THERMAL COMFORT IN THE HAVELIS OF JAISALMER – A STUDY OF THE THERMAL PERFORMANCE OF AN URBAN COURTYARD HOUSE.

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ABSTRACT

This thesis provides a detailed case study of the havelis of Jaisalmer, Rajasthan. Jaisalmer was selected as the study area not only because of the abundance and richness of the havelis in this region, but also because of the extreme nature of the climate in and around the area. In addition, the haveli has the added advantage of being a high-density urban form; economically and ecologically significant in the context of India's rapidly expanding urban population and associated energy and environmental crisis. Environmental data was collected in and around two havelis within the fort, over a period of twelve months, focusing on the larger of the two monitored buildings, Hotel Suraj. In addition a short transverse comfort survey was conducted on the streets of Jaisalmer, and subsequently evaluated in the wider context of accepted adaptive model comfort prediction equations. The results of the survey are applied to the assessment of the collected environmental data, in terms of predicted occupant thermal comfort. The relationship between indoor and outdoor temperature is examined in detail and an attempt made to develop indoor temperature prediction equations for each of four long term monitored zones in Hotel Suraj. With all results revealing mass as the governing factor for the modification of climate in the havelis, a substantial portion of this thesis is subsequently focused on developing methodologies for determining the decrement factor and time lag of indoor zones in relation to outdoors. A new finding is the impossibility of a shift in daily temperature cycle of more than 6 hours (or 0.25 of the cycle frequency). Considerable effort has been expended on the visual presentation of data for this study. This has involved the development of two stand-alone computer programs for the presentation of thermal data, included on the CD at the end of this thesis.
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and absorb other cultures, resulting in a history in which no single empire has dominated for long periods. India's most ancient civilisation dates from 5000 years ago, and is known as the Indus Valley civilisation. Since the first invasion by the Aryans of the north in about 1500BC (Sterlin, H. et. al., 1990), India has been invaded by a succession of powers including the Persians, Greeks, Turks and Mongols. In 1610AD the British invaded India, remaining rulers for over three hundred years, and eventually dominating the entire sub-continent. The British viewed India as a profitable source of raw material, and it is estimated that more than 50% of this population will be, by the end of this century, living in cities (Tombazis, 1995). Within the span time of a generation we built the equivalent of what has been built on this earth from the beginning of history (Tombazis, 1995). Clients are increasingly seeking 'low energy' buildings, not only for economic, but moral reasons. This was emphasised by Humphreys in 1992: "Now that it seems at least probable that the carbon dioxide we are generating is producing a warming of the earth, it seems to me that the reduction of the burning of fossil fuels is no longer just economically desirable, but perhaps a matter of survival for substantial numbers of the world's population. We should leave the world in a reasonable condition for the next generation, if it is within our power to do so." And succinctly by Tombazis in 1995: "From the ethical point of view we have come to accept that we cannot continue living and inheriting from our forefathers, whilst borrowing and mortgaging the future of our children."

1.2. India's history. India's location and geography is such that it has always been an invader's paradise. At the same time its natural isolation, large size and indigenous religions has allowed it to adapt to the manual collection of data. This could not have been achieved without the backing of Ashok Lall at the TVB School and Nick Weaver at UEL. The Vyas family generously gave hospitality and time, and graciously suffered my intrusions into their homes. Many friends and family have patiently borne the side effects of thesis writing, and their continued support has been enormously sustaining. In particular Ric Irvine who endured several months of the hot, dry season in Jaisalmer, and took many of the enclosed photographs. Audrey Jones and Jenny Norwood, who persisted with attempts at contact despite my seeming disinterest, and Dr. Debra Bekarian, who not only offered enthusiasm and support, but also spent several sleepless nights printing these final drafts. My father, Eric Matthews deserves a special mention for his encouragement and kindness throughout. Finally I would like to thank David Woodhouse of the Quality Assurance Department of the University of East London for his relentless "troubleshooting".

1.3. India today. Today India is the second most populous country in the world with an estimated annual growth rate of around 1.7% in 1996. Currently estimated at 950 million, India's population is expected to reach 1.15 billion by 2010 (Energy Information Administration, 1999). This rapidly growing population, along with increased economic development, has placed a strain on India's infrastructure, and ultimately on the country's environment. According to the World Health Organisation, New Delhi is one of the top ten most polluted cities in the world. India's electricity is generated overwhelmingly by coal (70 percent). Increased coal consumption over the past four decades has led to a nine-fold increase in energy related carbon emissions. Of the increase in the concentration of greenhouse gases is attributed to human activity, and an increasing component of this fraction result from the expanding demand for electricity for air-conditioning. Of the present total world energy consumption, 45% is used in heating, cooling and lighting of buildings, and a further 5% in building construction (Rigg et al., 1995), making building energy consumption the largest single global energy use sector. It is also that with the greatest, and easiest, potential for conservation. It is possible to achieve reductions of 50 – 70% by using known and tested concepts of passive, climatically adapted building design for new buildings (Rigg et al., 1995). The savings achieved by retrofitting and adapting existing buildings are much smaller. The world population has grown from some 3.8 to 5.2 billion in the past 20 years, and it is estimated that more than 50% of this population will be, by the end of this century, living in cities (Tombazis, 1995). Within the span time of a generation we built the equivalent of what has been built on this earth from the beginning of history (Tombazis, 1995). Clients are increasingly seeking 'low energy' buildings, not only for economic, but moral reasons. This was emphasised by Humphreys in 1992: "Now that it seems at least probable that the carbon dioxide we are generating is producing a warming of the earth, it seems to me that the reduction of the burning of fossil fuels is no longer just economically desirable, but perhaps a matter of survival for substantial numbers of the world's population. We should leave the world in a reasonable condition for the next generation, if it is within our power to do so." And succinctly by Tombazis in 1995: "From the ethical point of view we have come to accept that we cannot continue living and inheriting from our forefathers, whilst borrowing and mortgaging the future of our children."

1.1. Global concerns There is now a consensus amongst meteorologists and climate modellers that increasing atmospheric concentrations of carbon dioxide and other "greenhouse gases" will lead to significant changes in the climate of the world (Houghton et al., 1990). A large fraction of the increase in the concentration of greenhouse gases is attributed to human activity, and an increasing component of this fraction result from the expanding demand for electricity for air-conditioning. Of the present total world energy consumption, 45% is used in heating, cooling and lighting of buildings, and a further 5% in building construction (Rigg et al., 1995), making building energy consumption the largest single global energy use sector. It is also that with the greatest, and easiest, potential for conservation. It is possible to achieve reductions of 50 – 70% by using known and tested concepts of passive, climatically adapted building design for new buildings (Rigg et al., 1995). The savings achieved by retrofitting and adapting existing buildings are much smaller. The world population has grown from some 3.8 to 5.2 billion in the past 20 years, and it is estimated that more than 50% of this population will be, by the end of this century, living in cities (Tombazis, 1995). Within the span time of a generation we built the equivalent of what has been built on this earth from the beginning of history (Tombazis, 1995). Clients are increasingly seeking 'low energy' buildings, not only for economic, but moral reasons. This was emphasised by Humphreys in 1992: "Now that it seems at least probable that the carbon dioxide we are generating is producing a warming of the earth, it seems to me that the reduction of the burning of fossil fuels is no longer just economically desirable, but perhaps a matter of survival for substantial numbers of the world's population. We should leave the world in a reasonable condition for the next generation, if it is within our power to do so." And succinctly by Tombazis in 1995: "From the ethical point of view we have come to accept that we cannot continue living and inheriting from our forefathers, whilst borrowing and mortgaging the future of our children."
WHilst India’s per capita energy use and carbon emissions are lower than the world average, because of the country’s large population and heavy reliance on coal they result in a substantial percentage of the world energy use and carbon emissions. India faces great challenges in energy and environmental issues as it enters the 21st Century. A rapidly growing population and increased urbanisation will continue to increase demands for electricity generation. Whilst only a small fraction of India’s energy budget is currently used for air-conditioning, there is, nonetheless, an increasing tendency for the use of mechanical cooling in offices and homes in urban areas. Even more serious is the increasing use of building designs that will be comfortable only when air-conditioned, even in developments where, due to economic and infrastructure restraints, air

<table>
<thead>
<tr>
<th>Country</th>
<th>Per Capita Energy Use</th>
<th>CO2 Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>India</td>
<td>34.8</td>
<td>155.8</td>
</tr>
<tr>
<td>USA</td>
<td>121.7</td>
<td>148.1</td>
</tr>
<tr>
<td>China</td>
<td>935.7</td>
<td>94.9</td>
</tr>
<tr>
<td>Russia</td>
<td>26.8</td>
<td>31.5</td>
</tr>
<tr>
<td>Japan</td>
<td>3.8</td>
<td>8.0</td>
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*Urban population only **For all of the former Soviet Union.

Tbl. 1.1. India in a world context: 1995. (Energy Information Administration, 1999)
1.4 Traditional versus modern. It is nowadays widely recognised by architects and urbanists that traditional, regional architecture is generally climatically well adapted (Bowen, 1981; Heschong, 1990), and that the courtyard house, in particular, is well suited to the hot desert climate (Fathy, 1986; Karaman et al., 1981; Moore, 1983; Oliver, 1987; Talib, 1984). The principles of good thermal design used in such houses are equally valid today, and it should be possible for modern designers to incorporate these design principles in buildings suitable for modern living, thus conserving energy and providing better thermal comfort. However, most of the writings on regional architecture are based on scientific intuition, describing simple ideas, but inadequate as accurate guides for design. Per-Olof et al. (1985) confirm this view when discussing vernacular architecture in hot climates: "Local building traditions are a result of long periods of development which have often led to good solutions. Through experience a certain amount of knowledge, which cannot be understood or dealt with mathematically has been acquired. Because of our ignorance of the knowledge thus acquired there is a risk that we disregard factors that are of great importance! More recently research has begun to question the role of the courtyard in desert climates, and the high re-radiation levels recorded in smaller courtyards in very hot climates are coming under particular investigation (Danby, 1986; Hanna, 1991; Roaf, 1990). That the haveli form is climatically well adapted to this part of India is not doubted (Prasad 1988). In addition the haveli has the added advantage of being a high-density urban building form. Despite this, recent research has also shown that there is a current cultural trend for higher income families in northern India to prefer the lifestyle afforded by the suburban villa type of house (Prasad, 1987). The task of the modern architect is quite different from the indigenous house builder, and the kind of behavioural change that have taken place over the last fifty years are irreversible. However the principles of thermal design used in such buildings are particularly relevant today, in light of current environmental and financial pressures.

1.5 Aims It is with this background of rapidly expanding urban population and associated energy and environmental crisis, coupled with the currently unfashionable image of Indian vernacular architecture (with the indigenous population) that the author has studied the elaborate courtyard houses of Jaisalmer with the following aims. To accurately survey two havelis within the fort of Jaisalmer, in order to provide an exact record of mass, volume and construction.

To monitor temperature and humidity in several locations within the havelis over a twelve month period.

To measure air movement and surface temperatures in several locations within the haveli over a short period of time.

To relate recorded indoor temperatures to predicted human thermal comfort sensation.

To investigate and develop new approaches to the presentation of thermal building data in a style useful to architects and students of architecture.

To analyse the data collected with the intention of promoting an understanding of the way indoor temperature varies in relation to outdoor temperature and the attributes of the building in the hot, dry, desert climate of Jaisalmer.

1.6 Form of thesis The following chapter, chapter 2, sets the context for the havelis studied. The geography, climate and history of the living fortress of Jaisalmer are described and illustrated. The case studies, two medium sized havelis and a smaller courtyard house, are then introduced in chapter 3. Plans, sections and elevations of both havelis are shown along with limited drawings of the courtyard house. Chapter 4 details the method and equipment used for the collection of environmental data in and around both havelis. The recorded data is illustrated and basic statistics calculated. Chapter 5 gives an introduction to the science of thermal comfort, describing climate chamber and field study methods of prediction. A comfort survey conducted in Jaisalmer is analysed, and evaluated in the wider context of accepted adaptive model comfort prediction equations. The results are applied to the assessment of the data detailed in the previous chapter in terms of predicted occupant comfort level.

Chapter 6 discusses the problems associated with presenting large amounts of data, particularly if collected in many locations over long periods of time. The concept of temperatures represented as colours is explored and a temperature spectrum is proposed. A stand-alone computer program is developed and discussed. These principles are extended to develop a second stand-alone computer program designed to predict and present thermal comfort sensation levels. Chapter 7 examines the indoor temperature trends over a twelve-month period in the largest of the havelis. The relationship between indoor and outdoor recorded temperature, and indoor and outdoor recorded daily range is investigated and indoor temperature prediction equations for each of the monitored zones are proposed. Chapter 8 introduces the science of heat transmission under non-steady state conditions. It details two methodologies developed by the author with the intention of determining time lag between indoor and outdoor monitored temperature. Following the review of both methodologies the decrement factors of the internal spaces are examined in detail. Chapter 9 draws together the various strands spun in earlier chapters and makes suggestions for areas where further research is needed.

CHAPTER 2 JAIASLHER

Chapter 2 gives a comprehensive description of the living fortress town of Jaisalmer and its surrounding region. Location, topography, climate and history are detailed, illustrating the context in which the havelis of the fort were built.

