD was used to model thermal radiation and diffusion as mechanisms for thermal transport, and natural displacement ventilation flows. Field recorded surfaces temperatures are used in fluent's discrete ordinance (DO) radiation model to model natural displacement flows. The surface temperatures that were recorded during fieldwork are converted into fluxes of heat (W/m^2) for DO model in order to determine the impact of the buoyant flow of air. It is suggested that air velocity values through the transitional spaces in CFD model do confirm the field measurement.

The impact of the local wind regime on the volume flow rates through the transitional spaces is also calculated. This is done by correlating the change in the magnitude and direction of wind recorded at the Roof Top with the variation in air velocity recorded in the transitional spaces. The magnitudes were recorded at the Roof Top, while the directions are taken from meteorological data. The impact of certain magnitude and direction of wind is also linked to the building form and layout. It is predicted that whenever wind force supersedes thermal forces, the prevailing wind would become the driving force, with hydrostatic pressure between the inlet and outlet changing to reflect the existing scenario.

The impact of urban layout on inflows to the Casa de Pilatos is also predicted. This is done by using the general relationship between the wind velocity υ, within the canyon, and above-roof free stream wind speed U. Strong flow patterns may evolve from the canyon effect of narrow streets characterising the historic town. The dense urban structure with narrow and deep streets is meant to avoid direct exposure to undesirable solar heat and maritime hot and dry air currents. A further order of difficulty is introduced by the changing urban context. The historic parts of Seville are currently in the middle of a sprawling urban environment and are markedly different from the period when it was a city surrounded by suburban areas. It is suggested that the process of identifying the drivers for airflow through the transitional spaces is complicated by the conditions at the street level.

This section has summarized the field investigation and methodology used to conduct this study. Casa de Pilatos is presented as a single-case under investigation. Field data were used in conjunction with mathematical models in order to confirm the hypothesis. The determination of drivers for airflow through the Hall of Columns and Praetor Chamber and CFD projection of airflow patterns are part of the methodology. Field readings were taken in order to calculate convective cooling energy attributed to airflows, and adaptive comfort models were considered in order to evaluate the thermal conditions in transitional spaces. The complexity set by local wind regime and urban layout are also projected. The next section presents the summary of results.

8.4 Summary of Results

This section presents the thirteen objectives listed in the introductory chapter and response to these objectives provides a summary of results.

(1) To use field measurements to determine the magnitude and direction of air movement through the transitional spaces.

This was verified through physical investigation and air velocity data taken at the inlets to the Hall of Columns and Praetor Chamber. Anemometers were connected to a data logging instrument for continuous records of data through delogger software. The instrument was set to record air velocity every one minute. The recorded air velocity values have varied between 0.2m/s and 1.5m/s. Average air speed of 0.7m/s was recorded at 15:00h. Volume flow rates of up to 5.3m^3/s were recorded through 4.8m^2 opening in the transitional spaces. The low DBT recorded at the inlet to the Hall of Columns and Praetor Chamber do also confirm that air is driven from the garden-courtyards.

(2) To use field measurements to determine the temperature variation between the multiple-courtyards.

This was verified by recording temperature in a cross section of three courtyards namely the Grand Garden, Main Patio, and Small Garden in the Casa de Pilatos. The average of peak temperatures recorded in the Small Garden and Main Patio were 32.6^{0}C and 45.4^{0}C respectively, a difference of 12.8k. The DBT in the Main Patio has remained at least 8K higher than the DBT in the Hall of Columns for at least 5 hours (11:00h – 16:00h). The difference has quickly widened after 11:30h, when the temperature difference increases from 2K to 7K by 12:00h (noon).Temperature differences of up to 18k were recorded across the spaces in the Casa de Pilatos. This is because the garden spaces are sheltered from solar radiation, and vegetation has provided an environment in which thermal radiation is attenuated.

(3) To use field data to compare and contrast the daytime and night time dynamics existing between the courtyards and the open sky.

