A BIO-CLIMATIC APPROACH TO HOUSE DESIGN FOR SEMI-DESERT AND HOT CLIMATES
(with special reference to Egypt)

VOLUME I

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T O   E G Y P T

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ABSTRACT

The semi-desert and hot climate zones occupy one fifth of the Earth's surface. However, the design process for environmental control employs the same technical procedures as those of cold and temperate climates despite the differences in human response and the environmental factors in each zone. It is the thesis of this research to devise a bio-climatological approach to the design of building in these areas, with special reference to residential units.

Analysis of the housing problem in Egypt as a part of the global problem is considered. Both inside and outside the built environment metabolic rate, clothing, solar radiation, air temperature, air movement and humidity are the dominant parameters affecting human comfort. To assess the solar radiation contribution to the sensible effect of ambient air temperature, a computer program has been devised. A bio-climatic approach to the classification of climates is proposed, and analysis of the Egyptian climate and Cairo micro-climates emphasizes the importance of ventilation for relieving thermal stress. A method of assessing ventilation performance in relation to human comfort during overheated periods has been proposed with emphasis on the importance of studying the aerodynamics of residential units comprising multi-cell spaces. A survey of historical precedent in house design in Egypt is aimed at defining the characteristics of both old and contemporary residential units, and how they responded to their micro-climates.

As wind is the critical element determining the micro-climates within Cairo and possibly other cities of similar climate, a programme for wind tunnel experiments was carried out to examine the parameters affecting air movement around and within buildings.

A bioclimatic approach considering architectural design as a three phase process, ie analysis (feasibility studies), synthesis (spatial design) and appraisal (detail design), was considered. This included a procedure for optimization of ventilation systems. Conclusion and recommendations have been made for building forms, interior design, building regulations and new development design.

Contents

Chapter 1 : INTRODUCTION

1.1 Man and Shelter

Architecture is essentially a practical art which in applying the scientific achievements of the time attempts to satisfy man's fundamental need for shelter. Its aim is to provide means of creating the best possible environment which fulfils man's physiological, psychological and sociological needs. The importance of each of these needs varies according to variations in the environmental forces, without the knowledge of which it is impossible to design for them. Also, the importance of each of these forces and their attribution to the total problem will differ according to the difference in space, place and time. The designer is a multiple-problem solver who has to cope simultaneously with all the different sides of the problem if he is to achieve an integral solution. Since the procedure to be followed in devising a solution will depend on the problem under consideration, it is essential to identify the factors of the problem before embarking on a solution.

In semi-desert and hot climates uncomfortable physiological conditions are primarily caused by excessive heat, dryness and the failure of the body to dissipate the extra heat produced in the living process. Human physiological comfort is established when the mean skin temperature of a healthy body is maintained between 31°C (88°F) and 34°C (93°F) (230).and the skin is kept moist. The body is affected by the nature of the prevailing climatic conditions as well as by personal factors such as clothing, physical activity and the state of health. The interrelation of the various factors is complex, and the body's response to any one of them will be affected by the others, moreover, the final sensation will be the result of their simultaneous impact.

Besides the physiological needs, man requires psychological comfort which is of equal importance. Comfortable, healthy physical conditions do not necessarily secure psychological comfort, and the designer will need to consider the environmental factors influencing the psychological needs. In semi-desert and hot climates the colour schemes, landscape and proportions will have considerable influence on relaxing environmental pressure, especially during the overheated period. A fountain, besides humidifying the air, will convey a peaceful sense of coolness, reflecting the light in a relaxing pattern and enriching the acoustic quality of the space. The combined effect of the sun, water, fresh air and greenery will provide agreeable surroundings during periods of work as well as rest.

The basic attitude of the individual towards the environment is gained from the society, and his behaviour is only an attempt to fulfil his sociological needs. The architecture of any place should consider its social structure. The failure to satisfy the sociological needs will result in buildings which fall short of respecting the social structure, and may result in the breakdown of the social pattern. In upper Egypt the architects who designed the new Nubian towns ignored the social structure of the contemporary Nubian comminity. This resulted in disturbing the long-standing community relationships (230). Therefore designers should depend more on direct information from the grass roots of human needs and go beyond conventional preconceived notions, which are often inappropriate. The architect should attempt to combine all the available environmental and social forces in an integral solution to his design problem.

One may argue that the above-mentioned needs concern only the qualitative side of housing and it will be affected due to the quantitative needs. Hence the quantitative side of housing must be investigated to determine the economic forces affecting house design.

1.2 Population, Resources and Housing

The deterioration of human settlements is one of the worst problems confronting mankind today and this is most acute in the developing countries. One third of the world's population is living in shelters lacking even the basic protection from endemic disease (134). Visible signs of deterioration also occur in many developed countries illustrating the global dimension of this problem. The success or failure of a society in satisfying its needs will depend on the balance between these needs and the way in which the socio-economic system employs its resources. On these grounds the housing problem can be seen as the result of an imbalance between the needs and the production of the community. A society would be considered as having a housing problem if there is a conflict between the number of inhabitants and their housing needs on the one hand, and the resources and the way the socio-economic system employs them to fulfil those needs on the other. An increase in the number of inhabitants does not indicate a problem if it is balanced by sufficient resources employed in the right direction [1].

The world population in the present century takes on the aspect of an uncontrolled explosion. Between the years

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1 Faragany (277) reports an increase as high as 7% in the population of Kuwait between 1970-75, however the socio-economic system employing the available resources secured their needs including housing. In this case the population increase resulted in increasing the rate of development.

1400 and 1900 the rate of increase increased slowly from mearly zero to about 0·75% per annum (32). Between 1950 and 1970 the world population increased 44% at a rate of 2.1% per annum (from 2·5 to 3·6 billion). If this rate is maintained the total world population will double by the end of this century and could reach 54 billion people on Earth by the year 2100. This represents approximately one person per square foot of land and sea. However, the world population cannot increase indefinitely. Greely (130) reports that a number of studies have suggested 15 to 20 billion people as a likely stable world population. Population growth is more pronounced in urban areas where the rate of urban to total population is constantly rising.

In Egypt there are clear indications of severe housing problems. The population grouwth rate is high; the number of inhabitants has doubled from 13 to 26 million in the period from 1920 to 1960. It was 38 million in 1976 and 42 million in 1980. The rate of population increase in Egypt is currently 2·31%. Another important factor amplifying the problem is the geographical distribution of population; most of Egypt's population (99%) live on only 4% of the total country area. Moreover, the majority of them crowd into the small areas of urban centres. The population in these urban centres is rapidly increasing and this is best illustrated by comparing the rate of growth in rural and urban areas, table (1.1). It is important to note that the rate of urban growth is more than their natural growth. It includes rural immigrants to urban areas. In Cairo the rate in increase was 4% per annum in 1969, 2·1% due to immigration alone. The increase in Cairo's population is illustrated in table (1.2).

Another population factor which affects the ability of the socio-economic system to satisfy the inhabitants' needs is the age distribution. In Egypt approximately 45% of the total population is under 20 years of age. This sector of

Table (1.1) The percent of urban and rural population in Egypt, 1907 - 1976 (277).

Year	Urban population %	Rural population %
1907	19	81
1947	33	67
1960	37	63
1966	40	60
1976	44	56

Table (1.2) The increase in Cairo's population, 1882 - 1990 (63, 260).

year	1882	1897	1907	1917	1927	1937
population 1000s	399	590	678	791	1070	1309
year	1947	1960	1966	1970	1980	1990
population 1000s	2076	3335	4220	5700	8400	*1210

* Figure estimated by UN, (260).

population can be described as consumers rather than producers and consequently exerts pressure on the national economy[1]. However, the Egyptian society regards them as investment for the future. The population problem in Egypt is a result of the combined effect of all the above mentioned socio-economic factors. Hence, a coherent solution should aim at reducing both birth and death rates accompanied by increasing the percentage of producers in the population. Also it should aim at a better geographical distribution of the population, rural and urban, over a larger area. The increase of the global as well as the Egyptian population is accompanied by increasing demand on housing.

The housing needs of the world are of major concern. A reasonable allocation of resources towards the improvement of housing and related services is essential for development and improving the quality of hundreds of millions of people currently living in appalling conditions. In the past housing was considered as consumer goods, and not productive, therefore low priority was given to housing investment as well as to infrastructure not directly needed for industry. An indicator of the severity of the housing problem is the overcrowded dwellings in the less developed countries. In Egypt the overcrowding is above 3·5 persons per room in Cairo, and 2·3 persons per room in Alexandria (97). To meet their housing needs it is estimated that from 8 to 10 dwellings per 1000 inhabitants is needed to be constructed in the less developed countries. In global terms this means that in the urban areas alone 4 million to 5 million dwellings per annum are required (260). The rate of dwelling construction falls short of satisfying this demand as it varies from 2 to 5 per 1000

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1 Putting this population characteristic in other words, the active population was 28% (8·4 million) between 1965 and 1970 (260).

inhabitants in the less developed countries compared with 8 per 1000 inhabitants in European countries. In spite of the failure in satisfying the population demands, housing utilizes from 10 to 35% of the total global investment, and from 10 to 25% of the entire output of the industrial sector. Moreover, it employs 20 to 50% of the manpower of the construction sector.

In Egypt the acute housing problem was mainly a result of the national development strategy during the late fifties till the early seventies, emphasizing commodity sectors and de-emphasizing services, including housing. A wide gap has been developed between demand for and supply of housing and services (195). It is estimated that by the year 2000 the number of dwellings needed to balance the rising demand due to population increase will reach 2 million. At the same time the lag of housing construction behind the demand is up to 1•6 million units, amounting to 3•6 million dwelling units. The Ministry of Housing and Reconstruction designed their policy[1] to meet the demands of housing by the year 2000, table (1.3), figure (1.1). In 1974 the government outlined a strategy which would be employed to reduce the pressure on Cairo, the Nile valley and Delta. The strategy proposed the establishment of a new map for settlement; this included the reconstruction of the war-devastated Suez Canal zone and building new urban centres in the desert (Sadat, King Khaled and 10th Ramadan). However, this policy created an extensive demand on the construction sector. Because of the rapid rise in investment the construction sector, with its limited resources, failed to respond to the demand. Under these circumstances

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1 In Egypt prefabrication was introduced in 1972; by 1977 there were 11 factories of European origin. No attention was paid to the fact that they were developed in societies where incomes were higher and the socio-economic, cultural patterns were different. After 5 years (1977) they proved unable to produce a relevant unit for low income housing.