2.1 Jaisalmer - Geography Ghoda kije kath ka, pind kije pashad Bakhatar kije loh ka, tab dekho Jaisan {A house of wood, legs of stone, a frame of iron will get you to Jaisalmer alone} Agarawala, 1979 Jaisalmer is situated towards the western portion of the Thar or Indian desert in Rajasthan, at latitude 26°54' N and longitude 70°55' E. The town is about 550 miles away from Delhi, 180 miles from Jodhpur, and 50 miles from the Pakistan border.

2.2 Jaisalmer - Climate Within India it is possible to define six regions with distinct climates as shown in ill. 2.3 (Krishan, 1995). The six climates are normally designated as hot/dry; warm/humid; moderate; cold/cloudy; cold/sunny and composite. Jaisalmer falls at the more extreme end of the hot/dry climate, within which can be identified four different seasons, pre-monsoon, monsoon, post-monsoon and winter.

2.3. Climatic zones of India (Krishan, 1995)

Ill. 2.1 Map of India showing location of Jaisalmer (utexas, 1997)

The surrounding region is rocky and barren, relieved by sparse, scrubby weeds, but no trees. In the western extremes of the state, around the Sam area, the land is more desolate consisting mainly of sand stabilised into sand dunes, but continuously changing shape.

Il

There are no large hill ranges in the area and the rainfall is scant, making water a scarce and valuable resource. The available water is generally slightly salty and underground giving rise to the need for very deep wells. There are no perennial rivers in the district, but water accumulated during the rainy season gives rise to small seasonal rivers. These do not last long, usually drying up within weeks, allowing wheat and other crops to be grown on the catchment area. Small tanks, locally known as Khadeens, for the accumulation of rain water are common in this area and are used to irrigate grain crops (Somani, 1990).

2.4. Criteria for classification of climatic zones (Krishan, 1995)

Pre-monsoon, which is the hottest season, extends from April to June, with the daytime temperature often exceeding 45°C, cooling down to a minimum of 26°C at night. This is the most stressful season. Between 11am and 6pm the air temperature is higher than that of the 12 body and so during this period air movement actually decreases thermal comfort. Coupled to this extreme heat stress is the tendency, during this period, for very high wind velocities causing severe dust storms. Monsoon arrives late in Jaisalmer, around mid-July. In the eastern and south-eastern regions of Rajasthan the monsoon arrives earlier, towards the end of June, as the highland areas of the Aravalli and Hardoti channel the Arabian Sea branch of the south-west monsoon in this direction. Although the daytime temperatures are cooler during this period, with a peak value of around 36°C, the night time conditions remain hot with a minimum temperature of around 26°C. The humidity for this brief period is high with relative humidity reaching 80% at night, and remaining above 65% during the day, making conditions unpleasantly oppressive. The third season is the post-monsoon, starting early to mid September, with relatively high temperatures and clear skies. Daily temperatures range from about 20°C at night to over 35°C in the daytime. Humidity is low, and for the indigenous poulation of Jaisalmer, this is a relatively comfortable season. The final season is winter, which extends from December to March, January being the coldest month. The daytime temperatures for this period peak in the mid twenties, dropping to less than 10°C at night. Humidity is low. At this time of year Jaisalmer is inundated with tourists enjoying the cool temperatures and clear skies. Solar radiation is intense (800-950 W/m²) throughout the year and radiant heat emanating from the ground and surrounding objects during afternoons and evenings can cause considerable thermal discomfort. Apart from the very short monsoon season relative humidity is very low (25-40%), with precipitation generally less than 500 mm/year. The prevailing wind direction is south-westerly, but for four months of the year, November through to February, the wind blows from the north-east. Table 2.1 gives a summary of monthly air temperature (Ta in °C), and rainfall statistics (in mm) for Jaisalmer (reproduced from Krishan, 1995).

Month av. max Ta Month av. min Ta Rainfall
Jan
Feb
Mar

These figures describe one of the hottest, driest and consequently one of the least populated areas of India. Jeffrey Cook (1980) stresses the danger in considering the climates in arid regions as predictable. As well as the diurnal and seasonal changes and ranges, the calmness of the desert weather cycles is occasionally punctuated by exceptionally violent storms. During one of the author’s visits to Jaisalmer in August 1995 a young boy from the town was drowned during the floods at the beginning of the monsoon. It is not as extreme a situation as parts of the Sahara or Gobi, because of its relatively small size and the short distance to the sea and Himalayas modify its characteristics. As Spate(1984) describes it ‘the desert is not total - but it is bad enough’. Thus designing for the extremes of climate in this arid region is particularly demanding.

2.3 Jaisalmer - History

The early history of Jaisalmer is not well documented. It is believed (Mishra,1995) that in the remote past the major portion of Western Rajasthan, including the district of Jaisalmer, was submerged under water during Jurassic, Cretaceous and Eocene ages. The land began to emerge during Pleistocene and the last glacial periods. It is also believed (Mishra, 1995) that the western arid region of India was known to man at least thirty to forty thousand years ago, but there is no direct evidence of settlement in the Jaisalmer area during the early Stone Age. The Bhatis of Jaisalmer claim descent from Lord Krishna. After Krishna died the power of his people declined and many families moved away from the Indus settling in Afghanistan. However they suffered constant attack from the nomadic tribes of this area and could not retain their kingdom. They migrated towards India, settling first in the district of Punjab, but constant marauding by the Muslims of Afghanistan and Sind compelled the Bhatis to move further south-west. 14

From the tenth to the twelfth centuries AD the Bhati chiefs fought constant battles with the Muslim forces. At the beginning of the twelfth century Bhati Dusad Lanja was leader of the Bhatts in their capital, Lodurva, in the Thar Desert. He had two sons named Jaissal and Vijayraj. Dusad named Vijayraj as his successor and Jaissal went towards Tanot and Sind and established his power there. Relations with his brother were not good. Jaissal was jealous of his brother’s position in the capital and he plotted the seizure of his power. Jaissal, along with many other disgruntled chiefs, challenged his brother in 1158, but was defeated. Vijayraj became a powerful leader fighting off many Muslim invasions. When Vijayraj died his son Bhoj succeeded to the throne. In 1178 AD Muhammad Ghori and his large Muslim army left Multan to raid the important towns of north-western India. It is said (Tod, 1950) that Jaissal contacted Muhammad Ghori and sought his assistance in gaining the throne of Lodurva. Lodurva was one of the first towns to be invaded. It was completely destroyed, and all important temples were dismantled. Bhoj was slain in its defence. The Sultan continued his march and was eventually defeated by the combined Rajput armies near Abu. Jaisal still wanted the throne of the Bhati State. He plundered the treasures seized by the Turks and returned to Lodurva. The town was ruined and open to conquest. Jaisal was defeated and was forced to leave Lodurva. Some of his followers joined him but he died in 1181. Muhammad Ghori took the throne and appointed his son Jaisa as his successor.
invasion and so Jaisal sought a spot better adapted for defence. Ten miles away on the summit of a rocky ridge he discovered a Brahmin hermit. The hermit related the history of the triple peak hill they stood on. He said that Hare Krishna had come to the spot to attend a great sacrifice. Krishna foretold that a descendant of his would erect a town by the rivulet and a castle on Trikuta, the triple-peaked mount. It was pointed out that the water was bad. Krishna hit the rock and the water bubbled up as a sweet stream (Tod, 1950). The traditional date of the foundation of Jaisalmer fort is 1156 AD (Tod, 1950), but this is disputed by Somani (1990) and said to be 1178AD, after the Muslim invasion of Mohammed Ghori. All dates in this text correspond with the later theory. Construction of the fort together with a well and the Laxminath temple was started by Jaisal, but he did not complete the task before dying. He had two sons, the eldest was expelled and so it was the youngest, Salivahan who was named successor. Salivahan completed the fort some 18 years later along with Laxminath temple and the Jessal Kuwa well (Somani, 1990). The fort stand 30 feet above the rock, which is itself some 250 feet above the plain, and, at it’s widest point, measures 1500 feet across. These were not peaceful times. During this period the Bhatti Rajputs major opponents were the powerful Rathor clans of Jodhpur and Bikaner and endless battles were waged for the possession of small forts and water holes. Cattle stealing

was a major pass-time, along with falconry and the hunt. The Bhattis gained a reputation for being both ferocious and brave in battle and often treacherous as allies (Parwal, 1997). Jaisalmer was at this time one of the safer places in western India, and many affluent families moved there to escape invaders. Towards the end of the eighteenth century the nature of the conflicts changed. Alauddin Khilji, the then leader of the Muslims, had the kingdom of Delhi, Gujarat and the eastern regions of Rajasthan in his command and was intent on founding an ever-increasing empire. In 1308AD he began an attack on Jaisalmer. It is said (Coetz, 1978B) that by this time Jaisalmer was the only remaining independent power in Northern India. The people of Jaisalmer prepared vigorously for the invasion. Large quantities of corn and food were collected in the fort. Stone boulders were placed on the ramparts (the likes of which can still be seen today. (III. 2.7)). The countryside around the city walls was laid waste in order to prevent the enemy from growing food and fodder (Tod, 1950). The fighting continued for several years Ill. 2.6 Boulders on the ramparts of Jaisalmer fort. until in 1315AD the Muslim army breached the ramparts of Jaisalmer fort. The Bhattis knew that defeat was inevitable and so proclaimed the rite of Jauhar. Thousands of women and children surrendered their lives either by sword or fire. All valuables were burnt with them. The men, clad in ceremonial saffron and opium intoxicated, opened the gates and rushed out to meet a heroic death. The Bhatis proclaimed the rite of Jauhar fort some time before 1322AD (Somani, 1990). Fighting continued with the Muslim forces, with the people of Jaisalmer successfully capturing many of their horses and livestock. The Sultan in Delhi decided to send a strong force against Jaisalmer. It was a long battle, but the Bhattis were betrayed by one of their own. The leaders and their kinsmen met heroic deaths at battle and the women and children again committed Jauhar. The exact date is not known. After the fall of Jaisalmer the territory was in the possession of the Sultan. Several religious shrines were dismantled and the surrounding countryside was badly desolated. It was a turbulent period and Jaisalmer faced great hardship. Many of the wealthy migrated towards Sind and Gujarat.

The Muslim power began to wane after 1342AD and wealthy Jains began to return to Jaisalmer to settle. Soon after the town became a centre for religious and cultural activities. Jaisalmer's location, deep in the desert, made it a difficult area for the Muslim army, based in Delhi, to control. The Sultan, conscious of the slow demise of his power, was anxious to have Jaisalmer under a friendly power, and so it was agreed that the Rawals of Jaisalmer would pay an annual tribute to the Delhi Sultans in order to preserve a circumscribed independence. There followed a relatively peaceful era, allowing trade and commerce in the area to flourish. During the 16th and early 17th century there was a second extensive stage of construction in the fort, and it was during this period that the first of the case study havelis, Hotel Suraj, and the small courtyard house, Nohra, were built. Three gateways into the fort, and seven bastions were built. A second wall, 15 feet high, was also constructed, providing additional defence. Literary activities thrived and a good number of businessmen from northern India passed through Jaisalmer on their way to the western states. By the time the British invaded India, Jaisalmer was a very prosperous state, and a cluster of Jain and Brahminical temples had sprung up Ill. 2.7. Suraj Pol (sun gate). The inside the fort. The Maharawal at the time, Amarsingh, was third, outermost gate, built during a lover of the arts and sponsored many cultural activities in the second stage of construction. Jaisalmer. He desired more money for public works and the building of palaces and gardens, and so, in the early 1660s, imposed a tax on the rich. When the minister of state protested he was immediately put to death. The people of Jaisalmer paid the money. An additional 92 bastions were added beside the earlier 7 making 99 in total. As the opium trade with Afghanistan and China increased, so did the wealth amassed in Jaisalmer. Coetz (1978B) states that during the reign of Amarsingh Jaisalmer became one of the leading Rajput states, controlling the whole southern Thar Desert. But this prosperity was not to last. In the mid eighteenth century relationships with adjoining rulers took a turn for the worse and fighting broke out on the border territories of Jaisalmer. A fourth, outer, gateway to the fort was constructed with a connecting wall adjoining the main fort wall. The population began to move out of the fort and build homes on the slopes below. As a security measure, towards the end of the 18th century, a strong boundary wall, 30 feet high, was built encircling the downtown population.

In addition to the border troubles, Mulraj II, the then Maharawal, had to face the hostilities of his powerful nobles. He selected an ambitious man named Sarup Singh as his minister and together they managed to suppress the activities of the chiefs. Naturally the chiefs felt angry at their treatment and began to plot the downfall of the Maharawal and his minister. Sarup Singh reduced Raisingh's (Mulraj's son, and heir apparent) subsistence allowance and the already hostile atmosphere became considerably worse. In 1782AD Raisingh stabbed Sarup Singh to death. Mulraj rushed back to the palace, but he was too late. Raisingh had assumed power, and put his father under surveillance. However he only remained on the throne for three months before Mulraj was reinstated by his chiefs. Sarup Singh's son, Salim Singh, then only twelve years old was nominated as minister by Mulraj. Salim Singh would not forgive the murder of his father and as his power increased he diverted more energy into crushing those involved with his fathers death. He murdered dozens of chiefs as well as Raisingh and all his closest relatives. Mulraj stood by and watched the murder of his relatives, comparatively powerless against the cunning and ruthless mind of Salim Singh. For all his energy into crushing those involved with his fathers death. He murdered dozens of chiefs as well as Raisingh and all his closest relatives. Mulraj stood by and watched the murder of his relatives, comparatively powerless against the cunning and ruthless mind of Salim Singh. For all his cruelty Salim Singh was a very clever administrator and the ruling class flourished under his harsh taxation regime. Many imposing havelis were built in the downtown area of Jaisalmer, most notably Salim Singh's own haveli and the five Patwon ki havelis. Jaisalmer had become a centre for merchants indulging in the caravans trade with the neighbouring states and the prosperity was reflected in the fronts of the houses built at the time. The second case study haveli was built during Salim Singh's administration.

