THE ARCHITECTURE OF NATURAL COOLING

SECOND EDITION

BRIAN FORD, ROSA SCHIANO-PHAN AND JUAN A. VALLEJO

ROUTLEDGE

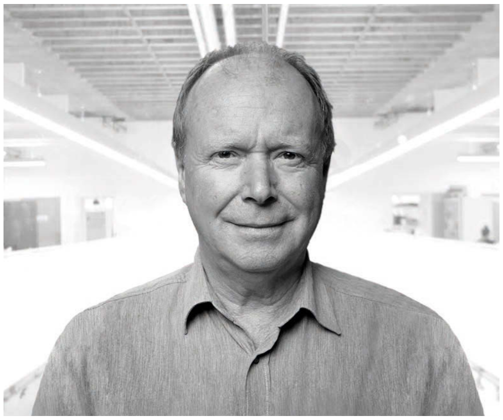
THE ARCHITECTURE OF
NATURAL COOLING

Overheating in buildings is commonplace. This book describes how we can keep cool without conventional air-conditioning: improving comfort and productivity while reducing energy costs and carbon emissions. It provides architects, engineers and policy makers with a 'how-to' guide to the application of natural cooling in new and existing buildings. It demonstrates, through reference to numerous examples, that natural cooling is viable in most climates around the world.

This completely revised and expanded second edition includes:

- An overview of natural cooling past and present.
- Guidance on the principles and strategies that can be adopted.
- A review of the applicability of different strategies.
- Explanation of simplified tools for performance assessment.
- A review of components and controls.
- A detailed evaluation of case studies from the USA, Europe, India and China.

This book is not just for the technical specialist, as it also provides a general grounding in how to avoid or minimise air-conditioning. Importantly, it demonstrates that understanding our environment, rather than fighting it, will help us to live sustainably in our rapidly warming world.



Brian Ford *(RIBA FRSA)* is an architect, an environmental design consultant and Emeritus Professor at the University of Nottingham. He was in private practice for over 25 years, including Peake Short & Partners and Short Ford Associates, where he has worked on innovative low carbon projects in Europe, USA, India, Australia and China. He initiated a series of multi-partner EU funded research projects on natural ventilation and passive cooling and has served as a member of the UK Government's Zero Carbon Task Force for Schools, an advisor to Building Green Futures (Bologna, Italy), and was until recently Vice-President of the International PLEA organisation.

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"Natural cooling is one of the most important aspects to tackle while designing, and surely one of the trickiest to master. Through a well-calibrated collection of theoretical principles and practical recommendations, all supported by a set of thoroughly analysed and presented case studies, this volume provides a reference book for the many professionals who, in response to global trends, are just approaching the matter, as well as for those in search for a deeper understanding of natural cooling principles and their possible practical applications."

Mario Cucinella
Architect, Hon FAIA, Int. Fellow RIBA
(Founder MCA Bologna and New York)

"This book brings together a uniquely comprehensive body of history, architectural science and contemporary practice that will stand as a primary source in the foreseeable future. The understanding of the specificity of climate lies at the heart of the book, serving as one of the foundations for natural cooling design. At the other pole of environmental design, human comfort is an essential parameter. Between these poles the book presents a systematic and comprehensive methodology for design that embraces precedent, science and technology."

Dean Hawkes
Emeritus Professor, Welsh School of Architecture
& Darwin College, Cambridge

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PART 2

PREFACE

Background

The construction industry is notoriously conservative and slow to change, and until recently, only the largest companies have engaged in research. However, concerns over global warming and the need for sustainable development have led to substantial investment (particularly in Europe) into the research and development of technologies and design approaches which will reduce our dependency on fossil fuels. The application of these techniques to building projects has spread around the world, in parallel with the research programmes, and is slowly becoming part of the mainstream, but there is a perceived knowledge and skills gap among construction professionals, which is seriously restricting further take-up. There is widespread understanding of the 'need', but a lack of widespread 'know how'. The transfer of knowledge from research into practice is therefore vital. But this is difficult in an industry which habitually dislikes change and which has traditionally undervalued research.

Over the last 30 years, developments in materials science, building energy technologies and design tools have been derived from a significant increase in research investment into energy efficiency in buildings. Major advances have been made in both our understanding and the application of bioclimatic design principles in buildings, and similar advances have been made in new and renewable energy devices, and their integration in buildings. Strategic thinking about these issues needs to be part of the early design process, and rigorous testing of options (using a wide range of analytic tools) is required in order to give clients the confidence to proceed with a radical solution. Not all projects can afford specialist testing and analysis, but simplified techniques exist, and this is where the *'know how'* really counts.

It is important for us to look at the scale of the task that faces us, in terms of reducing carbon emissions and their impact on global warming. Atmospheric carbon today constitutes approximately 410ppm (January 2019) compared with the pre-industrial concentration of 280ppm (pre 1850). Human activities are estimated to have already caused approximately 1.0°C of global warming above pre-industrial levels. It is clear that a radical reduction of global carbon emissions is necessary to avoid going above 1.5°C and the risks of catastrophic climate change. The IPCC's Special Report *(IPCC, 2018)* indicates that to limit global average rise to 1.5°C, global net anthropogenic CO_2 emissions must decline by about 45% from 2010 levels by 2030, reaching net zero around 2050.