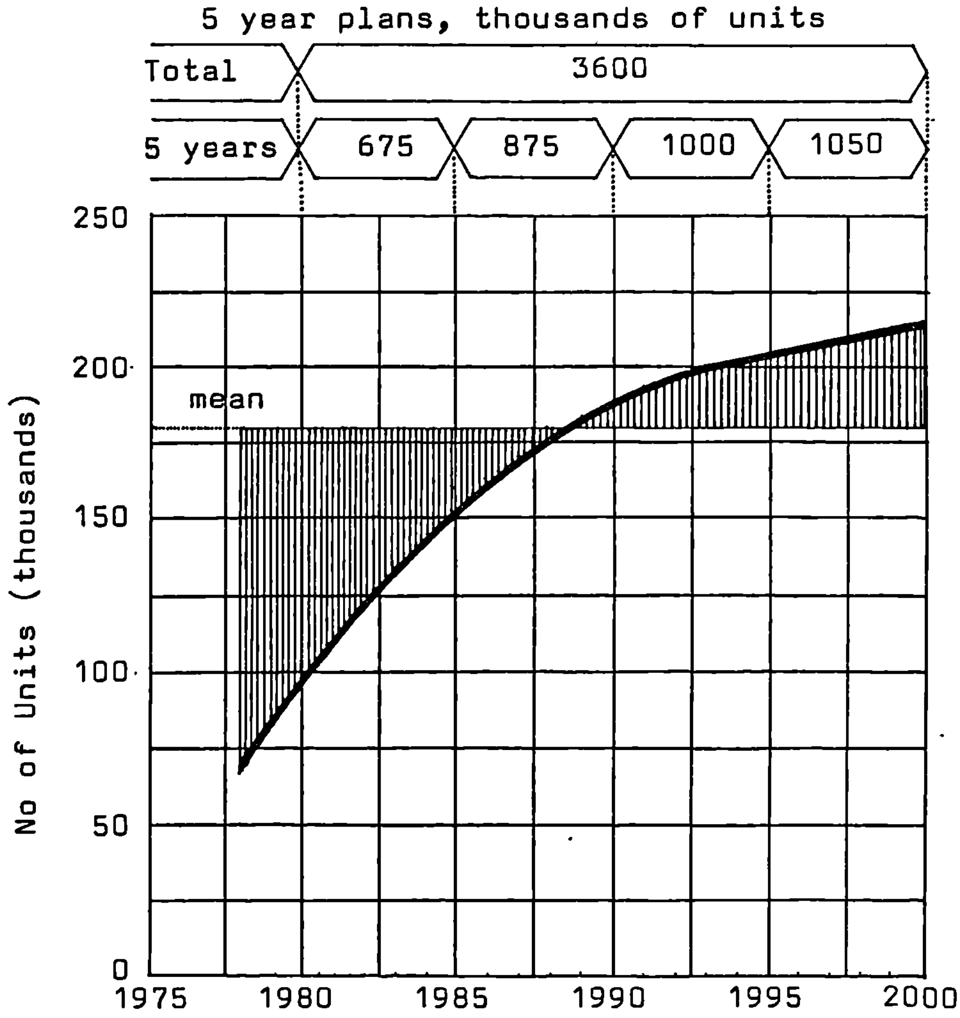


Figure (1.1) The Ministry of Housing and Reconstruction plan to meet housing demand in the year 2000.

Table (1.3) The dwelling construction plan to meet the housing demand in the year 2000.

year	81	82	83	84	85	86-90	91-95	96-2000	total
demand 1000s	110	125	135	145	160	875	1000	1050	3600

market equilibrium is achieved through rapid increase in the construction cost, figure (1.2). It has been estimated that the cost per square metre for low-cost housing production increased from a base level of 100% in 1962 to 120% by 65, 154% by 70, 278% by 74, 330% by 75 and 574% by 1976. Any housing policy should be based on a clear understanding of the future pattern of change in the economic system, complemented by a total energy analysis of the housing construction industry. The housing policy should aim at satisfying the user-requirements which should be broad and flexible to accommodate the full range of individual needs within the socio-economic group, while at the same time being precise enough to be of practical use to policy makers, planners, designers, builders and manufacturers. The dynamic relationship between housing needs and environmental factors such as climate, topology, density and amenity should be considered when developing housing standards and norms. During the fifties, sixties and early seventies the standards and norms for Egyptian housing were loosely defined into three categories, low-cost (economic), middle income (average) and high income (above average). A new building law passed in May 1976 included the standards of those three housing categories as set in an improved manner with special emphasis on space area and finishes (61), figure (1.3).

Due to the severity of the housing problem, low standards of design emphasizing only the space area and economy, and

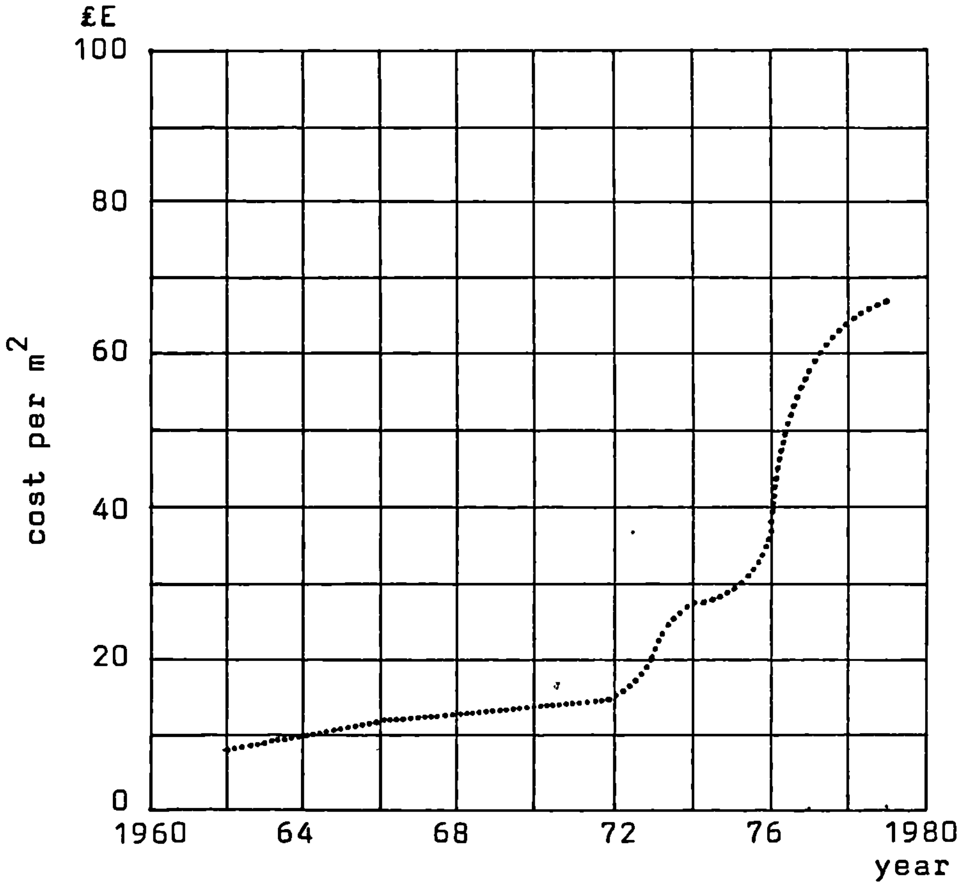


Figure (1.2) The increase in the cost of one m^2 of low-income (economic) housing in Cairo.

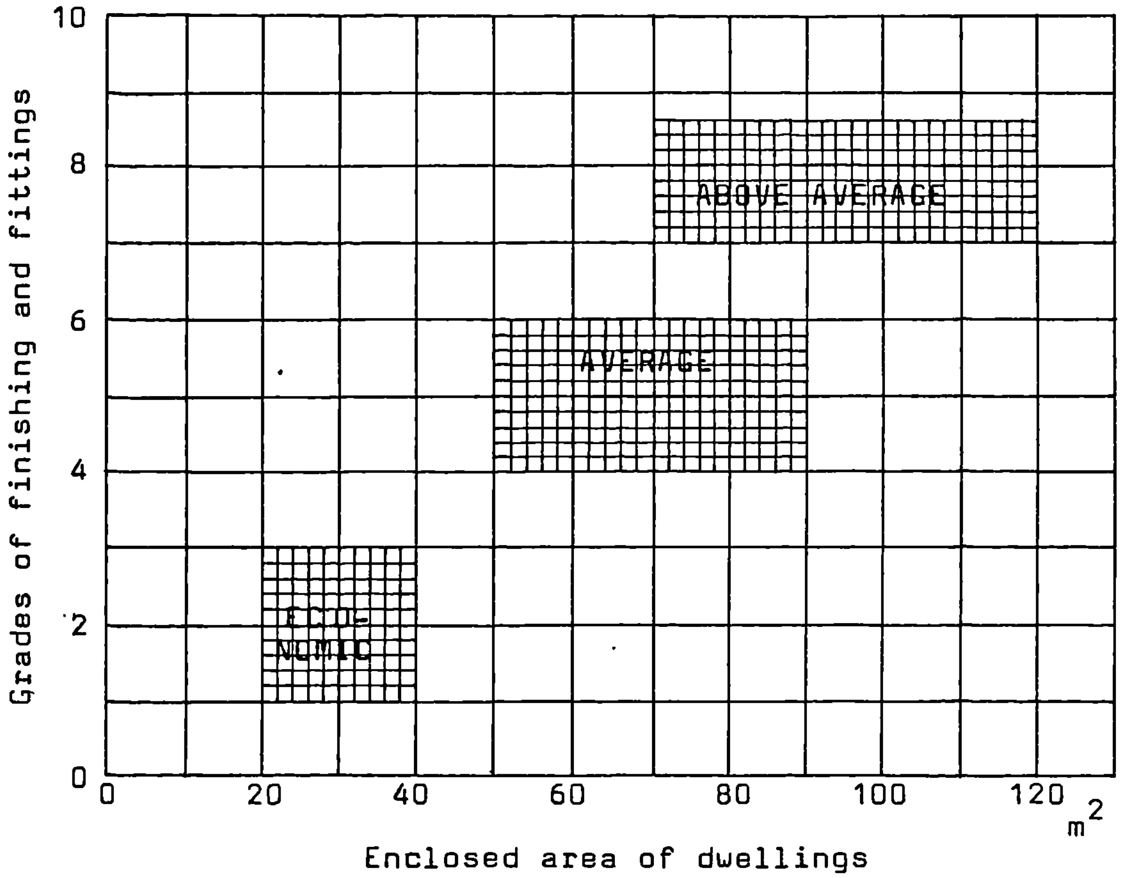


Figure (1.3a) Egyptian Ministry of Housing and Reconstruction standards May 1976 (after CU/MIT (61)).

SANITARY APLIANCES						JOINERY		FLOOR			EXTERNAL RENDERING	INTERNAL PLASTER	GRADE	
cold hot	kit. sink	bath	wall finish	wc	lav.	panel	frame	bed rooms	living	kit.+ bath				
			cem.			straw board	0.37	cement rendering			cement rendering		1	ECONOMIC
			"			"	0.5	cement tiles			sprayed plaster	render. and painted lime wash	2	
			"			straw board veneered	"	terrazo tiles			"	"	3	
			"			"	"	terrazo and timber			"	render. and water paint	4	AVERAGE
c			terra. plast			block board	"	vinil	vinyl	terrazo	"	"	5	
			ceram tiles 2.0 m			"	"	timber	vinyl	ceram.	"	"	6	
			"			block board veneered	"	timber blocks on tiles		ceram.	facings and good rendering	gyp. plaster	7	ABOVE AVERAGE
c h			"			"	"	parquet		"	marble, granolite, etc.	gyp. plaster + oil. and plastic paints	8	

Figure (1.3b) Egyptian Ministry of Housing and Reconstruction standards May 1976 (after CU/MIT (61)).

neglecting the physiological, psychological and sociological needs, have been executed. The designers needed a flexible tool to aid them in controlling the surrounding environment and designing economical houses integrating with their climate.