III.2.8. Façade of Patwon ki haveli* III.2.9. Salim Singh haveli*

* reproduced from Kamiya (1999)

In 1818AD almost all Rajput chiefs entered into friendly relations with the British and Jaisalmer followed suit (Somani, 1990). Salim Singh's power was still growing and Mulraj's 18
successor, GajsiSingh, was anxious to change this, but by this time this was a near impossible task. Attempts were made on Salim Singh's life, but in the end it was one of his own wives that successfully poisoned him in 1823. During his life Salim Singh was so powerful that no one dared to speak out against him. He collected immense wealth through bribery and murder, but his heavy taxes drove many families to emigrate from Jaisalmer. Agarawala (1979) states that Salim Singh was particularly cruel to the Palival Brahmins, famous as enterprise cultivators and land owners, eventually driving them southward out of the Thar Desert shortly before 1820. Their empty villages can still be seen, partially buried in the sand. The state never fully recovered from the loss of talent and trade resulting from Salim Singh's high-handedness. The population of the city continued to fall gradually throughout the late 19th and early 20th centuries, from 115,000 in 1891 to just 67,000 in 1931 (Ward, 1989). In 1938 electricity was introduced to Jaisalmer and a year later stone roads were constructed from Jaisalmer to Pokoran and Bikaner, but still the population declined. By the time Jaisalmer State was absorbed into Rajasthan in 1948 the city of Jaisalmer was almost deserted. The rise of shipping trade and the port of Bombay, coupled with partition and the cutting of trade routes through Pakistan sealed the city's fate. However the 1965 and 1971 Indo-Pakistan war revealed Jaisalmer's strategic importance. In addition the Indira Gandhi Canal, built in the 70's and passing about forty miles to the north-west of Jaisalmer transformed the desert economy. By this time many of the buildings in Jaisalmer, all in need of constant maintenance, had been empty for some time. After an unscheduled visit to Jaisalmer in January 1975, Indira Gandhi expressed her displeasure over the neglect of the fort town and in a letter to the Chief Minster of Rajasthan she suggested that measures should be taken immediately for the conservation of the town (Gosh, 1975).

2.4. Jaisalmer today Although in the late seventies Jaisalmer was considered to be a ghost town (Goetz, 1978A), today it is accessible by plane, train and regular bus services and has become a very popular tourist destination, offering camel safaris into the desert. This has, however, proven to be a double-edged sword. Previously the city's water was collected manually from a reservoir lake. The introduction of pumped water combined with the demands of the tourist has resulted in larger amounts of water being pumped into the city than the open drains can handle. The excess water is seeping into the foundations of Jaisalmer rendering many structures unstable. Carpenter (1994) has most recently highlighted this dilemma through the creation of the international campaign called Jaisalmer in Jeopardy (Carpenter, 1995). The funds from this charity go directly towards specific restoration projects in the city, but the 19 spectacularly carved havelis are being demolished and 'repaired' into banality at an alarming rate. The commercial pressures and high maintenance costs are proving too much for even the most committed conservationist. In the course of this study five new hotels opened within the fort alone, and one of the properties surveyed was been altered beyond recognition. Gradually, through the work of Sue Carpenter and Indian bodies such as INTACH, the Indian National Trust for Art and Cultural Heritage, the historical significance of Jaisalmer is slowly being realised, and the city is once again blooming.

Chapter 3 provides a record of two existing havelis and a small, adjacent courtyard house within the fort of Jaisalmer. It documents volume, mass and construction of the havelis, and discusses some of the patterns of life for which these mansions were designed.

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CHAPTER 3 THE HAVELIS

This chapter gives a detailed, illustrated account of two medium sized havelis and a third, smaller, courtyard house, located within the fort of Jaisalmer. Plans, sections and elevations of both havelis are shown along with limited drawings of the courtyard house.

3.1. Introduction The term 'haveli' is of uncertain origin, with various dictionary definitions, but amongst the alleys of north Indian towns its use suggests a distinguishable type of inward looking, urban courtyard house, and signifies a way of life, based on traditions, and patterns of etiquette and behaviour, that was more than just a form of architecture (Tillotson, 1994). Havelis are found in a belt that extends west to east over a broad area characterised by a predominantly hot and dry climate, although there are many other areas with the same climate. The area is also very dry, indicating that the water table is very low, and where rainfall is not very significant. The area is also briefly mentioned in the New Scientist (Dec 17th, 1975) as including the regions of Madhya Pradesh and Gujerat (Prasad, 1988) (see illustration 3.1.).

3.2. The haveli region (original utexas, 1997, edited by author).

This area is characterised by a predominantly hot and dry climate, although there are many other areas with the same climate. The area is also broadly influenced by Islam.

1 Possibly Persian - "a surrounded or enclosed place" (Waczziarg et al., 1982) 23
3.2. Building Surveys It was decided that detailed measurements of two medium sized havelis would be attempted in preference to limited measurements in many different buildings. Jaisalmer is one of the more traditional areas of India and privacy for women in the home is very important. Prolonged and thorough intrusions into family homes by outsiders are not readily accepted and so, consequently, none of the buildings in this study were occupied as family homes.

3.3. Jaisalmer fort showing location of havelis, and courtyard house.

3.4. Hotel Suraj This medium sized haveli is located on the Southeast face of the fort wall, not far from the Jain temple with the front, street elevation facing Northwest.

3.4.1. Hotel Suraj was surveyed during the first visit to Jaisalmer in June/July 1995. It was measured in sufficient detail for plans, sections and elevations to be accurately drawn at 1:50 scale. During a second and shorter visit in April 96 a smaller courtyard house, Nohra, opposite and belonging to the same family as Hotel Suraj, was surveyed.

3.4.2. During a third and final visit in March/April 97 a second haveli was surveyed in similar detail to Hotel Suraj. Plans, sections and elevations of both havelis are shown along with limited drawings of the courtyard house in section 3.4, towards the end of this chapter.

3.4.3. Also during the same visit, students from the TVB School of Architecture in Delhi surveyed fifty meters of streetscape running outside hotel Suraj in order to facilitate the investigation of air temperature and surface temperature around the buildings. This has not been included in this study.

3.4.4. The haveli is constructed of immensely thick blocks of the local honey-yellow sandstone, with thinner limestone panels in the more intricately carved areas. Both masonry and carved areas are composed of prefabricated panels assembled with stone keys or iron cramps – no mortar was used. This method of construction makes the changing of building elements a relatively easy task, the replacing of one prefabricated unit with another, and it is common.

3.5. Detail of brackets, first floor front room.

3.6. Detail of ceiling, first floor, back room.

3.7. Most private rooms at the back of the haveli, a pattern recurring on all floors. Immediately on the left as you enter the haveli are the male and female wash rooms with the family temple opposite to the right. These are all relatively recent additions. Light floods into the haveli through an almost central courtyard measuring approximately five meters by three with the longest axis running northeast/south-west. The courtyard is an extremely important element of any haveli, and considerable amounts of effort and money are spent to make the internal facades as elaborate as the outside ones (Jain, 1998). The courtyard of Hotel Suraj is no exception; it is the heart of the house, connecting other spaces, both horizontally and vertically. Scattered around the interior are small, carved niches designed to house oil lamps. In addition small metal hoops are embedded into the walls, columns and ceilings at regular intervals. The owner of the haveli Ill. 3.6. Light floods in to the central told how, before electricity, tapestries and heavy courtyard on the ground floor. cloths were hung from these during the winter months to remedy cold draughts.

3.8. In the summer grass blinds were hung in their place and regularly dampened so as to cool any incoming breeze. This is substantiated by Mrs Ali's description of zenanas (female quarters) in the havelis of Lucknow (1973): As they have neither doors nor windows to the halls, warmth or privacy is secured by means of thick wadded curtains, made to fit each opening between the pillars...The wadded curtains are called purdahs; these are sometimes made of woollen cloth, but more generally of coarse calico. Besides the purdahs, the openings between the pillars have blinds neatly made of bamboo strips, wove together with coloured cords. These blinds constitute a real comfort to every one in India, as they admit air when let down, and at the same time shut out flies and other annoying insects; besides which the extreme glare is shaded by them. And further in Sarah Tillotson's work on traditional life in the havelis of northern India (1988): Above ground, rooms and verandas were kept cool by tattis (screens) made up of fragrant roots of khas grass. Servants kept these constantly wet, and the evaporation of the water cooled and freshened the breeze as it passed through the tattis into the room which they shaded. A stone staircase leading up to the first and second floors and the kitchen open onto the north-west side of the courtyard. The thin wall of the kitchen is perforated with star shaped holes to enhance ventilation. Two semi-basement rooms are located at the far end of the haveli, one considerably larger than the other...
morning could well be used for entertaining dinner guests in the evening. Furniture and accessories were kept in the storeroom and brought out as and when required. At the front of the mahal, and overhanging the street is a semi-enclosed balcony or jharokha, providing a sitting platform ideally placed for views and breezes. In all havelis the jharokha is made with extra care; it is a showpiece, an expression of wealth. These jharokhas are ideal necessities for relaxing of an evening, allowing discrete participation with the outside world. Agaravala (1979) quotes the verse: Galyo sir gaddal bichhe, Amal bate apraman. Mahal changi drav mansa, Samajhtiya Jaisani. Translated as: In the projected balconies bedrolls are spread, One can share opium without discrimination. Prosperous people live in beautiful houses, Such is the city of Jaisalmer with beauty and taste.

3.3.8. First floor middle back room, drawing its light and air from the main courtyard.

The staircase to the second floor brings you out onto a roof terrace, secluded form the main street by a large, elegant room referred to by the owners as the winter room. This room, more than any other, is influenced by Mogul fashion. Both the street and roof terrace elevations are decorated with bangaldar roofs3, a feature described by Goetz (1978B) as post Mulraj II, dating this Ill.3.10. Street elevation of winter room, particular section somewhere around the mid showing jharokha with bangaldar roof eighteenth century. It was not uncommon for havelis to decorated with bangaldar roofs3, a feature described by Goetz (1978B) as post Mulraj II, dating this Ill.3.10. Street elevation of winter room, particular section somewhere around the mid showing jharokha with bangaldar roof eighteenth century. It was not uncommon for havelis to

3.3.9. Second floor roof terrace. 29

Continuing up the staircase brings us to the roof terrace. The party walls to the north-east and south-west are extended just over a meter above the floor level so as to make these areas private places to sleep at night. Above and to the south-west of the chandni is a brick constructed water tank, a recent addition. A further stair, leading to a throne-like platform, elevated to catch every breeze, surmounts the roof of the staircase.

3.2.2. The second haveli This is again a medium sized haveli, with a footprint about three quarters the size of that of hotel Suraj. It is located on the south-east face of the fort wall, with the front street elevation facing south-west.

3.12 Street façade of second haveli photo montage

Although there are palpable similarities with Hotel Suraj, the external influences experienced by the owners during their travels are manifest in the planning of this haveli. In contrast to the airy impression created by Suraj's open planning, this building is compartmentalised, probably influenced by the British need for privacy within the home. The boundary between male/public areas and female/private areas also seems more pronounced, but this may just be a product of the existing division of ownership. The haveli is two stories high, with a small basement covering with star snaped noiles to enhance ventilation. I two semi-basement rooms are located at the far end of the haveli, one considerably larger than the other. The largest has a single window, about half a meter square, opening onto the ramparts. Other than the door, this is the only opening on the ground floor. The basement is accessed through a trap door towards the rear of the haveli.