The built environment has a huge impact on the level of emissions, and everyone has a part to play. For an energy strategy in buildings to be based on a combination of efficiency measures and the integration of renewables, both professional practice and education within the construction industry must change. The transfer of knowledge gained from recent research, into practice, must form part of this process. But in order for carbon emission targets to be achieved, gaps in knowledge and skills also need to be addressed among all who work in the industry. This book is intended as a contribution to this process.

The benefits of natural cooling

Global demand for cooling is increasing at a spectacular rate. In 2010–11 world sales of air-conditioning went up by 13% *(Cox, 2010)*. Data from 2016 indicates that in the USA 87% of all buildings are air-conditioned *(EIA, 2012)*, and that air-conditioning represents 42% of the peak demand for electrical power. Investment in renewables is increasing, but new fossil fuel power stations are still coming on stream every year, and demand side efficiencies have a huge contribution to make to reducing greenhouse gas emissions from air-conditioning.

Alternatives to conventional air-conditioning are needed urgently. The rise in demand for air-conditioning in the USA, and the current dependency on it, is unsustainable. While in Europe and the USA peak load demand for air-conditioning threatens to disrupt supply, in India, China, Africa and parts of the Middle-East supply disruption is a regular occurrence, forcing many large consumers to invest in expensive back-up generating equipment. Summer demand for power often outstrips supply, resulting in rationing and the closure of factories and offices. Additionally, the use of local generators impacts severely the air quality thus limiting the potential for natural ventilation and increasing the anthropogenic waste heat dumped in urbanised areas. Alternatives to conventional air-conditioning are therefore urgently required to reduce peak load demand for electricity, and thus reduce the risk of supply disruption. Since the alternatives also exploit ambient heat sinks and are inherently 'low carbon', they will also reduce the need for investment in supply infrastructure.

This book presents both the historical tradition and contemporary practice in the design and application of natural (passive) cooling solutions in different parts of the world. Historically, many different strategies and techniques have been used to promote passive cooling during extreme summer heat. Evaluation of the contemporary applicability of these cooling strategies in different climate zones has generated guidance for practitioners *(Givoni, 1994; Santamouris, 2007)*. Improved understanding of performance issues along with post occupancy evaluation of buildings has led to greater confidence in our ability to anticipate user needs, and to avoid some of the pitfalls. Technical developments have expanded the range of options and the range of building types in which passive cooling can be successfully applied.

It is now a viable alternative to conventional air-conditioning in many parts of the world and is beginning to enter the mainstream.

Concerns over global climate change, our dependency on fossil fuels, and the implications of 'peak oil' *(Hirsch et al., 2005)* are changing the way we view our use of mechanical air-conditioning. This change is no longer taking place at the margins. Policy makers and politicians are now joining academics, environmentalists and built-environment professionals, to promote improvements in building performance and alternatives to mechanical air-conditioning.

There is now a need to both improve building performance so that demand for cooling is reduced, and to develop cost competitive alternatives to conventional air-conditioning to meet the residual cooling need. In Europe, the EU Performance of Buildings Directive (EPBD) promotes the alignment (and improvement) of building performance regulations in member countries. This has led to a radical reduction in the need for heating and cooling in new buildings, although air-conditioning use is still increasing in new buildings. Also, demand for cooling continues to increase in relation to the existing building stock, and so viable alternatives to conventional air-conditioning have a major contribution to make. Elsewhere in the world, policies designed to reduce demand for cooling (through improved building performance) have become a priority, and in many situations natural cooling is providing the low-carbon design-based solutions required for our future.

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Part 2 describes the detailed application of natural cooling principles and strategies in a series of case study buildings which also explore performance in practice. The compilation of these case studies would not have been possible without the assistance of both the designers and facilities managers. We therefore wish to thank:

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COOLING WITHOUT AIR-CONDITIONING

As the world around us is changing, so too should architecture. Indeed, today, professionals find themselves at a major crossroad. At stake is the question of how we should engage with the available resources, while also pursuing comfort, health, beauty and innovation. The global lack of resources and climate change are, in fact, the fundamental design problems of our time. With buildings accounting for some 30% of both total global energy use and CO_2 emissions (according to the UN Global Status Report, 2015) and Europe planning to achieve, despite the alarming population-growth and urbanisation trends, an incredibly ambitious target of an 80% reduction in carbon emissions already by 2050 (Roadmap 2050, commissioned by the European Climate Foundation), architects cannot afford to improvise any longer.