1.3 House Design and Climate

Climate is the most important environmental factor affecting our physiological comfort, our capacity for mental and physical work, and our leisure. From this point of view the residential building accommodating a wide variety of activities over 24 hours/day represents a design problem that encompasses all others. An unsuitable climate can induce lassitude and depression, affecting not only individuals but also the whole comminity.

Environmental control design for the overheated period in general, and the excessive heat stress in semi-desert and hot climates in particular, suffers the drawback of employing the same technical procedures as those of cold and temperate climates despite the difference in the human physiological response under these conditions. This is most felt in houses. Any attempt to formulate an approach to house design should work with and not against the forces of nature to make use of their potentialities to secure better living conditions.

A systematic approach to environmentally balanced shelter will exist on the borderlines of several fields. However, climatology would mark the beginning of the procedure which aims at a climatically balanced architecture. In between the two fields lie environmental factors concerning human physiological, psychological and sociological needs, In the course of this research the physiological needs and especially those concerning the thermal environment will form the main concern. The interaction between this aspect and other human needs will be examined.

The architect's aim will be to control the prevailing environmental conditions using the technology available within the socio-economic limitations. He should be able to modify these environmental conditions (230) by means of micro-climatology to less uncomfortable conditions (206). Applying a bioclimatological approach to the house design the designer can modify the environmental conditions to reach those of the optimum comfort. He can also achieve most optimum conditions required for special health problems employing mechanical techniques, figure (1.4). Extending the benifits of environmental control to the low income housing will essentially require employing natural energy-free techniques. Therefore, the first step towards environmental balance would be a survey of the dominant climatic elements in the location. Since man is the fundamental measure in architecture and the house is designed to fulfil his biological needs, the second step would be to evaluate the climatic impact in physiological terms. The third step should be the examination of the technological solutions available and applying the right action to counteract the undesirable effect of the climatic forces, and reinforce the desirable ones.

Designers throughout history have employed environmental control techniques, and were able to improve arid conditions to a high degree of comfort. The houses built during certain historical periods were successful in conditioning their climate to a more optimum environment, fulfilling the physiological, psychological and sociological needs of their inhabitants. However, we must take care in emulating single environmental control features of these houses, since the conditions governing their development and the needs they satisfied have changed.

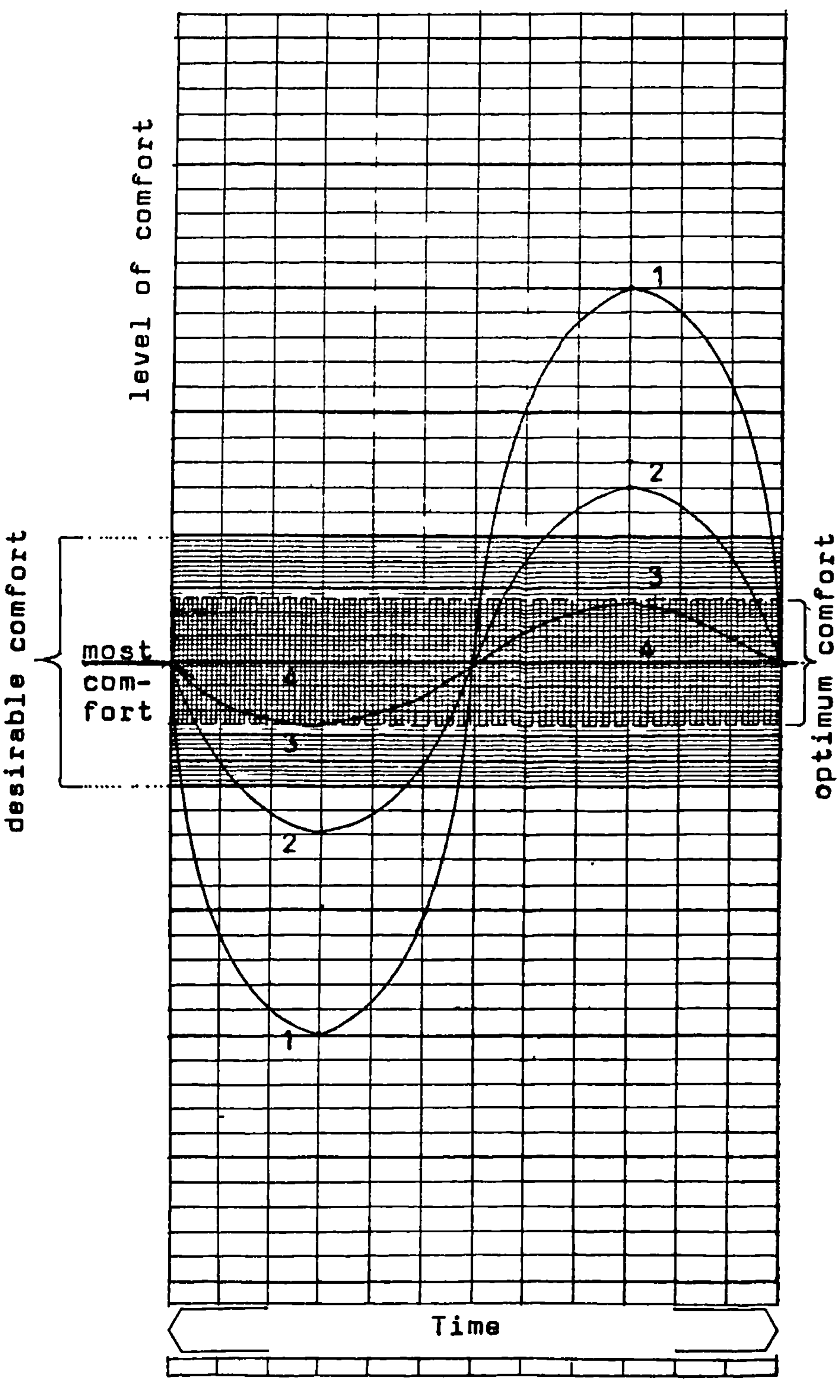


Figure (1.4) Ways of controlling the prevailing climatic conditions (1) to reach the optimum comfort conditions (3).

Natural air conditioning is possible in almost all climatic conditions provided the right technique is applied to the right place at the right time. To enable the architect to make use of the natural air conditioning technology he must be offered a flexible means of achieving this within the time available at each design stage. Considering the plan of work of an architectural team (223), the bioclimatic approach should include three stages, bioclimatic analysis, spatial design and detailed design stages, following which the experience gained should be fed into the next project. This research will follow the development of such a design tool.

Chapter 2 : CLIMATE AND BUILDING DESIGN

2.1 Man, Shelter and Climate

Since the beginning of creation, man had to struggle with his surrounding environment to survive. His struggle was to fulfill three basic needs:

1. Food - to overcome hunger
2. Clothing - to enable him to live in the changing climatic conditions
3. Shelter - to protect him from wild animals and severe climate

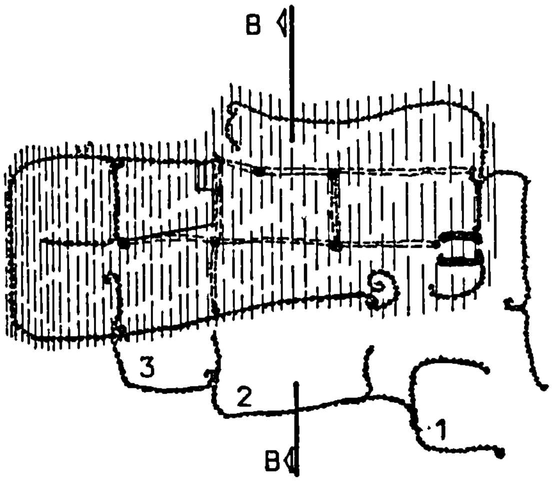
The house story began as man found himself in need for shelter to protect him from the wild animals and the hostile climate. He made his first house using basic constructional methods and from the materials he found around him. Where there were forests, he erected his wooden house and when he found rocks, he constructed masonry buildings. Slowly and gradually the development of man's house became the indicator of civilisation and a measure of mankind's progress through the ages.

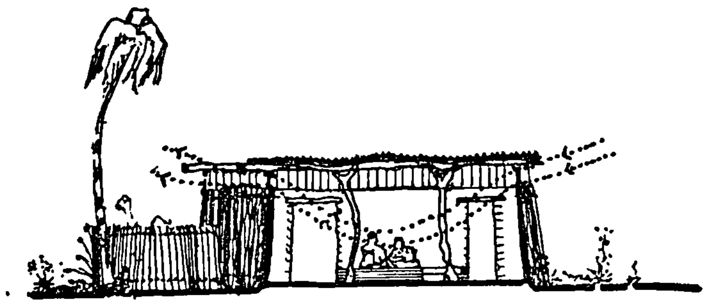
In various regions the adaptation of dwelling to a particular environment and an awareness of climate was integrated with the local technology, materials and craftsmanship, resulting in a house that was truly expressive of its regional characteristics.

The environment is the surroundings in which mankind exists. These surroundings include the natural and the man-made factors. The natural ones include: the geographical site, the climate and its elements, geology and the physical geography of the region. The man-made environment is that reflecting: the economic conditions, the social structure, beliefs and culture of the people. Perhaps the most important factor affecting human daily life and human behaviour is the climatic factor.

The adaptation of house to climate has been the aim of builders since the beginning of history, yet they have not overcome all the problems which enable them to achieve a natural thermostable environment. Olgyay (206) reports :- "the proportion of solid surfaces to openings in external facades depends as much on popular psychology as on the prevailing climate and the materials used". The deserts, hot arid areas, have a very long over heated period and bright sun which makes extreme demands on the inhabitants. Shelter is needed to reduce heat impact and provide shade. The experience of many centuries has taught the inhabitants to build compact buildings around closed courtyards, and to use forms with least exposed external surfaces. The use of flat, vault and dome roofs dominated in these areas. This has an underlying logic, probably discovered through trial and error over the years, figs.(2.1a,b,c). The envelopes of the semi-circular vault and the hemi-spherical domes are respectively 1·57 and 3 times the surface of their bases. With such envelopes, the radiation of high sun is diluted on the curved surface, resulting in a lower surface temperature which is further reduced by wind cooling. The curved surface is also suited to releasing the nocturnal outgoing radiation and so facilitates cooling.