On the first floor at the front of the haveli is the mahal, the grandest room in the haveli, Ill. 3.6. Stone staircase of Hotel Suraj traditionally used as a reception room, a place for the men of the house to conduct business. The walls of this room are plastered (approximately 15mm thick), and beautifully painted. Tillotson (1994) describes one such plaster as "... a Composition, made of freestone beaten small, lime, gum and sugar, which makes a dazzling white and is smooth as glass." Even though the plasterwork is severely damaged, the owner has resisted the temptation to renovate for fear of losing the original character. It is customary for the mahal of a Rajasthani haveli to be Ill.3.7. The mahal, the first floor front room of Hotel Suraj located, as in this case, above the entrance. Between the mahal and the courtyard is a small room, now converted into an on-suite bathroom, but originally intended as a storeroom. In fact all the large rooms in the haveli have an associated smaller storeroom. Traditionally only a few rooms- bathroom, kitchen, stores - in a haveli were designed for a specific function. Larger rooms were used instead as season, need and mood dictated (Prasad, 1998). A room used to conduct business in the
Hotel Suraj except that stone beams have been used in place of wood. The carving, although using similar motifs to Hotel Suraj, is not as intricate or as deeply set. There are two entrances into the building. The first, on the left, leads into the largest of the three courtyards. The staircase is situated in the northern corner of this space, and next to this, towards the back of the courtyard, is a trap-door leading down to the basement. This was the public side of the haveli, the male domain or mardana. On the first floor the staircase arrives at a narrow balcony/corridor overlooking the main courtyard. This leads to the mahal, which extends across the entire front elevation. Off to the right is a small room, still used as a store and so full that internal measurements were impossible. The mahal has two Jharokas overlooking the street, both capped with bangalidar roofs. The second entrance, on the right of the front façade leads into the female quarters or zenana. A small second courtyard provides some light to this long, thin plan, but on the whole this section is rather dark. To the left of the courtyard is the kitchen, with a second staircase opposite. The chamfered room off to the right was used as a family temple and so access to survey was not appropriate. Off the staircase on the first floor is a long thin room overlooking the battlements formerly used as a latrine. A larger room is adjacent with a smaller storeroom leading off towards the rear. Towards the centre of the haveli on the first floor is the third courtyard. Another chamfered room sits above the temple. Unlike Hotel Suraj, no recent alteration have been made to this building and stone washing troughs are still embedded in the mud floors of both this room and the mahal. The Indian method of bathing (in which a small pot is used to scoop water) III. 3.13. Mahal of 2nd haveli, showing washing from a container and pour it over the body) trough in bottom left hand corner. The plan is triangular in shape the longest side of which adjoins the Jain temple. The wing to the west and facing Hotel Suraj was the Mardana. This has not been altered during the conversion, and so has not been surveyed. This portion of the building is illustrated in Agarawala (1979). The wing to the north-west was the zenana and now no longer exists as documented. Ill. 3.13. Street façade of the Mardana of Nohra (Agarawala, 1979).

The Main entrance is through a huge gateway under the mardana. Carts could be driven straight into the courtyard through this entrance and two such carts are still in the owner's possession and kept in the basement.

3.3. Discussion. Today the havelis of Jaisalmer are well-documented (Agarawala, 1979; Tillotson, 1987) and noted for their outstanding beauty and design. Nath et al. (1997) claim "Civil domestic architecture in stone cannot be seen in more intrinsic beauty than in Jaisalmer", whilst Oliver (1997) states "the richly embellished havelis of the merchants mark a pinnacle of vernacular achievement". However, it is not sufficient to have a qualitative understanding of such buildings. To develop confidence in the natural heating and cooling methods used in these havelis we need to know the kind of thermal environment that prevails within. Chapter 4 details the method and equipment used for the collection of environmental data in and around both Hotel Suraj and the second haveli. As Hotel Suraj was the most accessible, and also the most elaborate, of the case studies, the majority of the field work for this thesis was centred in this haveli. Despite the intricately carved facades, Hotel Suraj is an exceptionally high mass building, particularly on the lower floors, and this is likely to significantly affect the climate indoors. Previous research (Gupta, 1984) carried out in similar buildings in the downtown area of Jaisalmer suggested the high mass construction shifted the indoor peak temperature by twenty-four hours. This resulted in a smaller indoor than outdoor temperature range, but still gave the peak temperature indoors in the day when higher temperatures can be better tolerated. The possibility of achieving a 24 hour shift in indoor temperature will be discussed in chapters 8 and 9.

3.4. Plans, sections and elevations. The following pages show the survey drawings for Hotel Suraj, the second haveli and Nohra courtyard house.
4.2. Field study periods Three field trips, of varying lengths, were conducted over an 18-month period. In addition, temperature and humidity loggers were left in-situ between visits.

March, 96. In March 1996 the author returned to Jaisalmer for 4 weeks in conjunction with a shorter visit by students from the University of East London and TVB (Delhi) schools of architecture. During this period sole access was granted to the haveli and a series of manual measurements were recorded throughout the building. In addition a small thermal comfort survey was conducted in and around the streets of Jaislamer. Access to the second haveli was secured, and a detailed survey and temperature and humidity logging begun.

March, 97. A return visit was made to Jaisalmer in order to retrieve the data loggers from both buildings and complete the survey of the second haveli.

4.3. Equipment

4.3.1. Temperature

The temperature of a zone is defined in terms of both air temperature and the temperature of the surfaces within the space (the radiant temperature). Radiant temperature is a more complex entity than air temperature. It varies not only with the position in the room, but also with the direction in which it is measured. This is usually addressed by calculating the mean radiant temperature (MRT) of the environment. This is defined as the uniform surface temperature of an imaginary black enclosure with which a person (also assumed as a black body) exchanges the same heat by radiation as in the actual environment (Balaras, 1994). However, the measuring of all surface temperatures in an environment and calculation of MRT is very time consuming. Nicol (1993) recommends the use of globe thermometer, measured using a globe thermometer, for the estimation of the effect of radiant temperature. The globe thermometer consists of a hollow sphere, generally painted black, measuring 40mm in diameter (roughly that of a table tennis ball), with a thermocouple or thermometer located at the centre. The temperature assumed by the globe at equilibrium is the result of a balance between heat gained or lost by radiation (from the surfaces) and by convection (from the air). In this study indoor and outdoor temperature was recorded using TinyTalk miniature, singlechannel dataloggers. These units are housed in 35mm opaque, flip-top film canisters, making them both small and lightweight. They are accurate to ±0.2°C and can store up to 1800 readings. They are sold as air temperature loggers, but since their arrival on the market in the early 90's there has been some dispute as to whether the temperature they record is actually closer to radiant temperature (due to the film canister housing). Nigel Oseland of the BRE conducted a simple experiment on a windowsill for two days. The results were as follows: (private communication).

He concluded that the TinyTalk loggers are more akin to globe thermometers than air temperature thermometers.

4.3.2. Humidity

Relative humidity was recorded using TinyTalk (RH) miniature single channel dataloggers. The specification is as above, with a range of 0 - 90%, and an accuracy of ±4% at 20°C. As relative humidity is dependent on air temperature, all recorded humidity levels have been converted to water vapour pressure values (Pa) as recommended by Nicol (1993) using the formula:

\[ Pa = RH \exp(18.956 - 4030.18 / (Ta + 235)) \] (millibars)

Where: Pa = water vapour pressure RH = recorded relative humidity Ta = recorded air temperature (from McIntyre, 1980)
4.4.1.2. Results Graph 4.1 shows the results of the summer95 temperature series. The logger located in the top front room (1) went missing after the second run and so data for the period 7th to the 21st July for this location is missing. The recording period for the summer95 series accounts for the tail end of the hot dry season and the very beginning of the warm wet season. On the 22nd June, the day before logging began, Jaislamer recorded the highest rainfall in 100 years. The following seven days show a gradual increase in daily maximum temperature, whilst daily minimum temperatures remain almost constant. On the 28th and 29th June the outdoors temperature logger (no.3) recorded maximum temperatures of over 47°C at 7.00pm. The recorded temperatures for the other monitored outdoor zones - the top floor courtyard (no.12), the ground floor porch (no.11) and the ground floor courtyard (no.9) - for the same period are 41°C, 41.5°C and 39.5°C respectively. This suggests that the external spaces in and around Hotel Suraj temper the ventilation air before it enters the haveli.

Logger no.4 (TopMid) actually located in a room on the near side of the section AA 48

3

1stFlFront 1stFlBack outdoor TopMid

40 temp

GrFiCourt Basement GrFiPorch TopFiCourt
The 10 day period from the 1st to the 11th July shows considerably lower maximum and minimum temperatures. Intermittent strong, dust-laden, warm winds were noted throughout this period, bringing some relief from the heat, but making night ventilation impossible. The next 7 days (11th to 18th July) were overcast, resulting in uncharacteristically small daily ranges. This period was particularly thermally stressful during the evenings and nights as outdoor minimum temperatures were often as high as 31°C. The last three days of the recording period marked the beginning of the warm, wet season, with hard bursts of rain (accompanied by children dancing in the streets). It is interesting to note that the temperature recorded in the basement remains constant, at around 30°C for the duration of the recording period. Graph 4.2 shows the water vapour pressure data for the summer95 period. For the first seven days of the logging period the recorded Pa in the porch and topCourt zones follow a similar pattern, with maximum values around 7am and minimum values around 7pm. However as the weather becomes more windy and overcast the pattern in the topCourt zone noticeably changes with daily values often peaking mid afternoon. The daily pattern in the porch zone remains constant, although the daily variation decreases. It is also noticeable that the water vapour pressure levels recorded in the basement show more variation than the temperature data recorded in the same location, particularly during the first seven days of the logging period.
Graph 4.2. Water vapour pressure (measured in millibars) recorded for the summer 95 series in Hotel Suraj.

4.4.1.3. Discussion. Table 4.1 gives a summary of the summer 95 temperature and humidity series statistics.
|     | 33.2 | 30.2 | 33.4 | 33.1 | 25.5 | 23.3 | 25.1 | MAX. | 42.2 | 38.8 | 47.7 | 40.1 | 37.6 | 38.8 | 39.3 | 35.7 | 40.6 | 33.7 | 42.2 | 41.8 | 37.1 | 31.4 | 29.0 | 29.5 | 29.5 | 27.0 | 30.7 | 28.5 | 28.8 | 28.5 | 29.2 | 29.9 | 27.7 | 27.4 | 8.3 | 12.7 | 22.6 |
In general table 4.1 shows most rooms in Hotel Suraj have similar average temperatures as that recorded outdoors (no.3). However the top middle (no.4), top front (no.1) and first floor front (no.7) rooms have notably higher average temperatures than outdoors over this period. Of the three mentioned the top middle room performs the worst with an average temperature 1.4°C hotter than outdoors. This is a small room with little opportunity for ventilation.

Ill. 4.3. Average temperature results from the summer95 series in Hotel Suraj.

4.4.2.1 Logger locations The author was not present for this logging period and with dozens of tourists passing through the hotel every week, security was a primary concern when choosing logger locations. The four rooms chosen are not for tourist use. The basement is seldom used. Occasionally the owner takes an electric fan down to give the room a bit of an airing, but otherwise the room is unventilated. The ground floor room is used infrequently and only by the owners. It has no windows, and so the only ventilation is through the door, which opens onto the courtyard. The external wall is buried to a height of 1.5m above floor level. The first floor location is a small room, formerly a corridor/balcony and now used only for storage. It has windows opening into the courtyard, but the wooden shutters, although ill-fitting, are constantly closed. On the
Now used only for storage. It has windows opening into the courtyard, but the wooden shutters, although ill-fitting, are constantly closed. On the second floor, the room is again used only for storage. It has two small windows, one facing the fort bastions, the other facing the chandni. Again both have ill-fitting shutters, which are constantly closed. Air changes in all the internal locations are therefore relatively small and constant. The external west wall of the first and second floor rooms was originally a party wall with the neighbouring haveli. Unfortunately this haveli is now only one storey high, and so both these rooms are exposed to solar radiation on the west elevation. External temperature was recorded on the ground floor of the main courtyard as this was considered the most secure outdoor location. The loggers were all fixed into position as for summer95.xls. The exact locations are shown in ill. 4.4.

4.4.2. Results Graph 4.3. shows the results for the Suraj-W95-96 temperature series. Results indicate that, for this period, all monitored rooms appear to perform well thermally, in general providing a warmer environment indoors than out. Although the basement shows no daily variation, it does show considerable annual variation. Results around mid January show a difference of up to 13°C between minimum outdoor and equivalent basement recorded temperature. Results are appreciably smaller for the rest of the monitored period.

<table>
<thead>
<tr>
<th>Date</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/19/96</td>
<td>15</td>
</tr>
<tr>
<td>3/5/96</td>
<td>10</td>
</tr>
<tr>
<td>2/20/96</td>
<td>20</td>
</tr>
<tr>
<td>2/6/96</td>
<td>15</td>
</tr>
<tr>
<td>1/23/96</td>
<td>15</td>
</tr>
<tr>
<td>1/9/96</td>
<td>15</td>
</tr>
<tr>
<td>12/26/95</td>
<td>10</td>
</tr>
<tr>
<td>12/12/95</td>
<td>10</td>
</tr>
<tr>
<td>11/28/95</td>
<td>10</td>
</tr>
<tr>
<td>11/14/95</td>
<td>10</td>
</tr>
<tr>
<td>10/31/95</td>
<td>10</td>
</tr>
<tr>
<td>10/17/95</td>
<td>10</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

Graph 4.3. Temperature data for Suraj-W95-96 series in Hotel Suraj.