It has been shown that daytime stratification of air is different from night time. Daytime stratification of air in the garden-courtyards has placed the cooler and dense air at the bottom; hotter and less dense air being at the Roof-Top. This stratification has naturally limited the flow of air from the garden-courtyard's base to the open sky. However, in the night time, there is an inflow of cool air from an open sky. Unlike the stratification in the garden-courtyards, thermal stratification in the Main Patio has hot and less dense air at the bottom of thermal stratification both in the daytime and night time. However, in the night time, the absence of solar radiation results into narrower variation in temperature between the Main Patio and Roof Top.

(4) *To determine the role of buoyancy forces as the driver for airflow through the transitional spaces.*

It has been shown that the temperature difference of 10k across courtyards leads to 3% variation in air density across the courtyards. Volume flow rates due to buoyancy effect are calculated by using equation-6.2. The internal and external air temperature is represented by the temperatures taken at the inlet to the Hall of Columns and the one taken in the Main Patio respectively, hence a temperature difference (ΔT) of 12.5K at 15:00h. Buoyancy effect has considered the height (*h*) between inlet and outlet openings (refer fig.6.27) in the Hall of Columns. Volume flow rates attained through the buoyancy calculations were between $0.8m^3/s$ and $2.8m^3/s$ bfrom 08:00h to 18:00h respectively. Low volume flow rates were reached at 08:00h in the morning, while higher volume flow rates were attained between 12:00h and 14:00h in the afternoon (refer Table 6.8). Because the theoretical volume flow rates (Q) are lower than field volume flow rates, the impact of stack forces in the Main Patio is also considered.

(5) To determine the role of stack forces in the hot-grey courtyard on the movement of cool air from garden-courtyards.

Due to the impact of direct solar radiation, Main Patio 'stack' has recorded considerably higher temperatures than other spaces. However, according to CIBSE (AM10 pp44), the Main Patio and surrounding spaces can be considered as single space because all the rooms are connected to the Main Patio by openings that are much larger than openings in the external envelope. The volume flow rate (q) was calculated from the known internal 'Main-Patio' and external 'garden-courtyards' air temperatures. The calculation of the stack effect has produced volume flow rates of between $1.3m^3/s$ and $4.6m^3/s$ between 08:00h and 18:00h. The impact of the stack effect is presented is within the range of field data (refer fig.6.30 and fig.6.31).

(6) *To determine the impact of prevailing wind pattern and urban layout on air velocity through the transitional spaces.*

Although generally there is a prevailing wind speed and direction, the meteorological and field data has shown a constant variation in these parameters (refer Table 6.10 and fig.6.32-36). The disparity between the theoretical and field recorded flow rates can be partly attributed to these variations. Furthermore, the wind speeds recorded at the Roof Top are far below the Seville's average wind speed of 1.4m/s. The garden-courtyards are 10 – 17 metres deep and purposely shaded from the local wind regime. However, the Main Patio is exposed to south-west prevailing winds (refer fig.6.38 – 6.39). The impact of wind speeds on the volume flow rates in the transitional spaces is estimated by using Equation 6.3. The average hourly volume flow rates calculated from the daytime wind speed data recorded at the Roof Top has range between $0.54m^3/s$ and $0.98m^3/s$. The impact of this range is shown in Fig.6.41.

(7) To use theoretical modeling to confirm the impact of temperature differences between courtyards on the magnitude and direction of airflow through the transitional spaces.

The analytical model was constructed by using Gambit software and then exported to Fluent software for CFD simulation. The model has used the data taken during the fieldwork and the process is presented in chapter seven. The magnitudes and direction attained from theoretical simulations were similar to those observed during field studies. The air speeds of between 0.5 and 0.9m/s were attained in both physical and theoretical investigations as a result of natural convection (details are provided in chapter seven).

(8) To determine the contribution of the building mass to heat balance in the transitional spaces.

The variation of temperature recorded in the transitional spaces and the Roof-Top has given an indication of the time-lag that is born out of building mass. The DBT of 30^{0}C at the Roof Top between 09:00h and 10:00h, were reached between 13:00h and15:00h in the Praetor Chamber (refer fig.6.17). A delay of at least three hours was attributed to the building mass. Surface and air temperatures were also used to determine the flux of heat from the 166m^2 of walls in the Hall of Columns.The heat balance has varied from 0.6kW at 13:00h to 2.5kW (36W/m^2) at 15:00h in the afternoon (refer Table 6.4 – 6.7).