In this compelling transition towards a low-carbon future, we are now absolutely forced to develop a radically new approach to architecture, thus minimising the use of energy-intensive technologies and reviving some low-tech solutions such as passive heating, cooling and, of course, ventilation. Such solutions can only be inspired and supported by a deeper knowledge and connection with the climate, the culture and the natural environment of a place. It is in this context that vernacular architecture, with people developing clever ways to address their needs and achieve protection and comfort from little or no available resources, can offer a reference that is worth mentioning. If Marco Polo could, to his surprise, enjoy an ice-cream during one of his travels to the Far East in the 13th century, thanks to a local construction typology able to store ice in the middle of the desert, we will probably, with the same surprise, constantly discover a wide array of passive local solutions able to effectively support and strengthen each of our design proposals and lead them towards their net-zero-energy goal. In other words, we are now chasing a sustainable future whose roots might still somehow lie in the past.

It is against this background, and given the possibilities offered by a more empathic relationship with the context in which they are called to take action, that professionals need to commit themselves to a deep paradigm shift, thus leading to an actual revolution in building design and construction. And to achieve this fundamental and urgent change, architects must acquire a better understanding of the principles of environmental design, while also developing a clear and systematic methodology allowing for their proper application at all design stages, from the very conceptual ones to advanced component design.

Natural cooling is definitely one of the most important aspects to tackle while designing (especially in hot climates) and surely one of the trickiest to master. Through a well-calibrated collection of theoretical principles and practical recommendations, all supported by a set of thoroughly analysed and presented case studies, this volume can therefore represent a reference book for the many professionals that, driven by the aforementioned global trends, are just approaching the matter, as well as for those in search for a deeper understanding of natural cooling principles and their possible practical applications.

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FOREWORD

01. Allegorical engraving of the Vitruvian primitive hut. Frontispiece of Marc-Antoine Laugier: Essai sur l'Architecture 2nd ed. 1755 by Charles Eisen (1720-1778).

The image of the *'Primitive Hut'*, the frontispiece of the Abbé Laugier's Essai sur l'architecture (1755) (fig. 01), beautifully represents one of the most fundamental purposes of the art of building, that is to provide shelter from the rigours and unpredictability of the natural environment. The transition from the unselfconscious building practices of the primitive to the self-conscious art of architecture was marked by the codification of the knowledge implicit in such buildings to allow it to be consciously applied to the design of buildings. In the western world, one of the first such codifications was Vitruvius' De architectura (The Ten Books on Architecture) *(Vitruvius, 1960)*. Written in the first century BC, this provided guidelines for the design of buildings for the wide range of climates embraced by the geographical span of the Roman Empire, from the chill, northerly latitudes of the British Isles to the warmth of the Mediterranean. In Book VI, Vitruvius directly addressed the relation of climate and building.

> *In the north houses should be entirely roofed over and sheltered as much as possible, not in the open, though having a warm exposure. But on the other hand, where the force of the sun is great in the southern countries that suffer from heat, houses must be put more in the open and*

with a northern or north-western exposure. Thus, we may amend by 'art' what nature, if left to herself, would mar.

Some thirty years ago I derived from De architectura a 'Vitruvian tri-partite model of environmental design' in which the environmental function of architecture is, as with the Primitive Hut, to mediate between, on the one hand, climate and, on the other, a notion of comfort *(Hawkes, 1996)*. In setting out such clear and well-founded principles for design, Vitruvius' *'art'* is the distant and distinguished antecedent of the methods of modern architectural science. In the twenty-first century the relationship between climate and architecture has acquired new and significant relevance as, in response to global environmental challenges, we seek to make buildings that achieve a new and necessarily more harmonious partnership with the natural environment. The present book stands as an important contribution to this growing and significant line of environmental theory and practice.

To establish the background, let's paraphrase the history of environmental design in architecture. For almost two millennia, from Vitruvius up to the end of the eighteenth century, the environmental, sheltering function of architecture was achieved, in all climates, by the organisation of the form and material of the building enclosure in relation to the conditions of climate. In The Architecture of the Well-tempered Environment *(Banham, 1969)*, Rayner Banham proposed a taxonomy of historical modes of *'environmental management'*, the *'conservative'* and the *'selective'*, that were defined by their relations of material and form to climate. In defining a third *'mode'*, the *'regenerative'*, Banham recognised the transformation that occurred at the end of the eighteenth century, with the innovations of new technologies for heating and ventilating and then of artificial lighting that came with the industrial revolution in Europe. Now buildings became less intimately connected to the natural environment as they could be warmed on cold days and lit after dark. In the twentieth century, after mechanical cooling systems were developed, it became possible to make the interiors of buildings cool in the hottest of climates. In a Darwinian process of architectural evolution, the new technologies were, for the whole of the nineteenth century and for the first decades of the twentieth, applied to buildings that were, in their fundamental conception, *'pre-mechanical'*, with their form still influenced by the requirements of natural illumination and, often, of natural ventilation. In other words, these buildings remained connected to the natural environment in which they were placed. But, at some point in the middle years of the twentieth century, the balance shifted, and buildings became deeper in plan and their enclosing envelopes, often diaphanous glass skins, became sealed as mechanical cooling and ventilation and artificial lighting provided all the elements of their internal environment. Technology had transcended nature. This strategy soon became universal and cities on all continents, with their clusters of glass skyscrapers in diverse climates, became almost indistinguishable one from another.