4.4.2.3. Discussion Table 4.2 gives a summary of the Suraj-W95-96 temperature series statistics for all data in each monitored zone. In addition the statistics for the temperatures recorded in January (the coldest month) are also shown. BASEMENT

<table>
<thead>
<tr>
<th>Zone</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GrFII-back</td>
<td></td>
</tr>
<tr>
<td>1stFII-back</td>
<td></td>
</tr>
<tr>
<td>2ndFII-back</td>
<td></td>
</tr>
<tr>
<td>MINIMUM</td>
<td>23.09 23.09 17.83 17.83 15.38 15.38 14.69 14.69 9.34</td>
</tr>
<tr>
<td>ST. DEV.</td>
<td>1.95</td>
</tr>
<tr>
<td>AVERAGE</td>
<td>0.45 3.58 0.77 4.24 1.64 4.39 1.97 4.91 9.34 2.59</td>
</tr>
</tbody>
</table>

Tbl. 4.2. Summary temperature statistics for Suraj-W95-96

The results from table 4.2 show that all indoor average temperatures are higher than outdoors during the winter period. As both the basement and ground floor back room are most likely coupled with the ground temperature, this is an expected result for these two zones. However, both the first and second floor rooms have average temperatures of almost 3°C higher than the outdoors over this period, with the average statistics for the month of January also showing the same pattern. This can only be a product of considerable passive solar gain through the external walls and shuttered windows of the rooms. Both range and standard deviation show a steep increase from the bottom to the top of the haveli, indicating an inverse relationship with the available mass in each monitored zone. The average temperature results have been transposed onto the Hotel Suraj section and are shown in illustration 4.5.

4.4.3. Suraj-S96 series

At 15:25 on the 3rd April 1996 the five temperature data loggers were replaced in hotel Suraj. They were reset to record at 2hr. 24min. intervals again giving ten readings per day. In all 1800 readings were collected over a six month period with the run ending on the 30th September 1996 at 13:00.

4.4.3.1. Logger locations

All temperature loggers were located as for the Suraj-W95-96 series (shown in Illustration 4.4). Unfortunately the data logger on the second floor was stolen sometime during this period and so data for the entire six months at this location is missing.

4.4.3.2. Results

Graph 4.4. shows the results for the Suraj-S96 temperature series.
Graph 4.4. Temperature data for the Suraj-S96 series.

It is immediately noticeable that the daily average outdoor temperature is much more stable over this six month period than in the previous data set, although the daily range seems to show more variation. This is illustrated in graph 4.5, which shows the calculated daily average temperatures for both the SurajW95-96 and Suraj-S96 data sets.
Graph 4.5. Calculated daily average temperatures in Hotel Suraj over a 12 month period.

The relationship between the basement and outdoors is inverted in the summer with the basement giving consistently lower temperature readings than outdoors. The summer temperatures in the ground floor back room seem to be slightly cooler than outdoors, whilst those of the first floor room are higher.

4.4.3.3. Discussion Table 4.3 gives a summary of the Suraj-S96 temperature series statistics for all data in each monitored zone. In addition the statistics for the temperatures recorded in June (the hottest month) are also shown.

<table>
<thead>
<tr>
<th></th>
<th>AVERAGE</th>
<th>MAXIMUM</th>
<th>MINIMUM</th>
<th>ST. DEV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASEMENT</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRFLBACK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1STFLBACK</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OUTDOORS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALL</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>JUNE</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                | 29.11   | 29.68   | 31.74   | 32.49    |
| BASEMENT       |         |         |         |          |
| GRFLBACK       |         |         |         |          |
| 1STFLBACK      |         |         |         |          |
| OUTDOORS       |         |         |         |          |
| ALL            |         |         |         |          |
| JUNE           |         |         |         |          |

|                | 29.93   | 35.65   | 39.26   | 41.77    |
| BASEMENT       |         |         |         |          |
| GRFLBACK       |         |         |         |          |
| 1STFLBACK      |         |         |         |          |
| OUTDOORS       |         |         |         |          |
| ALL            |         |         |         |          |
| JUNE           |         |         |         |          |

26.28
The results in Table 4.3 show that average temperature, range and variation in temperature all increase from the bottom of the haveli to the top. The first floor back room again has an average temperature higher than outdoors, although not to such a degree as in the previous data set. Both the Suraj-W95-96 and the Suraj-S96 series were combined into one twelve month series - Suraj-12months. The annual average temperatures and annual range for each of the monitored zones were calculated and transposed onto the Hotel Suraj section5. The results are shown in illustration 4.6.

KEY Annual Average Temperature Annual Range

Ill. 4.6. Annual average temperature and annual range for Hotel Suraj

Results over the one year period show that both the basement and ground floor zones have similar annual average temperatures to that of the outdoor monitored zone. This suggests that, when considered over a twelve month period, direct ground coupling cannot be accurately described as a passive cooling system. Ground coupling merely dampens the annual temperature range.6 This is in contradiction to the writings of many contemporary researchers (Givoni, 1990; Labs, 1981).

4.4.4 2ndhaveli-S96 series At half past five on the 3rd April 1996 five data loggers were placed in the second haveli, one in the basement, two on the ground floor and two on the first floor. They were set to record at 2 hours and 40 minutes intervals giving ten readings per day. In all 1800 readings were collected over a six-month period ending at four thirty on the 30th September.

4.4.4.1. Logger locations The exact logger locations are shown in illustration 4.7. Unfortunately both data loggers on the first floor were stolen sometime during this period and so data for the entire six months at these locations is missing.

4.4.4.2. Results Graph 4.5 shows the results for the 2ndHaveli-S96 series. Outdoor temperature recorded over the same period in the courtyard of Hotel Suraj has been included for comparison. 45

Data for the second floor back room was excluded as it was only recorded over a six month period. It also shifts the maximum and minimum temperatures forward in time. This is discussed in chapter 8 58

KEY 1 GrFlMainCrt 2 GrFlFront Basement and SurajOut not shown.

Ill. 4.7 Logger locations for the 2ndhaveli-S96 series.

4.4.4.2. Results Graph 4.5 shows the results for the 2ndHaveli-S96 series. Outdoor temperature recorded over the same period in the courtyard of Hotel Suraj has been included for comparison. 45
It is immediately noticeable that the courtyard of the second haveli is performing quite differently to the courtyard in Hotel Suraj, showing much less variation over this summer period. This may be because this haveli was closed and unoccupied during the monitoring period, therefore limiting the possibilities for cross ventilation (a marked characteristic of hotel Suraj). The basement of the second haveli, however, seems to show more temperature variation than that of Hotel Suraj, although still seems cooler than any of the other monitored zones.

4.4.4.3. Discussion

Table 4.4 gives a summary of the 2ndhaveli-S96 temperature series statistics.

<table>
<thead>
<tr>
<th></th>
<th>AVERAGE</th>
<th>MAXIMUM</th>
<th>MINIMUM</th>
<th>STDEV.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement</td>
<td>30.30</td>
<td>32.94</td>
<td>25.58</td>
<td>1.37</td>
</tr>
<tr>
<td>SURAJOUT</td>
<td>31.59</td>
<td>36.79</td>
<td>27.0</td>
<td>1.81</td>
</tr>
<tr>
<td>2ndFloorFront</td>
<td>32.10</td>
<td>41.77</td>
<td>24.51</td>
<td>3.16</td>
</tr>
<tr>
<td>1stFloorBack</td>
<td>31.37</td>
<td>36.0</td>
<td>27.38</td>
<td>1.61</td>
</tr>
</tbody>
</table>

The results from table 4.4 show that, at this time of year, the second haveli basement is not only over 1°C warmer on average than its counterpart in Hotel Suraj, but also shows considerably more variation over the same period. The converse is true when comparing the two courtyards. The courtyard of the second haveli is, on average, over 0.5°C cooler in the summer than that of Hotel Suraj, and displays much less variation for the entirety of this period. Results for the ground floor front zone are very similar to those of the ground floor back room in Hotel Suraj, despite the latter benefiting from a semi-buried external wall.

4.4.5. March96 series

In addition to the long term monitoring of the various zones in the two havelis, a series of manual measurements were recorded in Hotel Suraj during the March, 1996 field study period. The five temperature data loggers were reset to record at 16 minute intervals in the locations shown in illustration 4.4 in order to support the manual recording. The recording began at 9am on the 30th March and ended at 3pm on the 3rd April. An additional humidity logger, located next to the ground floor back temperature logger, was set to record at the same intervals over the same period.

4.4.5.1. Temperature results

Graph 4.6 shows the temperatures recorded over the March96 period.
Graph 4.6. Recorded temperatures over the March 96 period.

The outdoor temperature (measured in the courtyard) varies between a minimum of $24^\circ$C at around seven in the morning and a maximum of $36^\circ$C at around three in the afternoon. The shape of the outdoor temperature curve shows that the courtyard heats up considerably faster than it cools down. Furthermore, on the night of the 31st March and 1st April, both the first and second floor zones cool down as much as $2^\circ$C further than the courtyard. This may be attributable to internal gains in and around the courtyard at this period.

4.4.6. Courtyard surface temperatures - HAV-HT series. On the 1st April surface temperature readings in the main courtyard were manually recorded using the Digitron infra red thermometer. Readings were taken for the courtyard floor and six locations on each of the four courtyard elevations. These readings were repeated 6 times during the day, at 7:00am, 10:20am, 1:00pm, 4:00pm, 7:00pm and 10:30pm. In addition air temperature was simultaneously recorded on the ground floor of the courtyard.

4.4.6.1 Results Because of the problems associated with displaying many locations (26 in this series) on one graph, results of the hav-HT data set have been presented using images generated by the thermamator program, developed by the author and described in chapter 6. All surface temperatures are shown in the appropriate zone of a bird's eye perspective of the Hotel Suraj courtyard. The recorded air temperature is shown within the north-point. In addition solar perspectives of the central courtyard area of Hotel Suraj at 10:20am, 1:00pm and 4:00pm on the 1st April were graphically constructed, and are shown alongside the relevant results. These diagrams show which areas of the courtyard were exposed to direct sunlight at the time the results were recorded.

7:00am

7

A graphic technique used to draw buildings as seen by the sun (Los, 1981). 62
4.4.6.2. Discussion. Results from the hav-ht series show that surface temperatures on the ground floor of the courtyard, and particularly the courtyard floor are cool throughout the day. Between 7:00am and 10:20am the surface temperatures of the first and second floor elevations are similar to the air temperature recorded on the ground floor of the courtyard. However, between 1:00pm and 4:00pm these temperatures, particularly on the north and the east elevations, rise dramatically reaching a maximum of 47°C on the second floor at 4:00pm. The Hav-ht series was recorded at the beginning of April, and at this time of year the 1pm solar perspective shows that the sun does not quite penetrate to the ground floor of the courtyard, and so this area remains cool throughout the day. However, in May and June, when air temperatures are much hotter, and the sun higher in the sky, this is not likely to be the case, and the author would expect surfaces, even on the ground floor, to be considerably hotter than recorded air temperature during the afternoon. During this extreme hot, dry period it is very unlikely that the courtyard would pre-cool Hotel Suraj’s ventilation air.

4.4.7. Air movement - Vyas-Air series

Medium range kata thermometers were used to measure indoor air speeds at a height of 600mm above floor level. A grid was drawn on the floor plan and spot measurements taken at each grid point. The data collectors worked in 3 teams of 2, each pair being responsible for one of three rows of locations (row a, b or c). The cooling time of the Kata thermometer was measured using a stopwatch, whilst the air temperature was simultaneously recorded using a hand held digital III. 4.8. Recording velocity of air movement in Hotel Suraj.

III. 4.9. Recording direction of air movement in Hotel Suraj.

thermometer. The horizontal direction of the air movement was estimated using the smoke from burning joss sticks. This method was not used to estimate vertical direction as the heat from the joss stick would have made this unreliable. An average wind speed and direction measurement was recorded on the roof, using a vane anemometer, for the duration of the exercise. This process was repeated three times during the day, nine times in total. The morning readings were taken, as far as possible, between 9:00am and 10:00am, the afternoon readings between 3:00pm and 4:00pm and the evening readings between 10:00pm and 11:00pm. These nine runs are as follows:

29-3-96-EVE. Readings taken from 22:00 to 22:40 on the first floor giving 18 locations in total.

30-3-96-MORN. Readings taken from 9:35 to 10:27 on the ground, first and second floors, giving 33 locations in total.

30-3-96-AFT. Readings taken from 15:10 to 16:05 on the ground first and second floors, giving 29 locations in total.

31-3-96-MORN. Readings taken from 10:55 to 12:22 on the first and second floors giving 24 locations in total.

31-3-96-AFT. Readings taken from 15:40 to 16:10 on the ground and first floors giving 23 locations in total.

1-4-96-MORN. Readings taken from 10:23 to 11:25 on the ground first and second floors giving 28 locations in total.

1-4-96-EVE. Readings taken from 22:00 to 23:31 on the first floor giving 19 locations in total.

2-4-96-AFT. Readings taken from 15:33 to 16:09 on the ground and first floors giving 23 locations in total.

4.4.7.1. Results These recorded air speeds are shown on the following plans. The arrows represent the location, direction and magnitude of the air movement (see Appendix A for data in tabulated format).

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4.4.7.2. Discussion Illustrations 4.10. to 4.12. show estimated airflow patterns during the morning, afternoon and evening in Hotel Suraj. The 10:20am and 10:30pm courtyard surface temperature recordings discussed in section 4.4.6. are concurrent with the 1-4-96-MORN and 1-4-96-EVE air movement series and these results have been used to inform the likely vertical air movement within the main courtyard of Hotel Suraj.

Ill. 4.10. Estimated direction of air movement in Hotel Suraj between 10:00am and 11:00am at the beginning of April 1996.

Ill. 4.11. Estimated direction of air movement in Hotel Suraj between 3:00pm and 4:00pm at the beginning of April 1996. 68

Ill. 4.12. Estimated direction of air movement in Hotel Suraj between 10:00pm and 11:00pm at the beginning of April 1996.