(9) To determine the possibility for cooling from the conditions in the garden-courtyards.

The possibility for cooling is determined by comparing the enthalpy of air in the Small Garden and Main Patio (refer section 6.4.1). Free cooling only is possible when the specific humidity is sufficiently low and the enthalpy of the outside air is lower than the ambient enthalpy. When calculated for the conditions at 15:00h, the results in the Small Garden (31.4 ^{0}C and 38.3%RH) and Main Patio (43.6^{0}C and 19.7%RH) were 59.58 kJ/kg and 72.05 kJ/kg respectively. A significant part of the enthalpy difference is due to variation of air temperature (12.5kJ/kg). The impact of air moisture on the enthalpy difference between the Small Garden and the Main Patio is not significant (0.03kJ/kg).

The air from the garden-courtyards has significantly lower enthalpy than air in the Main Patio.

(10) To determine the amount of convective cooling attributed air flows through the transitional spaces.

The temperature difference and volume flow rates at the inlets to the Hall of Columns and Praetor Chamber were used to calculate the convective cooling energy. While much higher temperatures in the Main Patio could have a significant role in the movement of air through the Hall of Columns, the convective cooling calculations have used the estimated temperature difference of 2k (refer Table 6.11). This temperature difference has produced convective cooling energy of between 2.7kW (39.2W/m^2) at 08:00h and 4.9kW (71.4 W/m^2) at 16:00h.

(11) To determine the implication of additional heat loads on the convective cooling requirements in the transitional spaces.

The calculation did consider the Hall of Columns as a meeting room in order to determine the implication of additional heat loads on the thermal conditions in the transitional spaces. This was important because fieldwork was conducted in unoccupied functional spaces. The 69m^2 space has accommodated 20 people at 3.5m^2 per person. The required increment in volume flow rates (Q) is determined for conditions at 15:00h. Additional 8.8 air changes per hour are required in order to eliminate the additional heat gains. This means an increment from the recorded 23/hour (0.7m/s) to 31.8/hour (0.9m/s). Convective cooling has also been altered by widening the temperature difference between the Hall of Columns and Grand Garden. The average absolute humidity recorded in the Small Garden has ranges from 9 g/m^3 to 12 g/m^3, while maximum humidity that the same air can hold would range from 20.5 g/m^3 to 33.4g/m^3. It has been shown that while the WBT were lower by 6.7k – 14.7k, the air temperatures in the Grand Garden should be lowered by 2.8k to 3.3k between 08:00h and 18:00h to provide the temperature difference that is required to remove the additional heat loads.

(12) To determine the application of window-seats on the thermal comfort criteria of the transitional spaces.

The equation provided by Szokolay (1998) is used to calculate the cooling sensation attributed to air velocity values taken in the Hall of Columns. The calculations have realized an impact of as much as 2.7k from cooling sensation of airflow. The hourly average temperatures which were as high as 32.1^{0}C at 17:00h have fallen below 30^{0}C. This temperature is acceptable according to the comfort model provided by Nicol and Humprey (2002), which has produced a comfort temperature (T_c) of 28.2^{0}C with acceptable range of +/– 2^{0}C (refer chapter 6.5.1). Subjects would also experience additional cooling through conductive heat loss when in contact the tiled surfaces on the window-seat (refer fig.6.34 and fig.6.35).

(13) To determine the application of adaptive comfort models in the multiple-courtyards building.

Field data have shown DBT and humidity that has varied extensively in the Casa de Pilatos. Micro-climates ranging from hot and dry in the Main Patio, and cool and dry in the transitional spaces, to cool and humid at the garden fountains were provided in the Casa de Pilatos. Generally, the difference between the RH at 07:00h and 15:00h has been as much as 40% with temperature difference of up to 20k across the building. Cooling sensation of air flow from the garden-courtyards for subjects seated at the window-seat is considerable. The building is design in a way that the subjects are given opportunity to take corrective measure to meet their comfort requirement. The subjects would use different window-seats and migrated from the Main Patio in the morning to different parts of verandas and garden-courtyards in the afternoon. The work of various authors like Lisa Heschong (1979), Rapoport (1982), Fathy (1986), and Konya (1980) have also been used justify this approach to thermal comfort. It is suggested that the environment in the Casa de Pilatos cannot be evaluated by using model which are based on PMV or PPD calculations because the building's thermal sensations are born out of variable impacts and the connectivity of spaces.