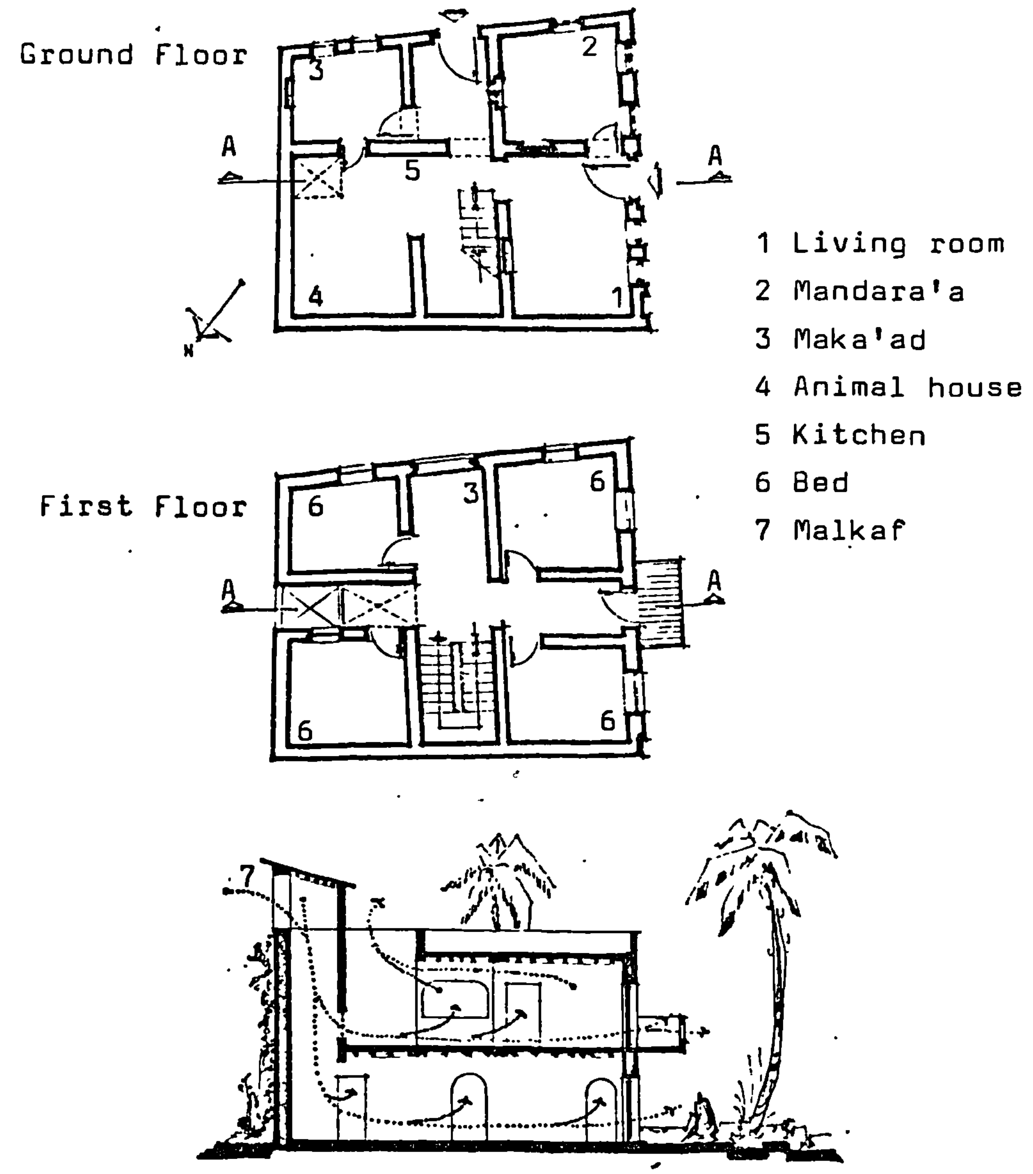
In warm-humid zones the problems are the avoidance of excessive solar radiation and the provision for moisture evaporation by breezes. The traditional buildings in these areas cope with these problems by allowing free air movement. The roofs are usually insulated and provided with large overhangs to protect against the sun and rain, and provide for shade. The floors are often raised to keep





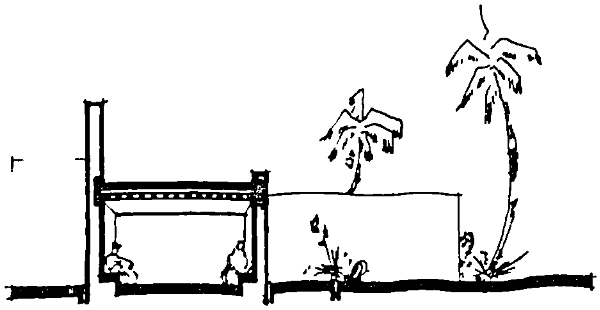
(B-B) Section through the living room.
Lower part of reed walls has mud plaster.

Figure (2.1a) Peasant house in Arab Atawlah village, Upper Egypt. Architect - Egyptian peasant. After A G Mohammed (192).



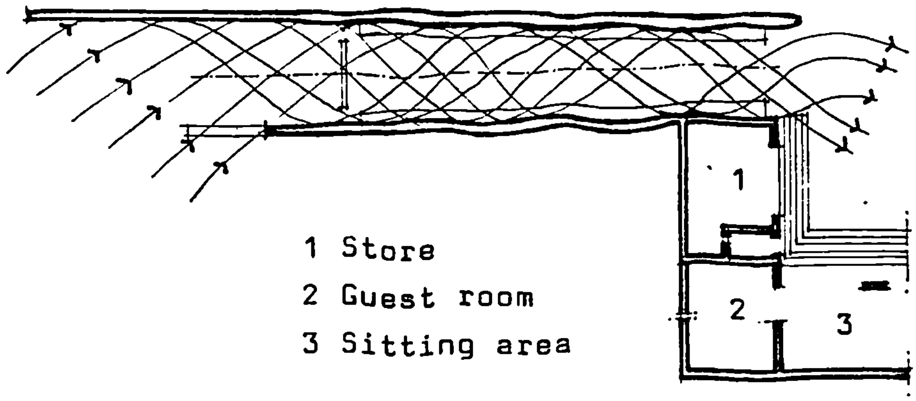
(A-A) Section through the Malkaf

Figure (2.1b) Peasant house in Shatb village, Upper Egypt.
Architect - Egyptian peasant.
After A G Mohammed (192).



Cross section through the Maka'ad

Plan of the summer Maka'ad



Longitudinal section through the Maka'ad

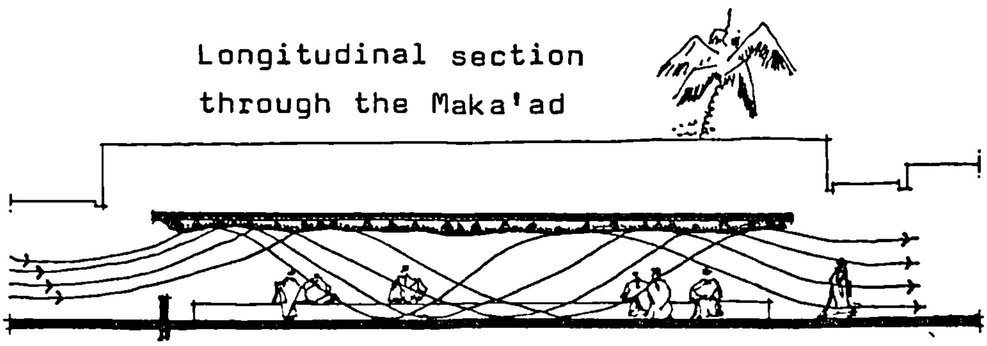


Figure (2.1c) El-Omeda Centre - the summer Maka'ad, Naga'a El-Tode, Upper Egypt - Architect "Egyptian peasant". After A G Mohammed (192).

them dry and allow air circulation underneath. The inclined roofs have been intensively used in the buildings located in these climatic zones.

Considering the technological limitations of the period and locale, and the overriding aspects of safety, the traditional building forms of the rural tropics show sound solutions for the climatic problems fig.(2.1).

2.2 The Elements of Climate

On our planet, Earth, life is regulated by the diurnal sweep of the sun's rays across its rotating surface. In any place, the climate is closely coupled with the amount of sun-radiation present at a given time. The sun is not only the largest body of the solar system, but also its main energy source. On Earth, the sun provides the energy for all weather processes, those that disturb the sea with its waves and currents, that generate the wind and develop the rain. The sun is a tremendous spherical mass of incandescent gas having a diameter of $1{\cdot}39 \times 10^6$ kilometres, and an average distance of 150×10^6 kilometres from the Earth fig.(2.2). As seen from the Earth, the sun rotates about its axis once every four weeks. However it does not rotate as a solid body, its equator takes about 27 days and the polar regions take about 30 days for each rotation (89). The sun is powered by thermonuclear processes that produce central temperatures estimated to be in excess of 20×10^6 ^oC (36×10^6 ^oF).

As estimated from the total energy received above the atmosphere, the surface of the sun (photosphere) is at an effective temperature of about 5762^oK. The emitted solar radiation is the composite result of the several layers of the sun which emit and absorb radiation of various

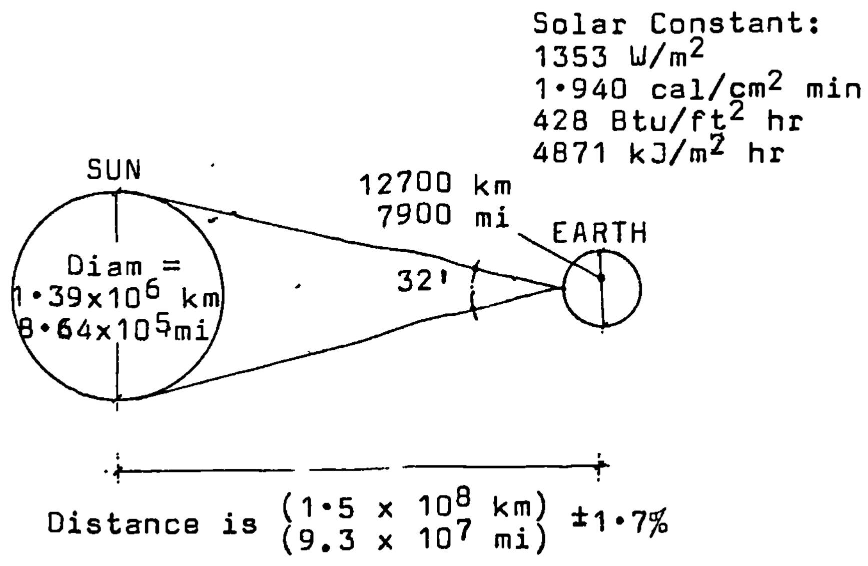


Figure (2.2) Schematic of sun-earth relationships. After Duffie (89).