Results from all air velocity data recorded on the second floor suggest that, throughout the day, the prevailing wind is the driving force behind indoor air movement on this level. However, the results for the first floor show evidence of stack effect within the central courtyard with air moving outwards from the courtyard in the hot afternoon, and inwards during the cooler evening, despite the constant direction of the prevailing wind. In the hotter months of May and June, with the sun penetrating to the floor of the courtyard the author would expect this effect to be increased. In general Hotel Suraj is well designed regarding air movement, providing ample opportunity for occupant control. Openings are located to facilitate cross ventilation and shutters are designed to enable varying degrees of air movement. In addition, the measurements recorded in the haveli suggest that, during the hottest part of the year stack effect within the courtyard would further facilitate ventilation, regardless of outdoor air velocity.

4.5. Conclusions. Results from the temperature data gathered in and around Hotel Suraj show that:

In the summer the majority of indoor spaces have cooler daily average temperatures than outdoors. 69

In the winter the majority of indoor spaces have warmer daily average temperatures than outdoors.

Most of the monitored indoor spaces have a similar, or slightly higher, annual average temperature than outdoors.

Daily temperature range and annual temperature range increase from the bottom to the top of the haveli at all times of year, giving a variety of maximum and minimum indoor temperatures.

The central courtyard contributes, by means of stack effect, to the ventilation of the indoor spaces from April through to July.

As discussed in chapter 3, only a few rooms in a haveli were traditionally designed for a specific purpose. Instead, larger rooms were used as season, need and mood dictated. The results recorded in Hotel Suraj indicate that, at any one time, there are a variety of indoor temperatures available. The occupants migrate around the haveli at different times of day, in the various seasons, taking advantage of the different climatic conditions in each place. Roaf (1989) also noted this "intra-mural migration" in her study of traditional housing in Yazd. In addition the results suggest that the available mass in Hotel Suraj is the largest factor governing the climate indoors. In high mass zones, such as the basement, with little or no daily fluctuation in temperature, long logging periods are essential, spanning, ideally, a minimum of twelve months. This chapter has detailed the temperatures achieved within Hotel Suraj over a twelve month period. Chapter 5 converts these recorded temperatures into predicted occupant thermal comfort sensation.

CHAPTER 5. THERMAL COMFORT IN JAISALMER

This chapter gives an introduction to the science of thermal comfort, describing both climate chamber and field study methods of comfort prediction. A comfort survey conducted in Jaisalmer is analysed, and evaluated in the wider context of accepted adaptive model comfort prediction equations. The results are applied to the assessment of the data detailed in chapter 4 in terms of occupant comfort level.

5.1. Introduction “The thermal qualities - warm, cool humid, airy, radiant, cosy are an important part of our experience of space; they not only influence what we choose to do, but also how we feel about the space.” Heschong (1990) In reality the temperatures recorded in a building mean little unless set in the context of occupant comfort. Olygay (1992) states that man’s energy and health depend in large measure on the direct effects of his environment. In excessively hot or cold conditions both health and productivity decline. Man, however, can survive in a wide range of environments. The following sections detail mans adaptive abilities and limitations. Later in the chapter upper and lower comfort limits for the population of Jaisalmer will be estimated over a twelve month period, and used to assess the performance of Hotel Suraj.

5.2. Heat Exchange mechanisms Man has developed thermal strategies to cope with adverse climates. The body keeps the temperature of the internal tissue more or less constant, regardless of the relatively wide variations in the external environment. The physical means of heat exchange between the human body and its surroundings comprise the processes of radiation, conduction, convection and evaporation. Radiation is in the form of electromagnetic waves, which pass from a hot object to a cooler one even through a vacuum. The amount of heat loss by radiation from the body to the surroundings is dependent upon the temperature difference between the body and the mean temperature of all the surfaces surrounding it. Conduction refers to the flow of heat from one object to another with which it is in contact. Little body heat exchange takes place via this route. Convection indicates the exchange of warm and cold molecules between the surfaces of objects separated by a fluid or gaseous medium. Heat loss or gain by convection is dependent upon the difference in temperature between the body’s surface and the air. A layer of air in contact with the surface is heated up, and because air is a poor conductor, heat loss relies primarily on the removal of this layer of warm air by air currents. Wind or cooling of the skin with an electric fan can be considered as a forced convection, and it is quite effective as a heat exchange route. Customarily convective heat exchange is assumed to be proportional to the square root of the air velocity (Givoni, 1969). The humidity determines the evaporative capacity of air and hence the cooling efficiency of sweating. Evaporation of sweat is the chief protective mechanism against over heating when ambient temperature rises above 32°C to 34°C (Samueloff, 1980).

5.3. Behavioural adaptations Man can also consciously control the amount of heat lost and gained by the body through behavioural changes. The most obvious reaction is to change clothing level, but people can also regulate their metabolic rate through a change in activity level, or maximise their surface area by adopting a different posture. However in an overheated climate there is a limit to how much clothing can be taken off. Cook (1981) points out in hot climates were radiation is dominant (as in Jaisalmer), more clothing rather than less may be desirable. Research by Berger (1988) indicates that in a hot dry climate the main discomfort felt is due to the dryness of the air. When humidity is below 20% the skin withers and chaps. Sweat evaporation increases the humidity of the air close to the skin and at temperatures above 37°C this air layer will be cooled. Under these conditions he suggests baggy white garments with small renewal rates, as most thermally suitable. In addition seasonal migration patterns can be observed in the people of Jaisalmer. Although food intake does not produce any significant variation of heat production throughout the day (McIntyre, 1980) it has been noted (Cook, 1981) that in overheated climates food is lighter, with less animal fats consumed. The author was surprised at the amount of piping hot chai (spiced Indian tea) consumed in Jaisalmer. Research by Clark et al. (1977) showed that in hot conditions, were the body is sweating, the intake of very hot 75°C drink will produce a sharp increase in the sweat rate, which paradoxically leaves the skin temperature lower than it was, and the person feeling cooler. A hot drink on a hot day is more effective at cooling the body than a cool drink.

5.4. The science of thermal comfort The advent of fire allowed human beings a mechanism, independent of the fluctuations of climate and their own metabolism, for coping with adverse climates. Fascination with this potential for control of the environment prompted the invention of mechanical systems that made natural thermal strategies seem obsolete by comparison. First the problem of heating was solved, and then Wilis Cartier invented air-conditioning. Once the technology to completely control the thermal environment was developed people became curious about what a truly optimal thermal environment might be. The science of thermal comfort was born. In 1966 the American Society of Heating, refrigeration and Air-conditioning Engineers defined thermal comfort as “that state of mind which expresses satisfaction with the thermal environment” (ASHRAE 1966). Three years later Givoni (1969) defined it as “the absence of irritation and discomfort due to heat or cold”. The science of thermal comfort has been concerned with predicting what set of conditions corresponds most closely to this optimal thermal environment, and how tolerant people are of deviations from it. As thermal sensation cannot be measured in any direct way scales of warmth sensation were developed. In this way subjective comfort votes were given numerical values and treated quantitatively so that statistical analysis may be carried out. Yaglou (1927) was using the first of these scales over seventy years ago, but the scale used throughout this project is the scale introduced by Bedford (1936) during his survey of conditions in factories in the United Kingdom.
Too warm
Comfortably warm
Comfortable (and neither cool nor warm)
Comfortably cool
Too cool
Much too cool

5.5. Climate chambers
Many attempts have been made to express some or all four environmental variables in one single figure or comfort index. Early work in this area was carried out using climate chambers - specially constructed rooms in which the thermal environment could be carefully controlled. The most widely recognised work done on climate temperatures is that done by Ole Fanger (1970). He proposed a model in which the heat produced through metabolism was equal to the heat lost to the environment from the surface of the body by convection, evaporation or radiation. Using the laws of heat exchange he devised a formula for predicting the comfort vote for a set of conditions - the Predicted Mean Vote or PMV. Fanger’s research was performed in steady-state conditions. Subjects remained in any one particular set of condition for three hours and so time was effectively stopped. It was Fanger’s stated view that ‘in all case thermal comfort is the ‘product’ which is produced and sold to the customer by the heating and air-conditioning industry’ (Fanger 1970), and in such an environment, conditions would be held more or less constant. However, in non-airconditioned buildings, the environment is constantly changing.

5.6. The Adaptive Model
The adaptive model of thermal comfort was first proposed in 1972 by Nicol et al. Humphreys (1993) described the adaptive principle this model is based on: “If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort”. An alternative technique was used. People were met in their normal environment, whilst performing their normal activities, and asked their opinion of the thermal environment. The environment is measured, but not altered as it is the reaction to their real life context that is being explored. Results from field surveys (Humphreys, 1976) indicated that in the long term people in different places adapt to the average conditions they experience. About 90% of the variation in the comfort temperatures can be explained by the variation of the average temperature. Comfort temperature is related to indoor temperature, which, particularly in free-running buildings, is related to outdoor temperature. These results are shown in graph 5.1. Each circle represents the results of one survey.

Graph 5.1. The relationship between the comfort temperature $T_c$ derived from a particular survey, and the monthly mean outdoor temperature (from Humphreys, 1978).

Humphreys (1978) was the first to show the strength of the relationship between outdoor temperature and comfort temperature indoors. Using regression analysis he showed that:

$$ T_c = 12.1 + 0.53T_o $$  
where: $T_c$ = Comfort temperature $T_o$ = Monthly mean outdoor temperature

To reinforce the notion that PMV was not telling the whole story Humphreys (1992) took published research from 5 such field studies and compared PMV with actual mean vote. He found that PMV was about 1.5 units too low at 20°C and about 1.5 units too high at 33°C and unbiased at around 27°C. This showed that people are comfortable in a much wider range of indoor climates than would have been expected from the results of climate chamber research. The discrepancy with PMV could be explained by behavioural adaptations to local climates. In Nicol’s field survey work in Pakistan (Nicol et al., 1994) it was shown that changes in clothing level accounts for about 3.5 - 4°C of the change in comfort level, and changes in air speed accounts for about 1-2°C. In this environment it was shown that

$$ T_c = 17.0 + 0.38T_o $$  
where: $T_c$ = Comfort temperature $T_o$ = Monthly mean outdoor temperature

5.7. The Jaisalmer comfort survey.
During the March96 field study period a short transverse thermal comfort survey of the general population in Jaisalmer was undertaken. Seventy-three people were interviewed in and around the streets of the fort during the morning, afternoon and evening of the 29th March and 2nd April.

5.7.1. Method
Illustration 5.1 shows the format of the questionnaire used for the Jaisalmer survey.

COMFORT SURVEY
1. Subject number (allocate)
2) Indoors/Outdoors
3) Date
4) Time
1. 2. 3. 4. 5.

6) Preference: Much warmer A bit warmer No change A bit cooler Much cooler
7) Preference:


III. 5.1. Jaisalmer survey questionnaire format

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The surveys were undertaken by groups of 2 to 3 researchers. One researcher asked the survey questions whilst the others simultaneously recorded the environmental measurements. Air and wet bulb temperatures were measured using a whirling hygrometer. Wet bulb temperature was converted into water vapour pressure using the formula:

\[ \text{Pa} = \exp(18.956-(4030/(\text{Tw}+235)))-0.667(\text{Ta}-\text{Tw}) \]

And into relative humidity using the formula:

\[ \text{RH} = \frac{\text{Pa}}{\exp(18.956-(4030/\text{Ta}+235))} \] (from McIntyre, 1980) where: \( \text{Pa} = \) water vapour pressure \( \text{Tw} = \) wet bulb temperature \( \text{Ta} = \) dry bulb temperature \( \text{RH} = \) relative humidity

5.7.2. Calculating comfort temperature. As the sample size in the Jaisalmer study is relatively small the Griffiths method has been used to estimate the comfort air temperature (\( T_c(\text{air}) \)) and the comfort globe temperature (\( T_c(\text{globe}) \)). Griffiths introduced this method in 1990 for assessing the mean comfort temperature for a small sample of comfort votes. He was dealing with data from buildings and groups of buildings in which he had small samples of subjects. The data was insufficient to produce a reliable regression estimate of the comfort temperature. Griffiths made the assumption that the increase in temperature for each scale point on the comfort scale was 3°C for a 7 point scale. This is the value obtained from climate chamber estimates. For each comfort vote he subtracted 3°C times the number of scale points above neutral (4) to obtain the temperature which might be expected to result in neutrality. So, for each subject, the estimated neutral, or comfort air temperature is calculated using the following equation:

\[ T_c(\text{air}) = \text{Ta}-(C-4)3 \]

Where: \( T_c(\text{air}) = \) comfort air temperature \( \text{Ta} = \) air temperature at time of comfort vote \( C = \) comfort vote (on a seven point scale) By taking the mean of these temperatures he obtained a mean comfort temperature for the sample. The results of the survey, including estimated globe and air comfort temperatures, are shown in table 5.2. C MEAN 4.59

<table>
<thead>
<tr>
<th>Tglobe</th>
<th>Tair</th>
<th>Twet</th>
<th>Pa</th>
<th>RH</th>
<th>TfingTip</th>
<th>Tc(air)</th>
<th>Tc(globe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34.28</td>
<td>32.15</td>
<td>18.28</td>
<td>11.80</td>
<td>0.25</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Tbl. 5.2. Results of the Jaisalmer comfort survey.