8.5 Conclusions and contribution to knowledge

The study has shown that the core climatic feature of the multiple-courtyards phenomenon is the characteristic temperature difference between courtyards. Convective air movement through the transitional spaces has taken place at a rate that is driven primarily by the variation of the thermal condition in the courtyards. It is concluded that buoyancy is the main driver for airflow entering the transitional spaces from the garden-courtyards and exiting the upper opening in the enclosed warmer courtyard. Theoretical modelling has confirmed the natural convection patterns and air speeds. The air speeds of between 0.5 and 0.9m/s attained through the theoretical investigation were consistent with the field results.

Overall, it is shown that significant amount of convective cooling is attributed to yard-to-yard air flows. Cooling is achieved through addition of moisture to the air with sufficiently low humidity in the garden-courtyards. Since the enthalpy does significantly increase as you move from the garden courtyards to the Main Patio, the air temperature in the garden-courtyards is lowered adiabatically for further cooling to be achieved through water evaporation. A temperature difference between the garden-courtyards and transitional spaces is increased by taking advantage of the low levels of moisture in incoming air from the garden-courtyards. Cooling is also provided through radiant exchange between the occupants and the walls, floors and ceiling.

Window-seat is an important climatic feature in the transitional spaces where cooling sensation of airflow is a necessary requirement to restore thermal comfort at peak temperatures in the summer season. The occupants are seated indoors as they exploit the thermal environments in the immediate outer spaces. It is shown that different window-seats would have different role around the year. Migratory life style makes it possible for usefulness of a particular window-seat to change hourly and from season to season. This feature is the evidence of the mechanism by which natural ventilation has maintained summer comfort in the Casa de Pilatos.

The comfort conditions in these buildings changes daily and across seasons. The multiple-courtyard environment gives users an opportunity to use their adaptive tendencies to meet their comfort requirement. This approach is contrary to contemporary approaches which have restrained the natural human tendencies into static or steady thermal environment. Unlike, air-conditioned buildings, the thermal environment in historic multiple-courtyard buildings cannot be evaluated by using models which are based on PMV or PPD calculations because these buildings' thermal sensations are born out of variable impacts and freedom to migrate from space to space. Thermal stimulus is part of architectural aesthetics and consideration that humans have natural desire for thermal contrast. The Casa de Pilatos is non-steady state thermal environment, and the building has very distinctive transients among its thermal environments.

Knowledge of the urban wind patterns is necessary for all studies related to natural ventilation of building. While the prevailing wind patterns need to be considered, the canyon airflow is a secondary circulation feature influenced by details of buildings and street. The multiple-courtyards concept has insured that the location of courtyards in respect to prevailing wind conditions did not reverse, but rather promote buoyancy and stack forces. In the Casa de Pilatos, this strategy is maintained by deep garden-courtyards, and orientation of the grey warm-courtyard in consideration of the prevailing wind direction and local wind regime.

The study of the Casa de Pilatos has shown that the transitional spaces in multiple-courtyard designs are robust in terms of its response to changing occupancy density. The variation in occupancy density has shown that temperature difference between courtyards can be used to mitigate additional heat loads. Convective cooling process can be altered to mitigate additional heat gains in the transitional spaces by taking advantage of low enthalpy and air moisture in the garden-courtyards. This phenomenon provides a robust strategy to accommodate such variations in occupancy density, and hence, various opportunities for further work.

The multiple-courtyard layouts are still widely used in schools, hospitals, and other public buildings around the world. However, they are used with unawareness of their inherent historical qualities and opportunities for passive cooling. In a world that is largely geared towards reduced energy consumption at uncompromised human comfort, historical multiple-courtyards phenomenon provides an example of passive thermal regulation of intermediate spaces and conditions for adaptive comfort. The control of inflow and outflow from a cool garden-courtyard to warmer dry-courtyard would help to control heat losses, gains and comfort in the transitional spaces. This study has observed that the historic multiple-courtyard buildings in semi arid climates were not created arbitrarily, but they were optimised to promote yard-to-yard convective flows for improved thermal qualities. However, due to limitation of this study, it was not possible to satisfactorily confirm every claim.