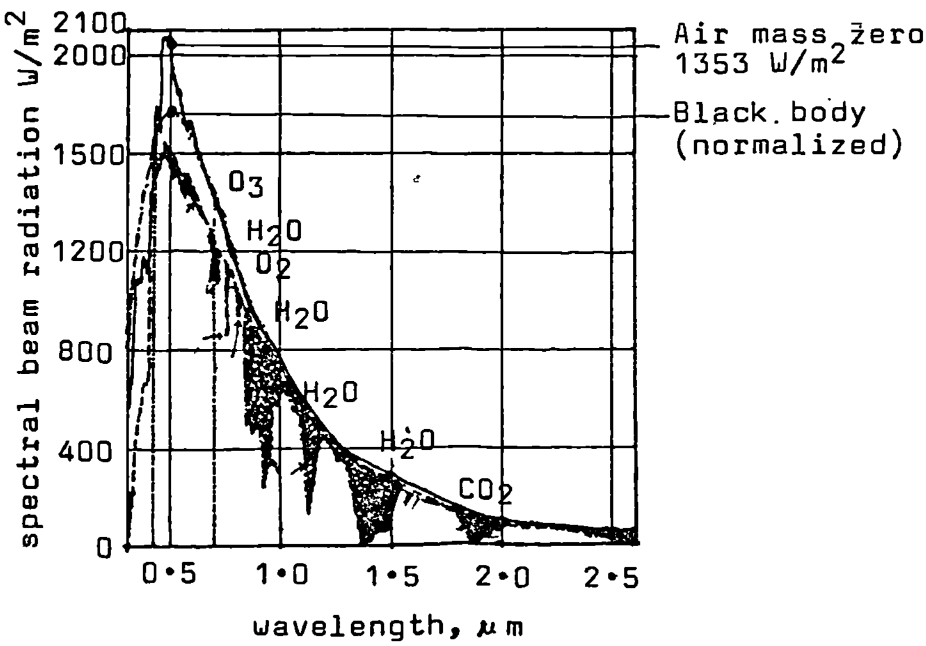


Figure (2.3) Solar spectral intensity above the atmosphere and as received at the Earth's surface, compared with black body (5762K) radiator. After Duffie (89).

wavelengths. However, for the purposes of this research, it is adequate to consider the sun as a black body radiator at about 5762 K, fig.(2.3).

The Earth's real form is not quite that of a perfect sphere but an oblate spheroid, a sphere flattened at the poles and bulging at the Equator. This first good approximation to the shape of the Earth was deduced by Isaac Newton. who reasoned that forces resulting from the Earth's rapid rotation should cause a slight decrease in the value of gravity at the Equator compared to that at the poles. Recent accurate measurements of the size of the Earth have established the Equatorial diameter to be very nearly 12,755 x 10^3 m (7927 miles) and the polar diameter 12,710 x 10^3 m (7900 miles) fig.(2.4a). The flattening of the sphere into an oblate spheroid by only 45 x 10^3 m (27 miles) out of 12,755 x 10^3 m is a ratio of 1/300. This is used to describe the Earth's oblateness, or ellipticity. The Earth revolves around the sun at as average distance of 149·6 x 10^6 km (about 93 x 10^6 miles). Its orbit is an elipse but when it is closest to the sun (the prehelion) on about 4th January it is 147 x 10^6 km distant, only 1·7% closer to the sun. The Earth's aphelion, on about 5th July, is the same distance further away from the sun. Thus, its path around the sun departs only a little from a circle. The sun not only beams its energy towards the Earth, but also radiates it in all directions, thus Earth intercepts only one half of a billionth of this radiated energy, an amount of 170 x 10^{12} kW. For our purposes, it will be sufficient to say that energy transfer takes place without the requirement of a medium, and this form of energy transfer is called radiation.

The seasons on Earth are the result of three main factors. These are:

a) The Earth's axis being tilted away from a perpendicular

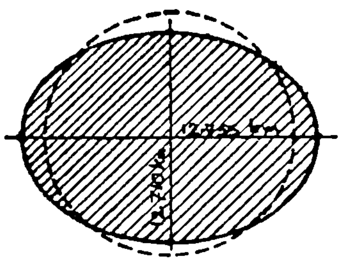


Figure (2.4a) The relationship between the sphere and the Earth's oblate spheroid shape.

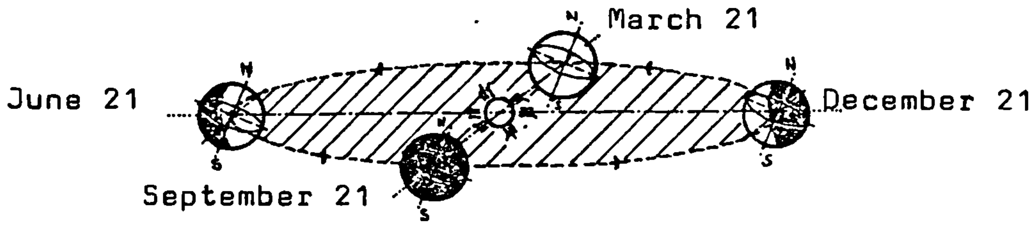


Figure (2.4b) Schematic diagram of the path of the Earth around the sun.

to the plane of ecliptic.

b) The revolution of the Earth about the sun.

c) The self-parallelism of the Earth's axis at all times of the year fig.(2.4b).

Variation in the illumination of the northern and southern hemispheres is also caused by the Earth's revolution about its axis, and is evident in the satellite photomosaics. The atmosphere of the Earth is a gaseous envelope that surrounds the solid and the liquid surface of the Earth. It extends upwards for hundreds of kilometers, eventually meeting with the rarified interplanetary medium of the solar system. The gas that constitutes the atmosphere is called air, a mixture of several different gases, the most prevalent of which are listed in table (2.1).

Table (2.1) The chemical constituents of the air.

Component	Chemical Symbol	Volume %	Mass %
Nitrogen	N_2	78•084	75•510
Oxygen	O_2	20•946	23•150
Argon	A	0•936	0•046
Carbon Dioxide	CO_2	0•033	0•046
Trace Components		0•003	0•014

The trace components consist mainly of: Neon, Helium, Methane, Krypton, Nitrous Oxide, Hydrogen, Ozone, Xenon, Nitric Oxide and Radon. At the same time, accurate mèas-urements show that carbon dioxide is a variable constituent not only in its concentration, which is higher near urban and industrial complexes, but also in its average volume percentage which has increased since the beginning of the century. Carbon dioxode tends to raise the temperature of the Earth as it absorbs and re-radiates some of the infra-red radiation emitted by the ground.

The word 'climate' comes from the Greek word 'Klima' meaning 'weather conditions of a place or area'. Thus, it is the weather that makes the climate of the world. The weather is fuelled by radiation from the sun, which warms the Earth's atmosphere and ground surface. The Earth then re-radiates heat to space. Radiant cooling and solar heating create temperature differentials between oceans and land, and between the equator and the poles. Temperature differentials in the atmosphere create pressure systems which generate winds and air movements. Moisture is generated by evaporation from the oceans and land surfaces, only to condense and fall as rain on the Earth again. Therefore, the principal climatic elements to be considered for human comfort and house design are as follows:

i) Solar radiation and longwave radiation to the sky
ii) Air temperature
iii) Wind and pressure systems
iv) Precipitation and humidity
v) Indirect effects on daily weather changes through movements of ocean currents, air masses and fronts.

2.2.1 Solar Radiation and Longwave Radiation

Solar radiation is an electromagnetic radiation emitted from the sun. The wave lengths range from about 0•28 to 3•0 microns and divide into three regions, fig.(2.5):

i) The ultra-violet (UV) waves which are shorter than 0•4 microns.
ii) The visible waves with lengths between 0•4 and 0•76 microns.
iii) The infra-red (IR) waves which are more than 0•76 microns in length.

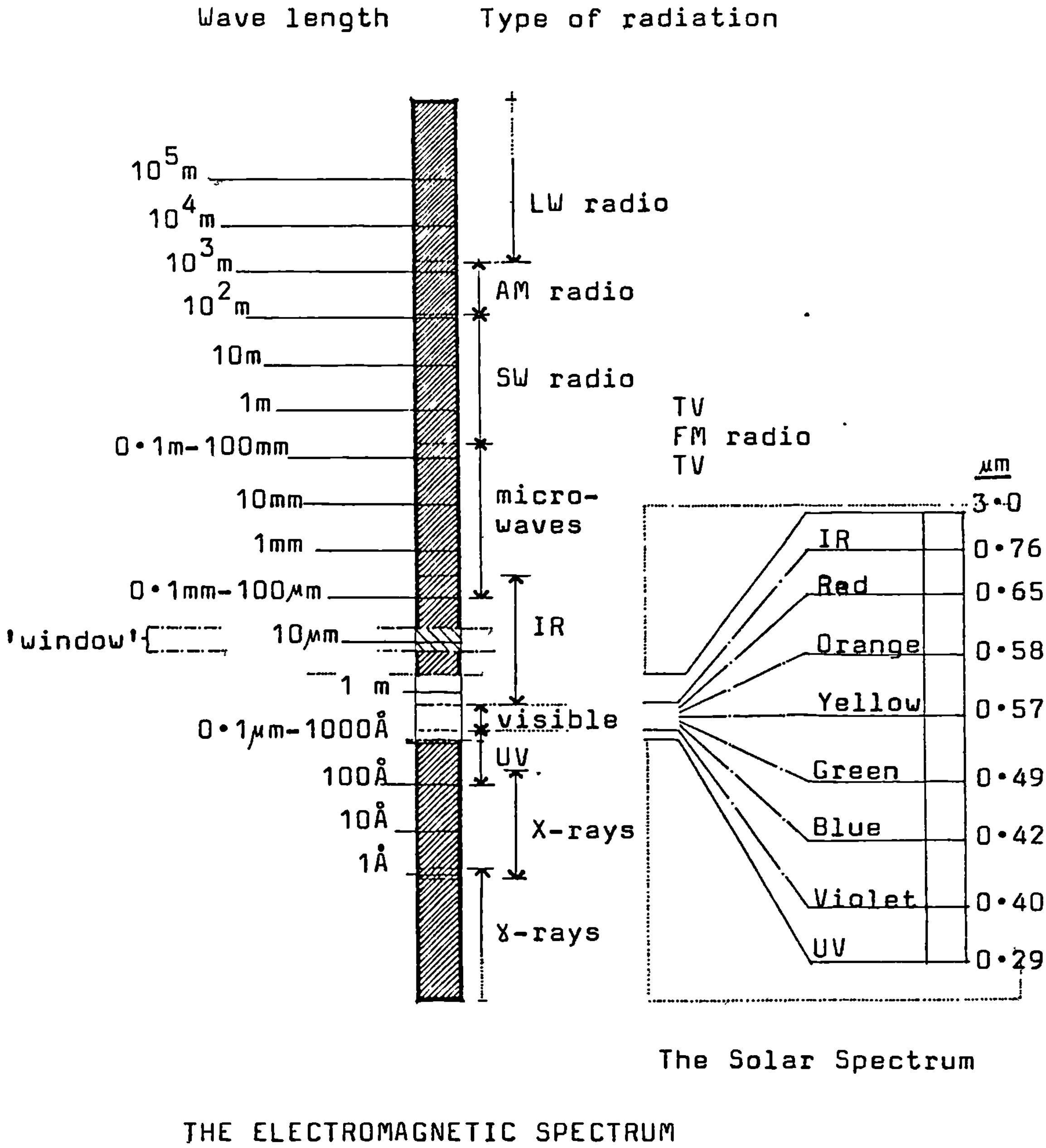


Figure (2.5) The solar spectrum in relation to the electromagnetic spectrum (199).