Since the middle of the twentieth century an alternative line of environmental thought has emerged in architecture. One of the first and most comprehensive expressions of this was Victor Olgyay's book, Design with Climate *(Olgyay, 1963)*. The title, with its emphasis on designing with not against climate, stands in clear distinction from the predominant, mechanically dominated approach of conventional practice. In addition, the book was one of the earliest expressions of the idea of regionalism in architectural discourse, predating by twenty years Kenneth Frampton's seminal essay on the subject *(Frampton, 1983)*. Here was a view of architecture working in harmony with nature and responsive to the challenges and opportunities of place, of each unique climate, to make buildings fit for the complex needs of modern society. In the half century since the publication of Olgyay's book, the idea of passive environmental design has gained wide support in both theory and practice, and there is now an extensive literature in the field that embraces a vast body of new research and practice that is applied to buildings of all types and in all climates.

It is against this background that the present book takes its place. In the array of passive possibilities in architecture the potential of passive cooling is particularly important. As the book shows, this is one of the oldest means of achieving comfort in buildings in hot places, with precedents from at least the thirteenth century in the Middle East, and there is a continuous history of its application in buildings of diverse function down to the present day. The authors have a distinguished record in the field, both as scholars and practitioners. In this book, they bring together a uniquely comprehensive body of history, architectural science and contemporary practice that will stand as a primary source in the foreseeable future. As with both Vitruvius and Olgyay, the understanding of the specificity of climate lies at the heart of the book, with climates as diverse as those of Europe, China and the USA, and the immense variations within these territories, serving as one of the objective foundations for natural cooling design. At the other pole of environmental design, human comfort is once again an essential parameter. Between these poles the book presents a systematic and comprehensive methodology for design that embraces precedent, science and technology. All this is reinforced by the six detailed Case Studies, gathered from around the globe, that illustrate the process by which theory becomes form, the final and most persuasive test.

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PART 1

CHAPTER 1
ORIGINS AND OPPORTUNITIES

The natural cooling of buildings developed empirically over many centuries, based on an understanding of seasonal and diurnal changes in the local climate, and through a process of trial and error, to provide relief from the extreme heat of summer. Different techniques developed in response to local conditions, often reflecting a profound understanding of the local environment. Anecdotal evidence of how these buildings worked has been available for many years, but it is only recently that significant research has contributed to a more detailed understanding worldwide. This increased interest in the origins of climate-responsive architecture is reflected in the many journal papers on this tradition, in the annual PLEA Conferences, and in recent books *(see Weber & Yannas, 2014; and Hawkes, 2012)*. This research is not just of academic interest, as the move to a low carbon future is now a major driver among design professionals globally. Many buildings now demonstrate that a 'climate aware' approach to design is both practical and cost effective. At the very least it can reduce dependency on mechanical air-conditioning, and in many locations can be completely avoided.

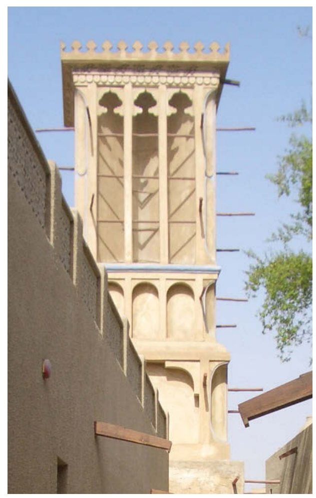
1.1. ORIGINS

The tradition of 'Natural Cooling', which incorporates a range of design responses to climate, has its origins in Egypt, where frescoes from the 13th century BC (fig. 01) depict buildings with a '*malqaf*' (traditional windcatcher) used to help ventilate and cool the interior (figs 02–03) *(Fathy, 1986)*. This approach subsequently spread eastwards as part of the Islamic tradition through the Middle East and Iran to north India (with the Moghul empire), and westwards across North Africa to southern Spain with the Moors.

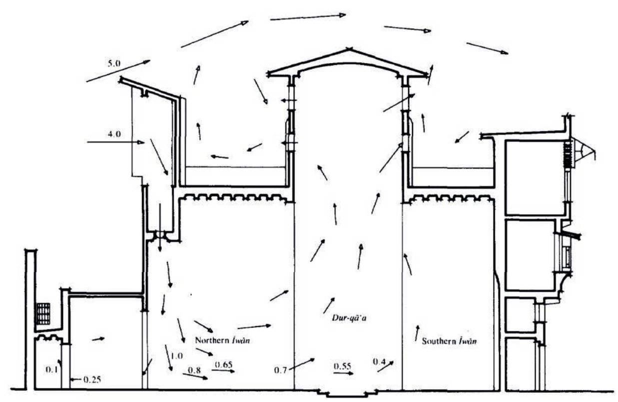
This tradition, which has been largely overlooked, is characterised by dramatic achievements. Travelling through the Iranian desert on his journey to China in the 13th century AD, Marco Polo commented on his being offered fruit flavoured water-ices to relieve the summer heat. The creation and storage of ice in the desert was made possible at the time through the construction of huge natural refrigerators. These typically consisted of a shallow pool, protected and shaded on its south side by a huge earth brick wall, and connected to a domed ice storage pit (figs 04–05). These shallow pools were provided with water from man-made underground water conduits '*qanat*' bringing water sometimes hundreds of miles from surrounding mountains to the desert '*caravanserai*' along the silk-route to China *(Beazley & Harverson,1986)*.