8.6 Limitation

The limitation of this study provides an opportunity for further work. Because it is unlikely for this strategy to be adopted based on a single case study, similar studies need to be carried out. This phenomenon would require study on precedents from various contexts in order to fully confirm the suggested driving forces and a combination of factors which have shaped the thermal environment. Particularly, the impact of changing position of radiant surfaces with respect to solar radiation requires additional field investigation (refer chapter 6.2.1). If similar studies are carried out in other locations, it will also help to rule out contextual & cultural issues. There is also an opportunity for further investigation on the applicability of this strategy in contemporary context bearing in mind building typology, contextual, and climatic issues.

Another opportunity for further work also comes from the limitation of this study. This limitation is found in the methodology of field measurement. This work has used spot measurements as a representative of a much bigger area. Difficulty with interpretation of data comes from the fact that measurement are taken from one point rather than an area. The random error in the plot of volume flow rates versus temperature difference shows that measurement from one point in the courtyard or inlet window may not be the representative of the total process. The actual pivotal process should involve the averaged data over a wider space.

Field experience should be the starting point and the valuable part of this kind of investigation. The historic builders shaped their environment with elements which were both formless and invisible. This is opposed to contemporary approach where the manipulation of form for visual effect is steering all design considerations. As a result, the conventional approach for solving climatic problems is to use high-end computing and fluid visualization software as a design tool. This distancing from the climatic elements seems to be in opposition to the very idea of investigation.

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APPENDICES

Appendix I: Vegetation in the Casa de Pilatos

ESPECIES DE LOS JARDINES DE PILATOS

JARDÍN GRANDE

Árboles:
- Higuera
- Júpiter
- Limonero
- Magnolio
- Naranjo
- Olivo
- Palmera
- Platanera
- Seibo (árbol nacional argentino, flor la capa del cardenal)

Arbustos:
- Algodón de Brasil
- Azalea
- Boj
- Aclepia (huevo de Viejo)
- Celinda (*Philadelphus virginales)*
- Datura
- Madroño
- Rosal

Vivaces:
- Acanto
- Agapanto
- Ave del paraíso (*Strelitzia reginae)*
- Cala (*Zantedeschia aethiopica*)
- Clivia
- Crinum (crinio africano)
- Guindilla
- Camelia
- Jacobínia (piña con flor)
- Papiro (*Cyperus Alternifolio*)

Trepadores:
- Bouganvillea
- Plumbago
- Stephanotis
- Rosal rambler (trepador)

JARDÍN CHICO

Árboles:
- Cyca revoluta
- Falsa pimienta (dátil como ciruelas)
- Júpiter
- Higuera (higos y brevas)
- Magnolio
- Naranjo
- Palmera (dátil)
- Paraiso

Arbustos:
- Arrayán (huele)
- Boj (no huele)
- Celinda (*Philadelphus virginales)*
- Datura (venenosa y curativa (asma, fumada))
- Rosal (rosas pitiminí, minis y trepadoras)
- Sineraria (flores moradas)

Vivaces:
- Acanto
- Cala
- Esparraguera
- Kalanchoe
- Violeta
- Ave del paraíso

Trepadoras:
- Bignonia
- Bouganvillea
- Jazmín de invierno (*Jasminum nudiflorum)*
- Parra Virgen
- Rosal rambler (trepador)
- Dama de noche

Appendix II: Field equipment accuracy and calibration

The equipment was chosen for their ability to provide a continuously recorded data. All data loggers that were used have allowed the set up of recording intervals, the start and finish time. The schedule of recording instruments is outlined in Table 1- 3 below.

Due to the nature of this work, precision of all equipment was an important factor. High precision equipment was required to detect low speed natural convection flows. Air speed anemometers that were used have accuracy of 1.5% (see fig.3). Their merit includes the short response-time (400 msec). They are also acknowledged for their durable Fast-Response Platinum Sensors (newportnet.org). Gemini Data Logger 'tinytag' (see fig.2) has an accuracy of 0.5deg.C and ±3.0% RH (geminidataloggers.com). The units have battery run circuit to store as many as 32,000 readings. Batteries were replaced in all tiny-tags to ensure uninterrupted and full performance during fieldwork.