Although the peak intensity of solar radiation is in the visible range, over one half of the energy is emitted as infra-red radiation. Solar radiation through the vacuum of the inter-planetary region at the speed of light - ($3{\cdot}0 \times 10^8$ m/s). At the upper limit of the atmosphere, extraterrestrial solar radiation varies, with the time of the year because of variations in the earth-sun distance, and in the output of the sun itself. It may vary by 3% due to the first factor and by 2% due to the second. For the purposes of this study, however, the extraterrestrial solar radiation will be considered as a constant of value 1353 W/m^2 ($1{\cdot}940$ cal/cm^2 min, 428 Btu/ft^2 hr, 4871 kJ/m^2 hr) (89). The earth rotates around its own axis once every 24 hours. The axis of its rotation, the line joining the northern and southern poles, is tilted to the plane of the elliptical orbit at an angle of $66{\cdot}5^o$ (ie a tilt of $23{\cdot}5^o$ from the normal) and the direction of this axis is constant. The earth moves around the sun in a slightly elliptical orbit at the rate of one revolution every 365 days, 5 hours, 48 minutes and 45•5 seconds. This orbit results from the gravitational pull of the sun and the centrifugal force due to the earth's momentum. Maximum intensity of direct solar radiation is received on a plane normal to the direction of radiation. If the axis of the earth was perpendicular to the plane of its orbit, it would be the equatorial regions which are always normal to the direction of solar radiation, but due to the tilted position, the area receiving maximum intensity is that between the tropics of Cancer ($23{\cdot}5^o$N) and Capricorn ($23{\cdot}5^o$S), and this is the main reason for seasonal climatic change, figs.(2.6) & (2.9). This earth-sun relationship affects the amount of radiation received at a particular point on the earth's surface in three ways:

i) The cosine law, which states that the intensity of solar radiation on a tilted surface equals the normal intensity multiplied by the cosine of the angle of

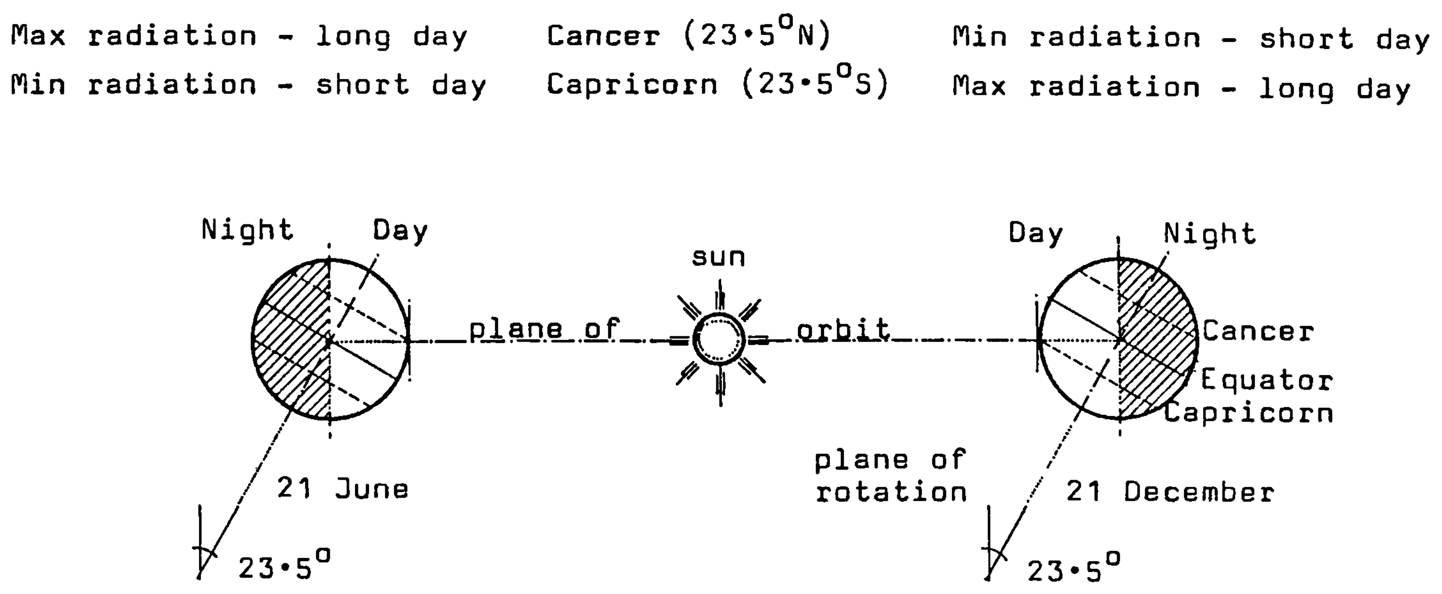


Figure (2.6) Earth-sun relationship and the seasonal climatic changes.

incidence, fig.(2.7).

ii) Atmospheric depletion, ie the absorbtion of radiation by carbon dioxide, ozone, water vapour, and dust particles in the atmosphere. Thus, the lower the solar altitude angle, the longer the radiation path through the atmosphere, and the smaller the part reaching the earth's surface, fig.(2.8). The radiation path may be considered as a function of the latitude, the time, and the declination of the position receiving it, table (2.2). The atmospheric depletion magnitude may differ with time due to the change in air purity, vapour, dust, smoke and other trace components content.

iii) Duration of sunshine; which is a function of both the length of the daylight period, and the sky cover.

The total solar radiation received at the earth's land-sea surface during the entire year is shown in fig.(2.10). It is clear that the highest amount of solar radiation is received in the tropical regions and not the equatorial ones. Moreover, the nature of the surface greatly affects the periods of heating up by day and cooling down by night, the most significant difference being that between land and water. This is mainly due to the following factors:

i) The greater specific heat of water; more heat is needed by water to raise its temperature by 1°C than is needed by an equal mass of rock.

ii) The sun's rays can penetrate water; therefore, radiant energy can be carried to greater depths than it can on the land.

iii) The movement of water; this aids the distribution of heat to a considerable depth, whereas land is heated rapidly on the surface, but penetrates for only a few centimetres.

iv) Reflectivity of water; the water surface tends to reflect and therefore waste a greater portion of the

$$\cos\beta = B/C$$

Area C > Area B

(I_C) Intensity C < Intensity B (I_B)

$$I_C = I_B \times \cos\beta$$

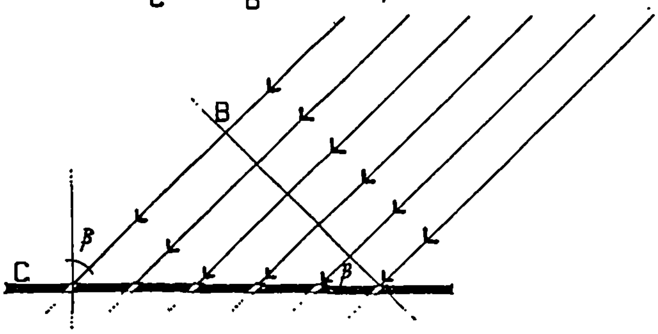


Figure (2.7) The angle of incidence.

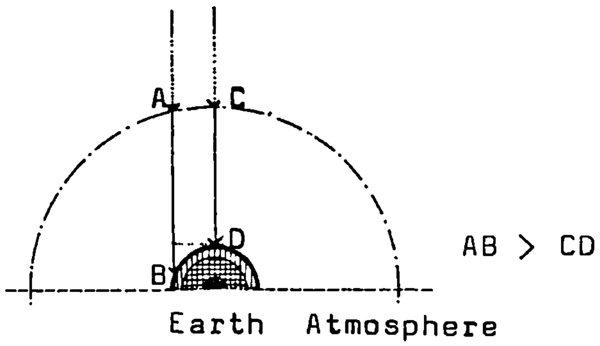


Figure (2.8) Difference in path length through the atmosphere with different latitudes.

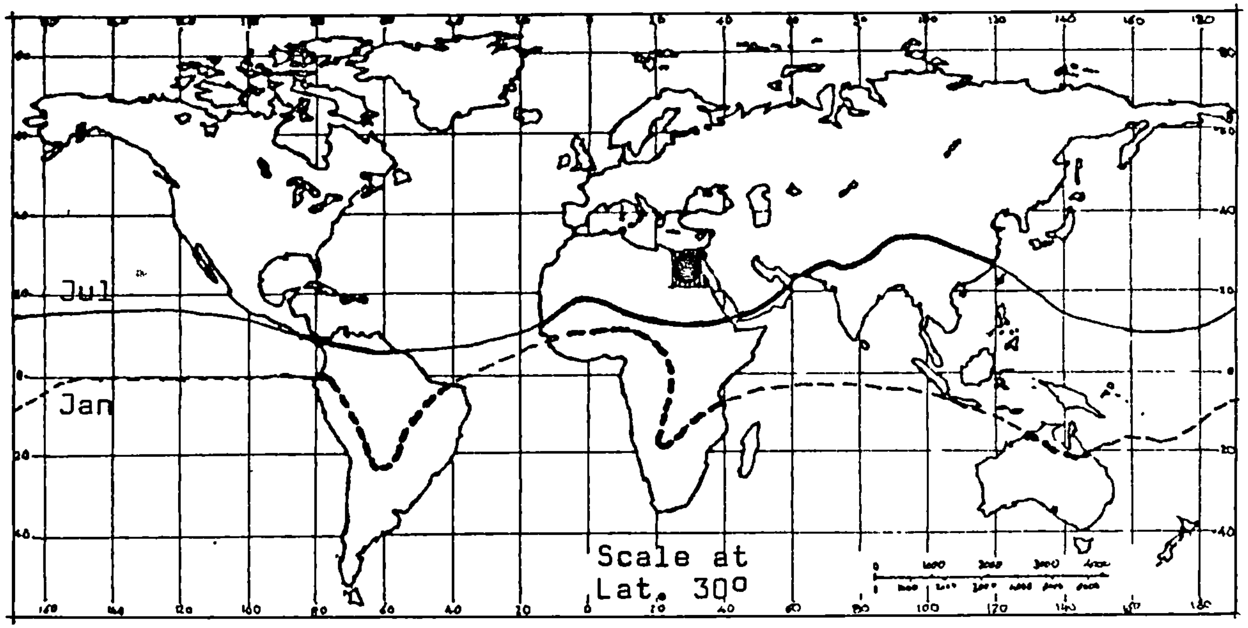


Figure (2.9) Seasonal shift in the inter-tropical convergence zone (ITCZ).