Under the clear night sky of the desert, long wave radiation from ground to sky causes surface temperatures to drop low enough to

01. Wall painting from the tomb of Nebamun. Egyptian Dynasty 18, about 1475 BC.

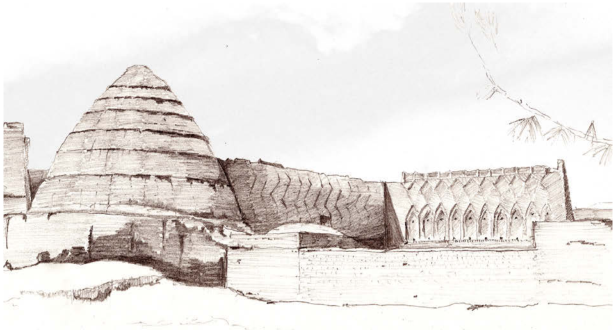


02. Traditional windcatcher *malqaf*, Dubai.

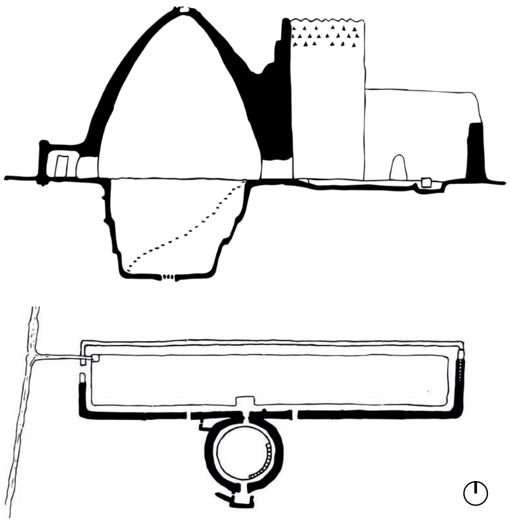


03. Section through the Qã'a of Muhib Ad-Din Ash-Shãf'i Al-Muwaqqi, showing how the malqaf and wind-escape produce internal air movement. All wind and airspeeds are given in metres per second.

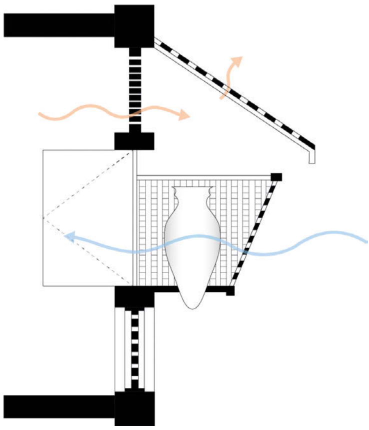
04



05



04. General view of the Ice House in Yazd, Iran.
05. Section and plan of the Ice House in Yazd, Iran.



06. Porous ceramic cooling window in Muscat, Oman.

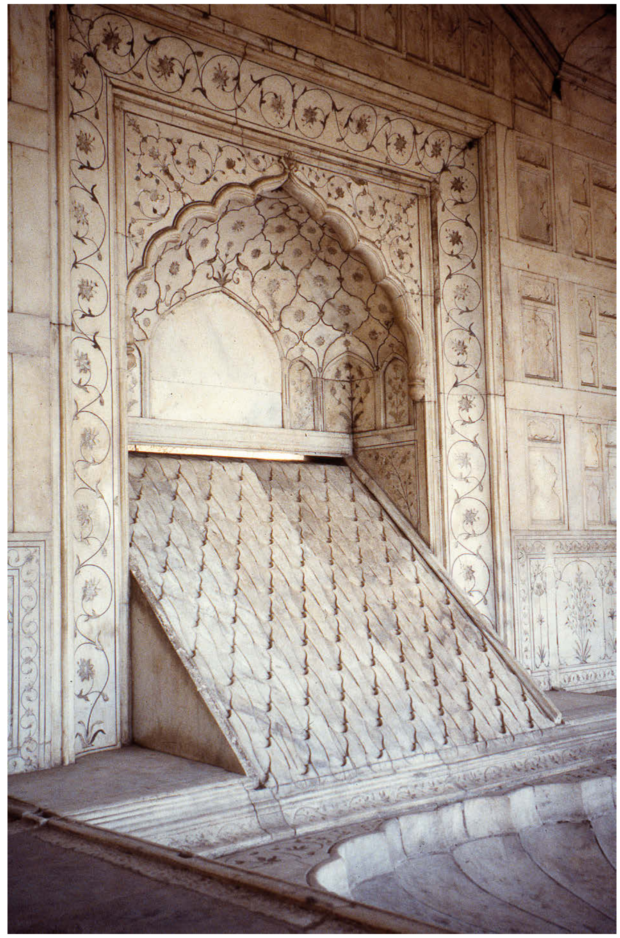
freeze a thin layer of water, introduced to the shallow pool from the *qanat*. On successive nights the depth of ice built up until it was about 300mm thick. The ice was then cut up and stored below ground level in a massive domed ice house. The temperature of the surrounding walls of the ice pit, although several degrees above freezing, were low enough and sufficiently stable to store the ice for many months. In this way, the extremes of the environment were turned to the advantage of the people living there. This reflects an attitude of respect and symbiosis between people and their environment, working with it rather than against it, to enhance the quality of their lives.