Fig.1 Hand-held anemometer and thermometer (Testo-MiniAnemometer), Source: www.surveysuperstore.co.uk/

Fig.2 tinytag data logger (gemini)

Fig.3 Anemometer (source: newportnet.org)

Fig.4 Infrared thermometer

Additional equipment were infrared thermometer and hand held anemometer. Infrared thermometer (fig.4) was used to remotely measure surface temperatures. Laser radiation is emitted from its aperture to detect the temperature of the target surface. The equipment emits 1mW with a wavelength 630 – 670 nm. It is listed as Class II Laser product which complies with CFR 1040.10. It was important that surface temperatures could be remotely detected due to size of the building, ceiling heights and site restrictions. The hand-held anemometer shown in fig.1 was used to take some spot measurements of air speeds. The accuracy and characteristics of the equipment are shown in table 4.

Table 1 – List of equipment used during fieldwork

	No.	Equipment	Brand	Objective
A	7	Data loggers	Tinytags	Air temperature & relative Humidity
B	2	Data Loggers with Air velocity Transducers	DataTaker	continuous recording of air speed
C	1	Infrared thermometer	Raytek MiniTemp	Surface temperature
D	1	Digital thermometer		Spot measurement of air temperature
E	1	Digital hand held Anemometer	RS 180 – 7111	Air speed
F	1	Digital anemometer + thermometer	testo 405-V1	Spot measurement of air speed, and temperature
G	1	Surface Thermometer	Testo 0900 0519	Surface temperature

Table 2: Data loggers used for recording temperature & relative humidity and their on site locations

No.	Model	Image	Details	On Site location
1	TinytagUltra		*Temperature* Range H & Relative *Humidity* -30 > 50 deg. C, 0 > 95% RH Part No: TGU-1500 (270018)	Roof-top
2	TinytagPlus		*Temperature* Range H & Relative *Humidity* -30 > 50 deg. C, 0 > 100% RH Part No: TGP-1500 (269835)	Hall of Columns
3	TinytagUltra		*Temperature* Range G Standard probe -40 > 125 deg. C, Part No:TGU-0020 (267007)	Praetor Chamber
4	TinytagPlus		*Temperature* Range H & Relative *Humidity* -30 > 50 deg. C, 0 > 100% RH Part No: TGP-1500 (389344)	Grand-Garden
5	TinytagPlus		*Temperature* Range H & Relative *Humidity* -30 > 50 deg. C, 0 > 100% RH Part No: TGP-1500 (389346)	Small-Garden
6	TinytagPlus		*Temperature* Range H & Relative *Humidity* -30 > 50 deg. C, 0 > 100% RH Part No: TGP-1500 (372900)	Main-Patio
7	Tinytalk		*Relative Humidity* 0 > 95% RH Part No: TK-0302 (169163) / (156037)	Praetor chamber

Table 3: Data loggers and anemometers for recording air speeds

No.	Model	Image	Details	On Site location
1	DataTaker DT500 Series 3		DataTaker Pty Ltd Made in Australia S/N 37591	Praetor Chamber and Hall of Columns
2	DT500 Series 3		DataTaker Pty Ltd Made in Australia S/N 41106	Roof Top
3	Air velocity transducers Model:8455-300		TRI INC St. Paul MN USA S/N 00090408 REV: A UK contact BIRAL Tel. 01275847787	Praetor Chamber and Hall of Columns
4	Air velocity transducers Model:		TRI INC St. Paul MN USA S/N 00090408 REV: A	Roof Top

Table 4 Details of hand-held anemometer

Operating temperature	0 to +40 °C
Probe type	NTC
Measurement range	-50 to +250 °C
Accuracy	±1 °C (-10 to +99.9 °C)
Resolution	1°C (-19.9 to +150 °C), 1 °C (remaining range)

Calibration:

The data loggers were calibrated among themselves in order to establish the difference between the observation equipment. This was done by setting all the data loggers to record air temperatures and RH from one spot within the University of Nottingham premises. This was done before setting off for field work. A maximum temperature variation of 0.5K was observed among the instruments. The RH readings have shown a variation of between 1% and 3% among six data loggers (see fig.5). This is consistent with accuracy of ±3.0% at 25°C shown in manufacturer's data sheets.