5.7.3. The wider context Table 5.2 shows that, at the time of the survey (end of March / beginning of April), the comfort air temperature for the residents of Jaisalmer is around $30^\circ$C. In order to confirm the suitability of both Humphrey's and Nicol's comfort prediction equations in the climate of Jaisalmer, values for $T_c$ for March and April have been calculated using both methods. Table 5.3 shows the results using both standardised monthly mean outdoor temperature (Krishan et al., 1995), and real monthly mean temperature (recorded in the courtyard of Hotel Suraj).

<table>
<thead>
<tr>
<th>MARCH</th>
<th>APRIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monthly Mean ($T_o$)</td>
<td>Monthly Mean ($T_c$)</td>
</tr>
<tr>
<td><strong>Humphrey's</strong></td>
<td><strong>Humphrey's</strong></td>
</tr>
<tr>
<td>Standard data</td>
<td>Real data</td>
</tr>
<tr>
<td>26.5</td>
<td>27.2</td>
</tr>
<tr>
<td>26.07</td>
<td>27.08</td>
</tr>
</tbody>
</table>

MARCH APRIL

<table>
<thead>
<tr>
<th>Monthly Mean ($T_o$)</th>
<th>Monthly Mean ($T_c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Humphrey's</strong></td>
<td><strong>Nicol's</strong></td>
</tr>
<tr>
<td>Standard data</td>
<td>Real data</td>
</tr>
<tr>
<td>26.5</td>
<td>27.2</td>
</tr>
<tr>
<td>26.15</td>
<td>26.52</td>
</tr>
<tr>
<td>27.07</td>
<td>27.08</td>
</tr>
</tbody>
</table>
Tbl. 5.3. Estimated comfort air temperature for March and April using Humphrey's and Nicol's equations.

<table>
<thead>
<tr>
<th></th>
<th>Humphrey's equation</th>
<th>Nicol's equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard data</td>
<td>31.5</td>
<td>31.5</td>
</tr>
<tr>
<td>Real data</td>
<td>32.17</td>
<td>32.17</td>
</tr>
<tr>
<td></td>
<td>29.15</td>
<td>28.80</td>
</tr>
<tr>
<td></td>
<td>28.08</td>
<td></td>
</tr>
</tbody>
</table>

Results from table 5.3 show that both Humphrey's and Nicol's comfort equations give acceptable results for Jaisalmer at this time of year. The average comfort temperature using real data for March and April is 27.84 using Humphrey's equation and 27.58 using Nicol's equation. Both these results are slightly lower than the value from the Jaisalmer survey. However, the survey was conducted only during the warmer times of day. If subjects had been interviewed during the cooler night-time or during the early morning hours, the comfort temperature may well have been lower. In addition, the level of humidity in Jaisalmer is very low, making higher temperatures slightly more tolerable. The effects of clothing and activity levels have been discussed in earlier sections. As the comfort temperature result achieved using Humphrey's equation appears slightly more representative of the survey results, it has been used for all further comfort analysis.

5.8. Thermal comfort in Hotel Suraj: More recent research has shown that the relationship between comfort and outdoor temperature is improved by using the running mean of the daily average outdoor temperature, instead of the monthly mean of the outdoor temperature (Nicol et al., 1995). This research also showed that the relationship was most improved when the running mean series was assigned a weight of 0.2. Results from analysis in Chapter 8, detailed in table 8.11, shows that this weight, assigned to daily average data, would give a cycle time shift of around 6 days. This is in strong agreement with the conclusion drawn by Nicol in 1992 that people adapt almost completely to a change of conditions in around a week. However, there are limits to the range of indoor temperatures that people can adapt to. Nicol et al.'s research (in press) on interior design temperatures in Pakistan, indicates that the comfort temperature ranges from 19.7°C to 31.3°C, in a climate with a monthly mean temperature range of 4.9°C to 35.5°C.

5.8.1. Method used for calculating comfort levels in Hotel Suraj:

The running mean series, with a weight of 0.2, of the Suraj12months, daily average series was calculated.

The predicted daily comfort temperature \( T_c \) was calculated using equation 5.1, replacing the monthly mean outdoor temperature \( T_o \) with the calculated daily value from the running mean series.

For a detailed description of running mean see chapter 8, section 8.5. 82

Using the Bedford thermal sensation scale, and assuming a 3°C increase for each scale point, upper and lower limits for each thermal sensation were calculated for each day. The lower limit for neutrality (4) was calculated as the predicted comfort temperature minus 1.5°C; the lower limit for comfortably cool (3) was calculated by subtracting 4.5 from the predicted daily comfort temperature, and so on.

Each division of the thermal sensation scale was assigned an appropriate colour.

The raw data (recorded at 2.4 hour intervals) for each of the monitored zones of the Suraj12months data series was, in turn, superimposed onto the thermal sensation graph.

5.8.2. Comfort level results. Graphs 5.2 to 5.6 show the predicted comfort results for the outdoor, and each of the four indoor monitored zones of the Suraj12months series. Predicted daily comfort temperature results ranged from a minimum of 20.22°C in the winter to a maximum of 30.83°C in the summer, well within the comfort temperature limits proposed by Nicol et al. for Pakistan.

Graph 5.2. Predicted outdoor comfort levels for the Suraj12months recording period (data at 2.4 hour intervals).

Colour associations are discussed in more detail in chapter 6, section 6.2. 83

Graph 5.3. Predicted comfort levels in the basement of Hotel Suraj from October, 1995 to September, 1996 (data at 2.4 hour intervals)
Graph 5.4 Predicted comfort levels in the ground floor back zone of Hotel Suraj from October 1995 to September 1996 (data at 2.4-hour intervals).

Graph 5.5 Predicted comfort levels in the first floor back zone of Hotel Suraj from October 1995 to September 1996 (data at 2.4-hour intervals).

Graph 5.6. Predicted comfort levels in the second floor back zone of Hotel Suraj from October 1995 to September 1996 (data at 2.4-hour intervals).

Data for second floor back zone only available for six months.

5.8.3. Discussion. The proportion of time that occupants of each of the monitored areas would experience thermal discomfort was calculated. Discomfort includes bands 7 (much too warm), 6 (too warm), 2 (too cool) and 1 (much too cool). The results are shown in table 5.4.

% OCTOBER NOVEMBER DECEMBER JANUARY FEBRUARY MARCH APRIL MAY JUNE JULY AUGUST SEPTEMBER

OUTDOORS
BASEMENT
GROUND
FIRST
SECOND
COLD
HOT
COLD
HOT
COLD
HOT
COLD
HOT
COLD
HOT
2.07
5.52
0.69
0
0
0
34.48
0
40.0
7.0
0
0
0
0
Graph 5.2 shows that the outdoor temperature is very rarely comfortable in Jaisalmer, being too cool in the winter and too warm in the summer. October, November and the end of February / beginning of March are the most comfortable times of the year. Although table 5.4 shows January as having the highest occurrence of thermally uncomfortable outdoor temperatures, graph 5.2 indicates that during May and the first half of June day time temperatures are often in the 'much too warm' (7) band. Whilst the inhabitants of Jaisalmer often experience discomfort in the winter months, it is the hot, dry summer months of May and June that are the most thermally stressful time of year. This is reflected in the results of table 5.4 which show that all monitored zones in Hotel Suraj perform well thermally during the months November through to February. Both the basement and ground floor back zone perform very well throughout the year. Even during the hot, dry summer months the recorded temperatures in both zones remain, on the whole, thermally comfortable. It seems ironic that, in the harsh climate of Jaisalmer, where exposed mass is so effective in keeping indoor temperatures within the bounds of human thermal comfort, basements are never inhabited, but rather kept as secure storage spaces for precious belongings. This is in contrast to the findings of Prasad (1988) in Old Delhi, where, during the hot season, inhabitants of the havelis often used the basements for a siesta midafternoon. In addition Roaf's research (1989) on the traditional houses of Yazd, showed that the basements in this area were often ventilated, and consequently used for sleeping during extremely hot periods. Although the first floor back zone appears, in table 5.4, to perform considerably worse than outdoors during the summer, particularly during the high stress months of April, May and June, graph 5.5 shows that this zone does moderate the summer climate to some extent. Whilst the temperature outdoors is often 'much too warm' (7) the temperature recorded in the first floor zone very rarely rises above 'too warm' (6). However, the results do indicate that both the first and second floor zones should be considered as winter rooms.
5.9 Conclusions Results from this chapter indicate that:

The comfort temperature for the indigenous population of Jaisalmer, at the end of March/beginning of April, is in the region of 30°C.

This is slightly higher than accepted adaptive model comfort equations would predict. Possible contributory factors are a) The very low humidity levels characteristic of the region. b) The survey was only conducted during the warmer periods of the day.

Of the comfort equations examined, Humphrey's equation proved more representative of the population of Jaisalmer.

The basement and ground floor back zones in Hotel Suraj perform very well throughout the year.

The first and second floor zones of Hotel Suraj perform well during the winter months. However, the first floor zone performs poorly during the high stress months of April, May and June. There is no second floor zone data available for this season.

This chapter detailed the predicted thermal comfort levels in the monitored zones of Hotel Suraj over a twelve month period. The results again show that each zone performs
differently at different times of the year, some being more comfortable in the cold season and others in the hot. Although the author has put considerable effort into the visual presentation of data in both this and the previous chapter, there still remain some problems with displaying large amounts of data, particularly over long periods of time. Chapter 6 describes two programs developed by the author for the visualisation of thermal data in terms of temperature and predicted thermal comfort sensation. When used with the data discussed in chapter 4 these programs allow the user to examine temperatures or predicted thermal sensation in any monitored zone, at any time of day during the monitoring period.

References - Chapter 5


CHAPTER 6. PRESENTATION OF RESULTS

This chapter discusses the problems associated with presenting large amounts of data, particularly if collected in many locations over long periods of time. The concept of temperatures represented as colours is explored and a temperature spectrum is proposed. A stand-alone computer program, designed to animate temperature data over time is developed and discussed. These principles are extended to develop a second stand-alone computer program designed to predict and present thermal comfort sensation levels.

6.1 Introduction "findings, if potentially useful to the designer are often communicated in a language she finds difficult to understand" Sir Hugh Casson, 1976. During the course of this research large amounts of temperature data was collected in many different locations over long periods of time. Whilst graphical representations of data are, in many instances, appropriate and informative, it was felt, in the following circumstances,
6.6. Key Features. The aim throughout was to keep the program simple and convenient to use, whilst still being visually striking. Several features
predecessor, Visual Basic is easy to understand because it is close to English. In addition it has the advantage of a simple visual method of
initially, but the principles of the program could later be extended to the animation of other environmental variables with only minor changes.
file (preferably in Bitmap format). Both methods had advantages, but the latter option held most potential. It involved more effort and time
The second option was to develop a stand-alone computer program that could import any data file (preferably in Excel format) and any picture
video being associated to a specific data set.

The following sections describe the evolution of two presentation tools developed in order to address these shortcomings.

6.2. Temperatures represented as colours The sensation of warmth is not originally perceived by the eye, but even so we find it natural to talk of
warm and cold colours. Although the association of colour with thermal sensation is open to individual interpretation, research has shown that
certain general reactions are common (Luscher, 1971; Sivik, 1974). Heschong (1990) suggests this originates from the way we perceive
temperature. Our thermal sense is a separate sense located in specialised nerve endings. These thermal nerve endings are heat-flow sensors -
they monitor how quickly our bodies are losing or gaining heat, and thus judge how much colder or warmer than body temperature an object
is. Our thermal sensors therefore cannot perceive temperature at a distance. Instead we have learnt to rely on other senses to give us advance
clues. Thus reds and browns remind us of the light from a warm fire, and blues feel cold, like water and ice. These reflex associations were used to
develop colour spectrums that would immediately give an idea of relative temperature.

3.3. Initial temperature spectrum The initial temperature spectrum, shown in illustration 6.1, had blues representing colder temperatures, reds
representing warmer temperatures and yellow in the centre as the neutral colour. 92

III. 6.1. Initial temperature spectrum.
This colour set was used to display selected data from the Summer95.xls temperature series, as part of an exhibition of the author’s research, in
the Herron Gallery at the University of East London. The data for three consecutive hot days was combined to produce data for an average hot
day. The temperature range for the period was divided into 9 two-degree bands, and a different colour from the colour set allocated to each
band. Each recorded temperature was thus converted to a colour and then transferred onto the associated logger zone on the drawn section of
Hotel Suraj. The process was repeated for each of eight different times of day. Illustration 6.2 shows the colour-coded sections. This gave an
attractive result, but it was thought that the middle tones were ambiguous. Red is definitely hot and blue is definitely cold, but is yellow
perceived as cooler or warmer than green?

6.4 Final temperature spectrum. Research carried out by Sivik in 1974 demonstrated that ‘orangy-red’ and ‘greenish blue’ were most strongly
III.5.2. Manually coloured sequence associated with hot and cold respectively. In order to for Hotel Suraj, avoid the previous ambiguity, two such
hues, with 100% saturation, were chosen to represent the hot and cold extremes of the new spectrum. All middle tones were achieved by adding
a varying percentage of whiteness to either of the polar hues. The resulting spectrum is shown in illustration 6.3.