UNDER THE CLEAR NIGHT SKY OF THE DESERT, LONG WAVE RADIATION FROM GROUND TO SKY CAUSES SURFACE TEMPERATURES TO DROP

This understanding is elaborated further in a long tradition in the Middle East of using various techniques to encourage air movement and natural cooling both within and between buildings. Water jars mounted in specially designed window openings in Muscat, Oman (fig. 06), cool the air passing over them into the room by the process of evaporation, at the same time keeping the water at a stable temperature. These windows have a sophisticated design which simultaneously allowed for shading, through the external shading, control of the evaporative cooling effect, through the internal shutters and stack ventilation, through the low and high level openings. In a similar manner, woven '*khus*' matting suspended over window and door openings are still commonly used in parts of northern India. *Khus* mats are made from the root of a plant from the Jasmin family, and add a delightful fragrance to the air as it passes into the interior.

Passive cooling and ventilation of buildings in Iran, incorporating wind catchers, porous water pots and '*salsabil*' (figs 07–08), have been widely applied and very effective for several centuries. In this tradition, wind-catchers guide outside air over water-filled porous pots, inducing evaporation and bringing about a significant drop in temperature before the air enters the interior. Hassan Fathy was also aware of this tradition in Egypt, adapting, developing and re-applying these techniques to cool and ventilate schools and housing projects *(Fathy, 1986)*. In a field study which Fathy describes, on measurements of temperature and air velocity within a house with '*malqafs*', the pattern of airflow and the benefits of enhancing air movement within the building are illustrated.

The movement of cool air between adjacent courtyards is remarked upon by Fathy, who refers to the tradition of promoting natural convection between adjacent courtyards having different hygro-thermal properties. This strategy was so effective that a pavilion placed between the two courtyards became a highly desirable location during the heat of the summer day. This space was known as '*taktabus*' in Arabic and as '*tablinum*' in the Roman tradition. This natural cooling strategy is embodied in many residences across the southern Mediterranean and north



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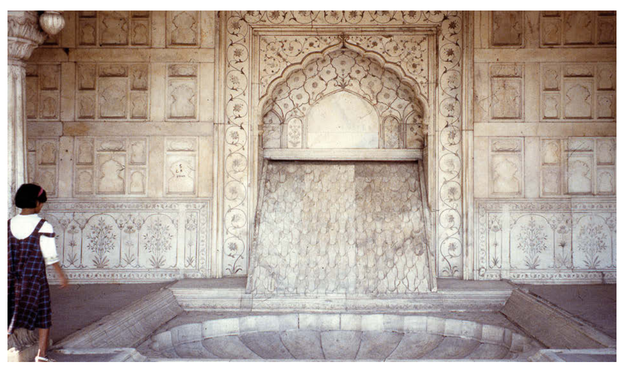

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07. Sloping *salsabil* in Red Fort, Delhi, India.
08. Salsabil and lotus pool in Red Fort, Delhi, India.

Africa from the 5th century BC to the present day.

In Seville in southern Spain, a sixteenth century house, the Casa de Pilatos, incorporates this strategy within its design (figs 09–10). Seville (latitude 37°N) experiences mild winters and hot dry summers (mean max air temperature of 37°C in July, with relative humidity of 35%). The Casa de Pilatos is a mixture of Italian Renaissance and the Spanish '*Mudéjar*' tradition *(Irwin, 2004)*. Mudéjar was the term given to the architecture which (after the Moors had been ejected) had inherited Islamic features.

A PAVILION PLACED BETWEEN THE TWO COURTYARDS BECAME A HIGHLY DESIRABLE LOCATION DURING THE HEAT OF THE SUMMER DAY

From the outer court, the visitor passes through a protected arrival gateway into the central formal paved courtyard, around which the building is organised. The whole courtyard is paved, and the visitor naturally keeps to the shade of the cloisters, lined with beautiful tiles '*azulelos*'. Glimpses of green are obtained through grilled openings '*rejas*' in the narrow rooms surrounding the courtyard, and on entering, the cool of the interior provides relief and where window seats invite a moment of rest to view the adjacent courtyard, full of an almost tropical greenery: palms, citrus trees, flowers and a central fountain (figs 11–12). The seated visitor feels a gentle cooling breeze across face and arms, as air moves from the cool green courtyard to the central paved courtyard. The movement of air and the cooling it induces is not just a happy accident. The building has been designed to exploit this phenomenon.