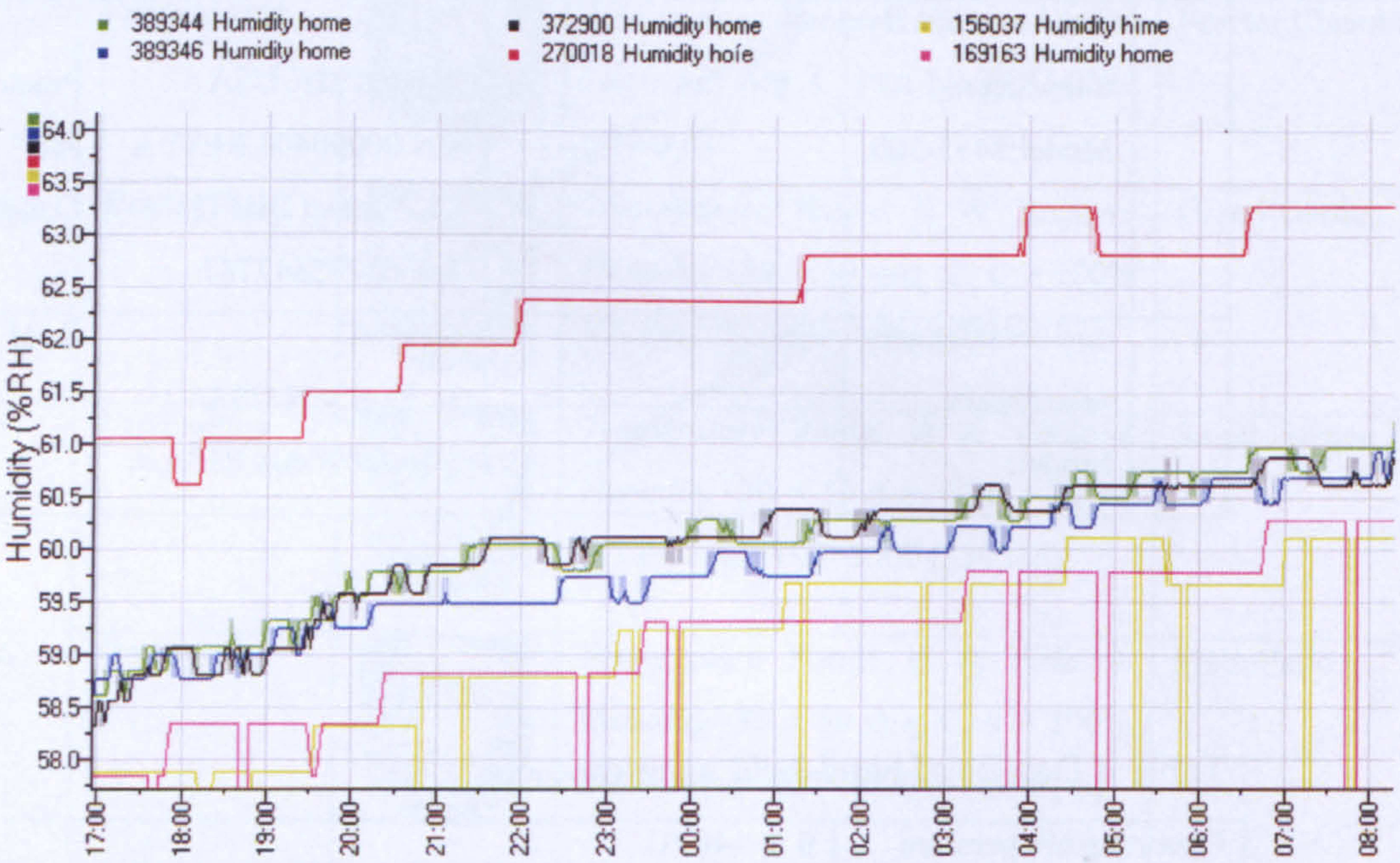

Fig.5 The overlay of relative humidity recordings from six data loggers