Table (2.2) Cross-section from pole to pole of the mean monthly global solar radiation[1] at the 40°E meridian during the IGY[2]. Givoni (122)

Lat	January	March	June	August	Yearly Ave
85°N	0	126	2721	873	419
80°N	0	314	2428	921	502
70°N	63	628	1674	1088	753
60°N	167	837	1800	1256	921
50°N	356	1047	2009	1967	1256
40°N	670	1172	1512	1470	1549
30°N	1172	1884	3098	2805	2219
20°N	1507	2219	2386	2302	2512
10°N	2093	2512	2093	2093	2093
0	2093	2093	2093	1884	2093
10°S	2009	2009	2093	1884	2009
20°S	2512	2302	1800	1884	1967
30°S	2930	2512	1381	1674	1884
40°S	2093	1591	753	1088	1674
50°S	1883	1172	335	628	1256
60°S	2135	963	84	293	879
70°S	2344	754	0	42	670
80°S	2554	544	0	0	460
90°S	2930	502	0	0	335

1. Solar radiation in $J/cm^2/day$.

2. IGY is the International Geophysical Year (1957-58).

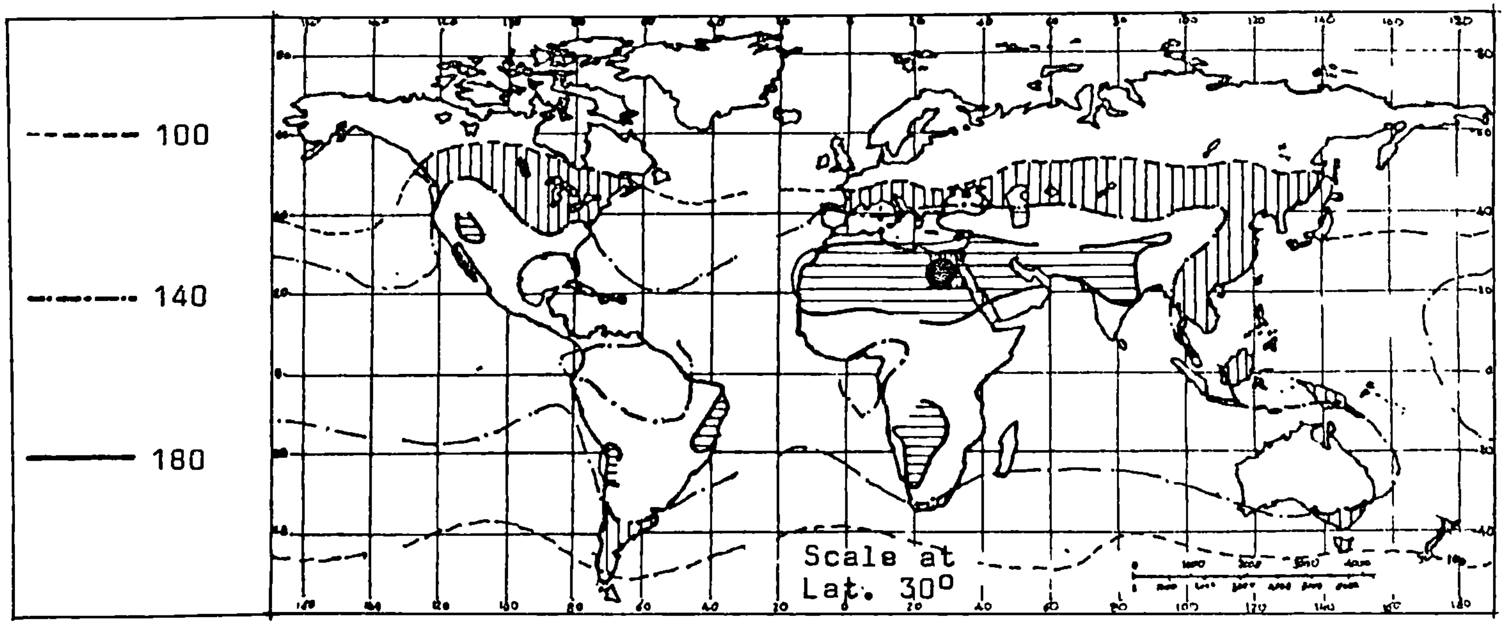


Figure (2.10) Total solar radiation (kWh/m^2 year) on land/sea surface during the whole year.

sun's rays than the land.

v) Latent heat; the water surface uses a considerable amount of heat energy as latent heat for evaporation.

The total effect is that water tends to heat up slower than the land surface, and accordingly, it cools down more slowly. The cooling effect of land or water is mainly due to the re-radiating of their energy in the form of long-wave radiation.

The terrestrial heat balance implies that the yearly average of total outgoing radiation from the earth and the atmosphere is in equilibrium with the total incoming solar radiation. Thus, longwave radiation emitted by the surface of the earth to the atmosphere and outer space depends on the difference between the temperature of the earth's surface and that of the medium absorbing its radiation. Moreover, longwave radiation is emitted in all directions by the gases of the atmosphere, and the earth absorbs the downward components; at the same time, most of the earth's outgoing longwave radiation is absorbed by the atmospheric gases. Water vapour is the principle longwave radiation absorbant, with carbon dioxide to a lesser extent. The only waveband within the atmosphere which is unaffected by absorption, between 8 and 13 microns, is called the 'window', fig.(2.5), and this is the cause of the direct loss to outer space. The net radiative heat loss is highest when the atmosphere is clear and dry, and decreases as the amount of dust, water vapour and, most important, cloud, increases. Geiger (116) indicates that the effective outgoing radiation is roughly in inverse proportion to the relative humidity, assuming a cloudless sky. He also quotes the following formula for the net radiation loss from a given surface, for a cloudless sky:

$$R = 8{\cdot}26 \times 10^{-11} \times T^4(0{\cdot}23 + 0{\cdot}28 \times 10^{-0{\cdot}074P}) \times 0{\cdot}07$$

where: R = net radiation from the horizontal surface, expressed in W/m^2

P = water vapour pressure in millimetres of mercury (mm Hg) measured close to the ground

T = absolute temperature (273 + ^{o}C)

Thus, knowing the Earth's temperature and the vapour pressure over a certain area, we can calculate the approximate amount of outgoing radiation. The major portion of the terrestrial radiation is within the band 5 - 50 microns, with maximum intensity occurring at about 10 microns. It is strongest towards the zenith and practically ceases towards the horizon. In desert climates terrestrial radiation is at a maximum and in these areas it can be utilized as an energy source. The total amount of heat absorbed by the Earth each year is balanced by a corresponding heat loss, fig.(2.11). Without this cooling the thermal balance of the Earth could not be maintained and its temperature and that of its atmosphere would increase and would soon be unfavourable to most forms of life. The longwave radiation to the atmosphere indicates that annual values for Earth-atmosphere and atmosphere-Earth radiation are both approximatelyequal to the incoming, undepleted solar beam. Kirchnoff's law (131) states 'At a given temperature the ratio of the absorptive power to the emissive power for a given wavelength is the same for all bodies'; hence, a good absorber is a good radiator and vice versa. The Earth's surface releases longwave radiation via 3 basic methods:

i) by longwave radiation to cold outer space; some 84% of this radiation is absorbed in the atmosphere and only 16% escapes to outer space;

ii) by evaporation, the Earth's surface is cooled as water changes into vapour and mixes with air;

iii) by convection, air heated by contact with the Earth's warm surface becomes lighter and rises to the upper atmosphere where it dissipates its heat to space.

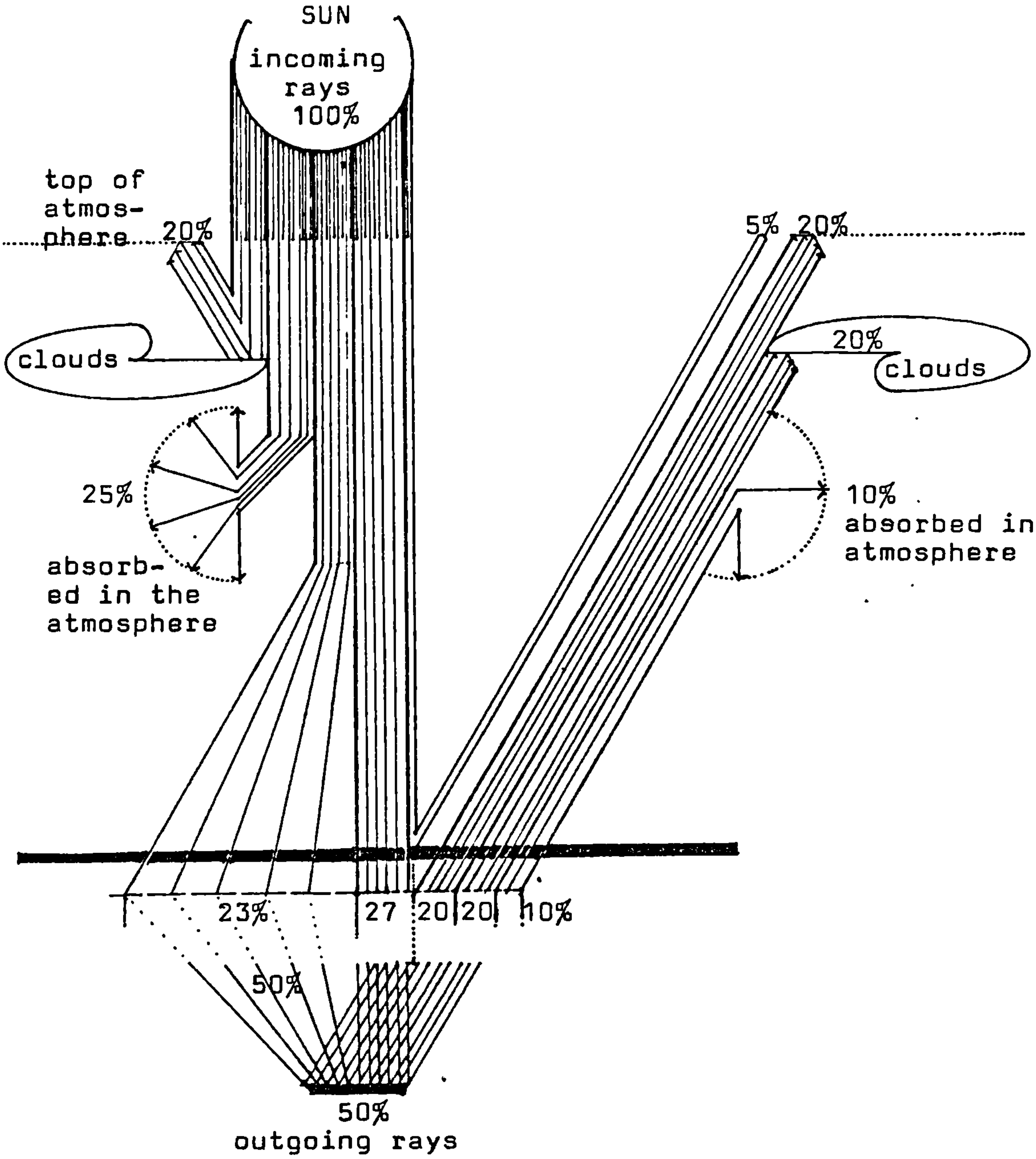


Figure (2.11) The passage of radiation through the atmosphere and heat release from the ground.

Wind is basically a convective current in the atmosphere, tending to even out the differential heating of various zones. It has been theoretically calculated , assuming a still atmosphere, that the average temperature at the Equator would have been 33°C instead of 27°C, and at the North Pole it would have been -40°C instead of -17°C as it is now, (148).

The radiant heat transfer types affecting house building for human habitation are as follows:

i) direct shortwave radiation from the sun;
ii) diffused shortwave radiation from the sky-vault;
iii) shortwave radiation from the surrounding terrain;
iv) longwave radiation exchange between the building and the sky;
v) longwave radiation from heated ground and nearby objects such as vegetation and landscape.