III. 6.3. Final temperature spectrum.
Due to the problems associated with colour authenticity and reproduction, the colour spectrum is also shown, in illustrations 6.4 and 6.5, using
the Natural Colour System developed by Hard (1969). This is a systematic method of describing the relationship between colours purely from
their perceptual qualities. The system describes hue as the degree of similarity of any colour to the four basic colour attributes: yellowness, redness, blueness and greeness. Saturation is described in terms of ‘Chromaticness’ which means the degree of similarity to the most
conceivable colour strength of a certain hue. Brightness has no directly comparable dimension in the Natural Colour System; instead each
colour is described according to its visual similarity to whiteness and blackness. Black is signified by the letter s, which represents the Swedish
equivalent Svart.

III. 6.5. Middle tones of the colour spectrum shown using the Natural Colour System.
The more time that was spent discussing and experimenting with this and the previous colour spectrum, the more it became apparent that the
human eye was very sensitive to colour changes, being able to detect even the slightest alteration in hue. This was essential as the temperature
range for a hot-dry area such as Jaisalmer is very large (over 50°C annually), and so for this approach to be useful, a large number of different
colours would be required. This method of presentation proved especially effective in demonstrating indoor thermal
performance as relative to outdoor recorded temperature, but the procedure, by hand, was very time consuming.

6.5. Automating the process. With large data sets a method for automating the process was needed. Two options for achieving this were
investigated:

- The first was to create a playable video file for each of the data sets. This could be created in an application such as Director with each playable
video being associated to a specific data set.

- The second option was to develop a stand-alone computer program that could import any data file (preferably in Excel format) and any picture
file (preferably in Bitmap format). Both methods had advantages, but the latter option held most potential. It involved more effort and time
initially, but the principles of the program could later be extended to the animation of other environmental variables with only minor changes.
As the author had very little programming experience, a language was needed that was relatively easy to learn, but with good graphical results.
Visual Basic, a language evolved from the BASIC (Beginner's All-Purpose Symbolic Instruction Code) programming language was chosen. Like its
predecessor, Visual Basic is easy to understand because it is close to English. In addition it has the advantage of a simple visual method of
creating the application's appearance and a straightforward mechanism for responding to events (such as the click of a mouse button).
6.7. Thermamator…. an overview. Thermamator is a thermal-data presentation tool, designed as an alternative to the graph. It enables the user to identify any number of monitored zones on a pictorial representation of a building, or studied area, and link these zones to columns of data stored in an Excel spreadsheet. Each cell, in each row of data in the spreadsheet is, in turn, converted into an appropriate colour (see section 6.4). The colour is automatically applied to the linked zone on the picture. The program moves through the data set, row by row, enabling instant and effortless visual comparisons of the thermal characteristics of different building zones, and their variation over time.

6.8. Instructions for use. 6.8.1. Preparation of input files. Temperature data files. These must be imported in Excel v.5 format. Time/Date information must be held in column A, with column headings in row 1, as shown in Illustration 6.6. These column headings will be used to prompt the user to identify each temperature zone on the picture file.

III.6.6. Temperature data layout - time in column 1, column headings in row A.

Picture files. These must be imported in bitmap format. The colouring of the zones is achieved with a flood-fill method. By double clicking with the left mouse button the user identifies a x, y co-ordinate. The program then flood-fills from this point until a black boundary is reached. It is therefore necessary to surround each data logger zone with a black boundary. The simplest method of achieving this is on a high magnification screen in an application such as Microsoft Paint.

6.8.2. Loading picture files. Select Load BMP File from the File menu. A dialogue box will appear allowing you to move through the directory tree and select any available BMP file (Illustration 6.7).

III.6.7. Importing picture files - select Load BMP File from the File menu.

6.8.3. Loading temperature data files. Select Load Txt File from the File menu. A dialogue box will appear allowing you to move through the directory tree and select any available Excel file. A dialogue box will appear asking for the number of temperature channels in the selected data set. This is usually the total number of columns minus the date/time column.

6.8.4. Linking temperatures to zones. A message box appears asking for the first temperature zone to be identified with a doubleclick of the left mouse button on the appropriate area of the picture file (Illustration 6.8). The zone is then flood-filled with grey. If the selection is correct click Accept and the message box will once again appear asking for the identification of the second temperature zone. If however the area coloured grey is not correct select Cancel and the message box will reappear asking once again for the identification of the first temperature zone.

III.6.8. Linking temperatures to zones.

6.8.5. Changing the temperature range. By default the temperature range is set from 9°C to 47°C. Forty colours are pre-programmed into the application, each one indicating a temperature increment of 1°C. To change the temperature range select Change Temp. Range from the Options menu. A dialogue box appears allowing the user to input alternative minimum and maximum temperature values.

6.8.6. Animating the data. Once all temperature zones are identified the Play button is enabled. Click on this and the programme runs from the beginning to the end of your data set at a default interval of 0.25 seconds (Illustration 6.9). To change this interval select Speed from the Options menu and tick the preferred setting. To move manually through the data set use the Rwd and Fwd buttons.

III.6.9. Animating the data.

6.8.7. Quitting the application. The animation is halted using the Stop button, and selecting Exit form the File menu terminates the application.

6.9. Further developments. In the same way that temperatures can be represented as colours, so can the feeling of warmth and coolness. The principles of Thermamator have been extended to the animation of comfort level, based on Humphreys' comfort temperature equation (1978), which showed that the most basic images created in Paint to be used in the program, as well as being convenient for screen capture images and scanners. 2. The end user must have the facility to set the temperature range. By default this will be set to suit Jaisalmer's climate, but if the program is to be used in other climatic zones it must allow the user to input alternative minimum and maximum values. 3. The program must be able to cope with data sets of different sizes, not only different numbers of columns, but also different lengths of file. 4. The linking of a data column to an area on the picture file must be simple and visual. The end product, named Thermamator, is a distributable application contained on 3 HighDensity diskettes or CD for use with Windows 95 or Windows NT. It is installed using Microsoft's Setup Wizard.

6.10. Applying the same principles used for temperature/colour association in Thermamator, the seven divisions of the Bedford Scale of thermal comfort are to be related to the temperature outdoors in the following manner:

\[ T_c = 12.1 + 0.53 \cdot T_o \]  

Where:  
\( T_c \) = comfort temperature indoors \( T_o \) = monthly mean outdoor temperature

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Applying the same principles used in temperature/colour association in Thermamator, the seven divisions of the Bedford Scale of thermal sensation (Bedford, 1936)2 were each assigned an appropriate colour. Applying these colours to Humphreys’ equation (equation 6.1) and assuming each thermal sensation division spans $3^\circ$C3 gives illustration 6.10.

III.6.10. Thermal sensation spectrum.

More recent research (Nicol et al., 1995) has shown that the relationship between comfort temperature indoors and outdoor temperature is improved by using the running mean4 of the daily average outdoor temperature, instead of the monthly mean outdoor temperature. The equation used for calculating the running mean of a series is:

$$e_i = W \cdot Y_i + (1-W) \cdot e_{(i-1)}$$

The value of the exponentially smoothed series already computed in time period $i$ = value of the exponentially smoothed series already computed in time period $(i-1)$ = observed value of the time series in period $i$. $W$ = subjectively assigned weight or smoothing coefficient (where 0 “9”) Then Checks for characters other than 0 through to 9 Beep KeyAscii = 0 End If

End Sub

FrmTimeInt.

Private Sub cmdCancel_Click() Unload cmdCancel.Parent

End Sub

Private Sub cmdEnter_Click() TimeInt = frmTimeInt.txtTimeInt.Text Weight = 0.2 * TimeInt / 24 Sets exponential weight depending on time interval between logger recordings

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frmThermal.cmdplay.Enabled = True frmTimeInt.Hide

End Sub

Private Sub txtTimeInt_KeyPress(KeyAscii As Integer)

Dim Key As String

Key = Chr(KeyAscii) If (Key < “0” Or Key > “9”) Then Checks for characters other than 0 through to 9 and . If Key “.” Then Beep KeyAscii = 0 End If

End If

End Sub

Module, declarations

Public TheTxtFile As String
Public TheBmpFile As String
Public c As Integer
Public anchorX() As Single
Public anchorY() As Single
Public tempX As Single
Public tempY As Single
Public Columns As Integer
Public ComfTemp As Long
Public TimeInt As Long
Public HalfLife As Long
Public Weight As Long

Declare Function ExtFloodFill Lib “gdi32” (ByVal hdc As Long, ByVal x As Long, ByVal y As Long, ByVal crColor As Long, ByVal wFillType As Long) As Long

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Public Function FixPath(InPath As String) As String

Dim T As String

T = InPath If Right$(T, 1) “\” Then T = T + “\” Sticks a backslash on the end of Inpath if there is not one there already FixPath = T

End Function

Public Sub SetFillColor() Dim a As Integer

On Error GoTo fileerror

For a = 1 To Columns If frmThermal.Label1(a).Caption < (ComfTemp - 7.5) Then frmThermal.picBuilding.FillColor = &HF23100 If temperature more than 7.5 deg C below Comftemp set floodfill colour to dark blue ElseIf frmThermal.Label1(a).Caption < (ComfTemp - 4.5) Then frmThermal.picBuilding.FillColor = &HFF8A8A more than 4.5 deg C below comf temp - mid blue

ElseIf frmThermal.Label1(a).Caption < (ComfTemp - 1.5) Then frmThermal.picBuilding.FillColor = &HFECDCD more than 1.5 deg C below comf temp - light blue ElseIf frmThermal.Label1(a).Caption < (ComfTemp + 1.5) Then frmThermal.picBuilding.FillColor = &HE6E6E6 less than 1.5 deg C above comf temp - light grey ElseIf frmThermal.Label1(a).Caption < (ComfTemp + 4.5) Then frmThermal.picBuilding.FillColor = &HD0D0FF less than 4.5 deg C above comf temp - light blue

End If

End Sub

End Module
Else frmThermal.picBuilding.FillColor = &H107FF more than 7.5 deg C above comf temp - dark red End If

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Const FLOODFILLBORDER = 0 Const FLOODFILLSURFACE = 1

Next a Exit Sub

fileerror. MsgBox "You have reached the end of this data set.", vbOKOnly + vbInformation, "End of file" frmThermal.Timer1.Enabled = False End Sub

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APPENDIX D EXCEL MACRO FOR AUTOMATION OF STEPPED CORRELATION METHOD.

Sub MacroStepCorr() 'Outdoor temperature in column B, with heading in row 1' 'Indoor temperature in column C, with heading in row 1 Dim i As Integer For i = 1 To 400 'sets no. of stepped correlations performed' Application.Run "ATPVBAEN.XLA!Mcorrel", ActiveSheet.Range("$B$1:$C$7154").Correlates column B to column C to C7154. ActiveSheet.Range("$E$1").Offset(3 * i), 0, "C", True 'Prints correlation result in column E, offsetting 3 rows per loop' ActiveSheet.Range("$D$1").Offset(3 * i), 0.Value = i 'Prints step no. in column D, next to appropriate correlation result' Range("C2").Select 'Selects column C, row 2' Selection.Delete Shift:=xlUp 'Deletes column C, row 2, shifts remaining column C cells up' Next i End Sub

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Golden Haveli is a 42 room hotel and derives its name from the nickname of Jaisalmer, “Golden City”. The city stands on a ridge of yellowish sandstone embellished by a fort at the top, known as Jaisalmer Fort or Sonar Killa. The vision behind Golden Haveli is to offer a Heritage Hotel experience to guests and bring them close to the natural beauty, grandeur and history of Jaisalmer. Five years since its inception, Golden Haveli Hotel continues its mission with immaculate hospitality and aesthetically done Luxury Rooms. The professional team is passionate to provide comfort to valued clients and ensure a perfect retreat to weary travellers. Book Best Hotels in Jaisalmer from 452 Jaisalmer Hotels on Yatra.com. Yatra Hotels price range starts from ₹190 per night in Jaisalmer with Free Cancellation and Instant Discount. There are a number of best hotels in Jaisalmer which not only offer a comfortable stay but also give a glimpse of the opulent lifestyle of the former royal families of Rajasthan. Jaisalmer is The Sun City of India, boasting age-old forts, palaces and temples. Equipped with luxury amenities and comfort, this hotel houses spacious rooms, suites, multi-cuisine restaurants and cafes which offer culinary delights. Apart from this, desert camps and village fairs are organized by the hotel which is synonymous with the vibrant spirit of the city. % of Jaisalmer properties. Up to 30% off with Agoda Insider Deals! Prices drop the moment you sign in! All guest accommodations feature thoughtful amenities to ensure an unparalleled sense of comfort. Whether you’re a fitness enthusiast or are just looking for a way to unwind after a hard day, you will be entertained by top-class recreational facilities such as massage, garden. Enjoy unparalleled services and a truly prestigious address at the Hotel Haveli. The rooms of the Jaisalmer Desert Haveli Guest House are rich in characters, comfortable and are decorated in a luxurious traditional style. All of the rooms feature modern en suite bathrooms with running hot and cold water. The rooms are outfitted like traditional guest house, and they feature the left side welcoming proudly the guests. 3. Jaisalmer Hotel’s Gem. The Desert Haveli Guest House. Staying here is essential because one can experience the soul of the Jaisalmer. This fort bears the blessings of God the lord Krishna (history says & many traces are still in the fort proving the historical story.