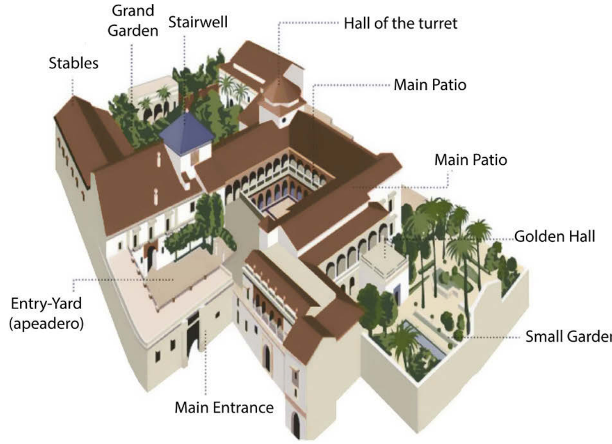
The central courtyard, being entirely paved, and with no greenery at all, was heating up under the burning sun (the surface temperature of the sunlit paving could reach 50°C+). This caused a plume of warm air to rise from the central courtyard, pulling fresh air from the significantly cooler green courtyards on either side, through the openings in the narrow ground floor rooms, and providing relief to the occupants in the process. Due to the thermal capacity of the paving in the courtyard, this effect would continue through the night as well. The variable influence of the wind would be minimised due to the central urban location of this house, so it is highly likely that these localised thermal differences in temperature would dominate in driving air through the building.

It is evident from the layout of the house that the ground floor rooms were occupied during the summer, and the family moved up to the first floor in winter, to occupy south facing rooms overlooking the gardens. This '*nomadic*' adaptation to the changing seasons has been common in many cultures, to cope with the extremes of climate.

The Casa de Pilatos raises many questions: was this natural cooling strategy reliable? Did it result in significant cooling of the building interior? How did it respond to changing conditions of wind and sun? Research has demonstrated that the strategy was reliable in providing thermal comfort for the building's occupants, and in achieving significant cooling *(Ernest, 2011)*. The research has shown that the airflow pattern and the convective cooling achieved are driven by the thermal differences between the courtyards, and there is little correlation with wind speed or direction, demonstrating that the strategy is robust under varying environmental conditions *(Ernest & Ford, 2012)*. The controlled grilled openings' size, the scale and proportion of the spaces and the careful integration of different techniques such as shading, evapotranspiration and thermal mass all contribute to the successful cooling of this building in summer.

In north India the Mughal palaces and gardens exploited evaporative cooling to provide thermal relief and to delight the senses. Thin water chutes '*salsabil*' and other evaporative cooling techniques were features of Mughal architecture from the 13th to the 17th centuries. The intense dry heat and dust of the summer in north India calls for the creation of an internal 'refuge' or haven from the extremes of the external world. The diurnal swing in temperature is '*dampened*' by the mass of stone and earth, and the air is further cooled by the evaporation of water in the ventilation airflow path. The coolness of their interiors and the use of evaporative cooling has been widely commented on, but it was only relatively recently that measurement of conditions within these buildings was undertaken *(Ford & Hewitt, 1996)*. Results of measurements in a number of step wells, well-houses '*baoli*' and bath houses '*hammams*' reveal that they were very suc-

09



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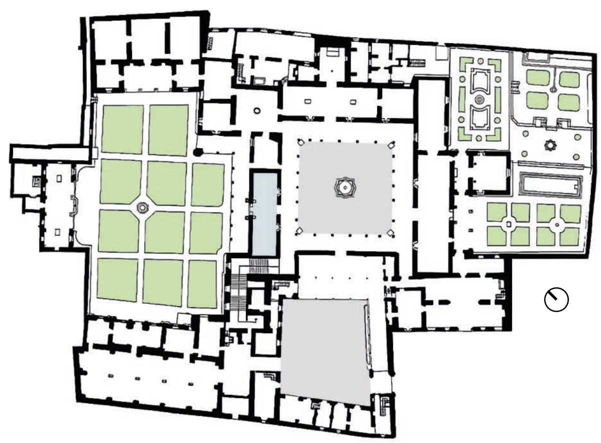

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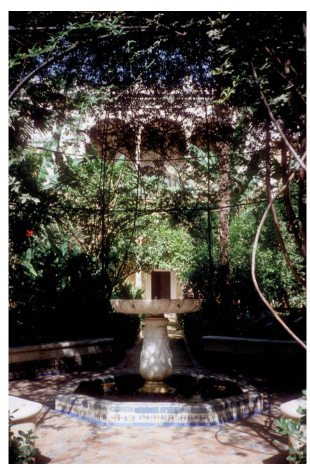

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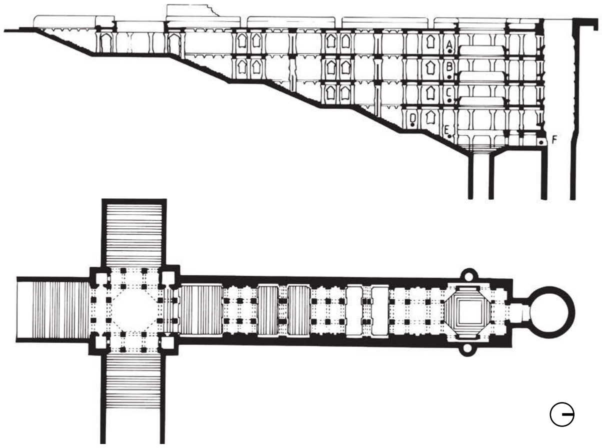
09. 3D view of Casa de Pilatos, Seville, Spain.
10. Floor plan of Casa de Pilatos.
11. Green courtyard in Casa Pilatos.
12. Window seat next to open grille in Casa Pilatos.



13. Plan and section of Adalaj Step Well, Gujarat, India.

cessful in providing shelter from the extremes of summer heat.

The '*step well*', which can still be found very widely in Gujarat and Rajasthan, was constructed as a source of water, a shrine, and a meeting place and retreat in the hot season. Usually strictly aligned on a north-south axis, the structure consists of a series of broad flights of steps and covered platforms leading down to the water. In contrast, the '*well-house*' consists of a group of retreat rooms arranged around the well shaft, and sometimes on a number of levels. The '*bath house*', imported by the Moghuls from Persia and comprising a series of interlinked chambers, is usually set above ground but constructed from massive stone or earth brick walls supporting vaulted '*double*' roofs.

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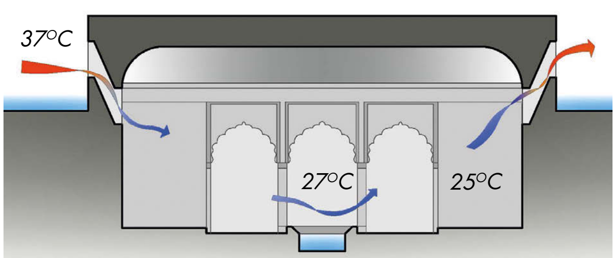

14. Rai Praveen Mahal, Summer Room.
15. Section of Summer Room, Rai Praveen Mahal.

The main staircase of the Adalaj step well is over 70 metres long, falling in five flights to a depth of 20 metres below ground (fig. 13). At each level a pavilion structure provides bracing to the retaining walls of the staircase, as well as cool retreats and meeting places, becoming progressively cooler as you descend. Measurements made in April 1995 showed a progressive lowering of the air temperature from ground level (35°C) to the lowest level (23°C), and progressive increase in absolute humidity (2.8gr/kg above external). Within thermally massive structures coupled to the earth (which also have low air change rates), one can expect stable air temperatures close to the annual mean external air temperature. However, in this case the very low air temperature (4 degrees below the annual mean) reflects the additional effect of evaporative cooling. The porous stone walls of the well act like a wick in drawing up water which then evaporates, absorbing the latent heat in the water and thus reducing the air temperature while raising the internal absolute humidity. The Adalaj step well has been providing a cool retreat for locals and travellers for over 500 years, and continues to do so today.

The design strategy of combining high thermal capacity with evaporatively cooled air was adopted in many Mughal era buildings, and is exemplified perfectly in the beautifully atmospheric summer room in the Rai Praveen Mahal in Orchha, Madhya Pradesh *(Ford & Hewitt, 1996)*.

WITHIN THERMALLY MASSIVE STRUCTURES COUPLED TO THE EARTH ONE CAN EXPECT STABLE AIR TEMPERATURES CLOSE TO THE ANNUAL MEAN EXTERNAL AIR TEMPERATURE

Orchha (latitude 25°N) experiences a composite climate and summers (from March to June) are extremely hot (daily max 45°C+) and dry (below 20% relative humidity).

Built towards the end of the 16th century, the main rooms in the house look north over an orchard and garden. On the north side, underneath a raised terrace, is a room partially sunk into the ground and flanked by two large open water tanks. As the visitor descends into this elegant room, the relief from the intense summer heat and the peace and tranquillity of the space leave a deep impression. Although the pools are empty now, the original intention of the architect is still clear: small openings on each side of the space with deep reveals to prevent solar gains encourage the movement of evaporatively cooled air across the space (figs 14–15). Even without water, spot measurements at mid-day in August revealed a 10°C difference between inside air temperature and outside in the shade *(Ford & Hewitt, 1996)*. The presence of the water pools would have induced evaporative cooling of the airstream and made this room comfortable in the most extreme heat of summer. The form and architectural expression of these buildings derived from the need to respond to the cultural and climatic context while creating a habitable and comfortable environment in what were often extreme conditions.

In comparison with the hot dry summer conditions of north-west India, the warm humid summer conditions of south-west China prompted another response to promote convective cooling. The fishing village of Zhouzhuang (latitude 31°N) is located at the junction of two large lakes (Baixian & Beibai) about 30km south-east of Souzhou, and west of Shanghai. The region experiences cold winters (mean minimum January air temperatures of 1°C), while summers are warm and humid (mean max 32°C in July with absolute humidity of 20g/kg). The settlement grew around a network of natural and man-made waterways, and many of the buildings within the old town date back to the Ming Dynasty *(Lau et al., 2014)*.

The entrance to Zhang's house faces almost due west, adjacent to a landing stage from the canal. It is the house of a wealthy