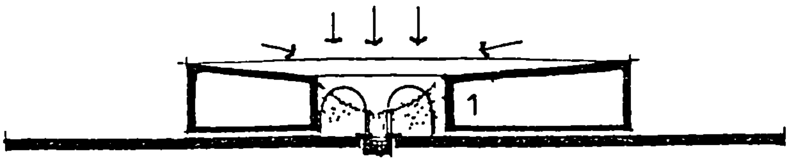
2.2.2 Air Temperature

Air temperature can be considered an index of its heat content. The main factor determining ambient air temperature in the layer where human beings live is the rate of heating and cooling of the earth's surface. Air temperature can vary by about 145°C (260°F) according to the distance from the hottest zones, and the change in seasons. The highest ever recorded was 58°C (136·4°F) at San Luis, Mexico, while the lowest was -87·4°C (-125·3°F) at Vostov, Antarctica, a variation of 145·4°C (261·7°F). The highest mean annual temperature is about 30·6°C (87°F) at Massaiva, Eritrea and Lugh Ferrandi, Somali Republic in Africa, while the lowest mean annual temperature is -57·8°C (-72°F) recorded at Pole of Cold, Antarctica, a variation of 88·4°C (159°F), (131). The air layer near ground level gains heat by means of conduction, convection and radiation. The layer in direct contact with warm ground is heated by conduction, therefore for the first few centimetres above ground level some very large temperature gradients can exist. Griffiths (131) has measured air temperatures at different levels using thermocouples during the hot season on Southern Arabia; he found the temperature at the surface 71·1°C (160°F), while it was 37·7°C (100°F) at 120 cm, a gradient of 2800 dry laps rate. When the surface temperature was 76·6°C (170°F), air temperature at 5 cm was 48·8°C (120°F), a gradient of 5500 dry laps rate. These values are extremes but they give some idea of the different orders of magnitude involved. This heat would be transferred mainly by convection, with turbulence and eddies in air currents playing only a secondary role. These heat gradients occur when the surface temperature of the earth is higher than the ambient air temperature. At night, however, and during cold winters, the surface of the earth may be colder than the air, hence the net heat exchange would be reversed and air in contact with the ground will be cooled. Annual and diurnal air temperature patterns depend on the variation in the adjacent surface temperature.

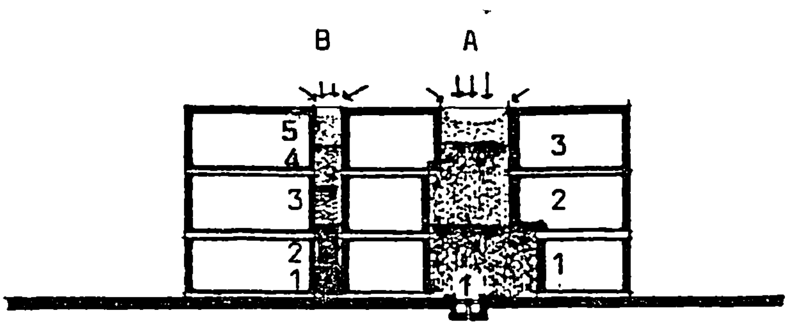
Change in altitude also alters the temperature of the air; when a mass of air rises it moves from a higher to a lower pressure region and so expands and is cooled. Conversely, when an air mass descends, it is compressed and heated. These are known as 'adiabatic cooling and heating processes' and the rate of temperature change is about 1°C per 100 m (5·4°F per 1000 ft). Moreover, when water vapour condenses to a liquid, the latent heat evolved provides energy to heat the air or reduce the cooling effect. In the free atmosphere air temperature decreases with altitude up to the stratosphere. This decrease is known as the 'laps rate' and it varies with the season and time of day, but averages about 0·60°C per 100 m (3·5°F per 1000 ft). During the day the laps rate near the ground is greater than that at night owing to the conductive heating of the lower air layer in contact with the earth. The heated air expands, becomes less dense and rises, making the lower air layer unstable and so constantly mixing with the upper layer. During the night the Earth's surface becomes cooler than the air and so air layers near the ground are colder than those above. This results in a reversal of the normal vertical temperature gradient near the ground, a phenomenon known as 'surface inversion'. The conditions promoting surface inversion are: long night; clear skies; dry air; and absence of wind. The cold air near the ground tends to concentrate in low areas, such as valleys, where tha temperature may be several degrees lower than that over higher ground. It is interesting to note that the court-yard houses in hot arid areas make use of the surface inversion phenomenon during the night. The deep courtyard houses of Cairo, which are a later development of the early single story ones, make use of this phenomenon during both the day and the night, fig.(2.12a & b).

Gates (114) suggests that the temperature pattern of the world, fig.(2.13), consists of five zones as follows:

a) Arctic; from the North Pole south to where the mean July temperature is 10°C (50°F),
b) North temperate; from the southern boundary of the Arctic zone to where the mean annual temperature is 20°C (68°F).
c) Tropic or Torrid; south from the southern boundary of the north temperate zone to the isotherm of the mean annual temperature of 20°C (68°F) in the southern hemisphere. This zone is the hottest and has the least temperature variation, with the minimum annual temperature range.
d) South temperate; from the southern boundary of the tropical regions, isotherm of 20°C, to where the mean January temperature is 10°C (50°F).
e) Antarctic; from the southern boundary of the south temperate zone to the South Pole.

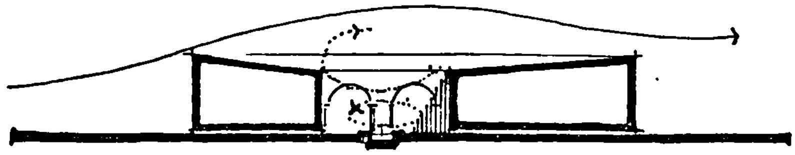


1) Cool, clear night with maximum ground radiation to sky. Cold air stored in courtyard (one temperature grade).

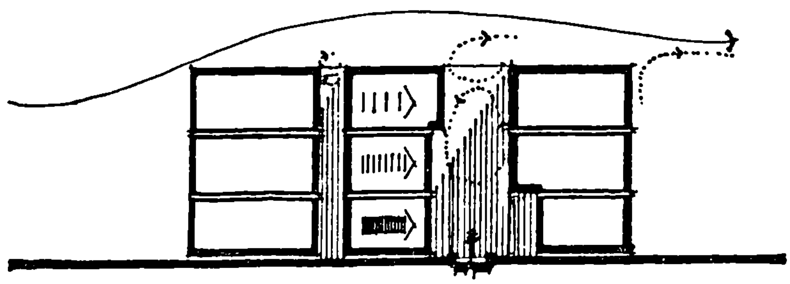


2) Cool, clear night with maximum ground radiation to sky. Cold air stratified into approximately 3 zones in courtyard A, and 5 zones in courtyard B.

Figure (2.12a) The use of the surface inversion phenomenon in court-yard houses in hot climates. Night time conditions.



1) Sunny, hot ground for some part of the day.
Single storey courtyard type (Ur).



2) Ground shaded and cool for most of the day.
Multi-storey courtyard type (Islamic).

Figure (2.12b) Day time conditions in the courtyard houses in hot climates.

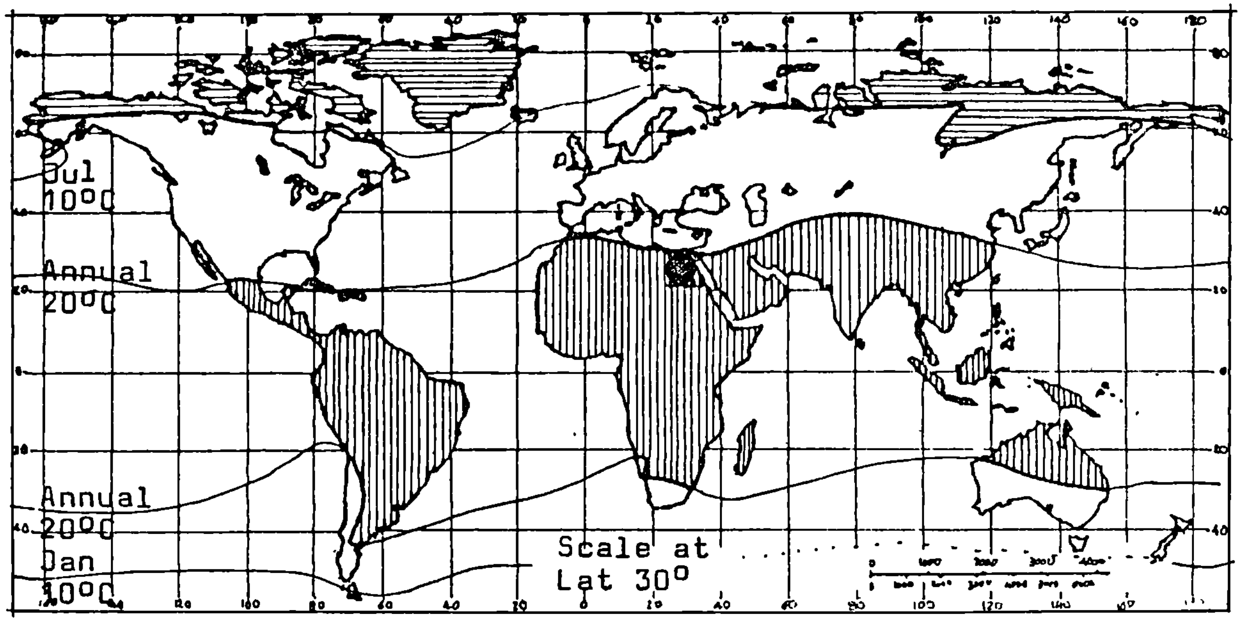


Figure (2.13) The temperature pattern of the world, as suggested by Gates (114).

This type of division has its limitations due to the very wide zones involved and , moreover, depends on one climatic factor only. However it is interesting to note that the 20°C (68°F) mean annual temperature isotherm approximately coincides with the limits of the Trade Winds in each hemisphere.

2.2.3 Wind and Pressure Systems

Air flow in the lower atmosphere may fall into one of two groups - the primary flow, usually called the general circulation (or global circulation) of the atmosphere; and the secondary flow (or local wind pattern). The principle determinants for the distribution and characteristics of wind are the seasonal global distribution of air pressure, the rotation of the earth, the daily variation in heating and cooling of land and sea, and the topography of the particular region and its surroundings. Air movement is measured by its direction and speed. In the hot zones near the tropics where maximum heat stress near the ground occurs, the air expands and its pressure decreases. The air then rises vertically and flows off at a higher level towards colder regions. Part of this air, having cooled down at the high level, descends to the surface in the temperate regions of both the northern and southern hemispheres, from whence cooler heavier air is drawn in towards the Equator. The area where the air rises, and where these northerly and southerly winds meet is known as the tropical front, and is usually referred to as the 'Inter Tropical Convergence Zone' (ITCZ). In this zone one may experience either completely calm conditions, or only very light breezes of irregular direction which are called 'Doldrums', figure (2.14).

The Trade Winds are affected by the atmosphere's rotation with the earth, the atmosphere tending to lag behind the earth. Where the rotation is fastest at the Equator, a

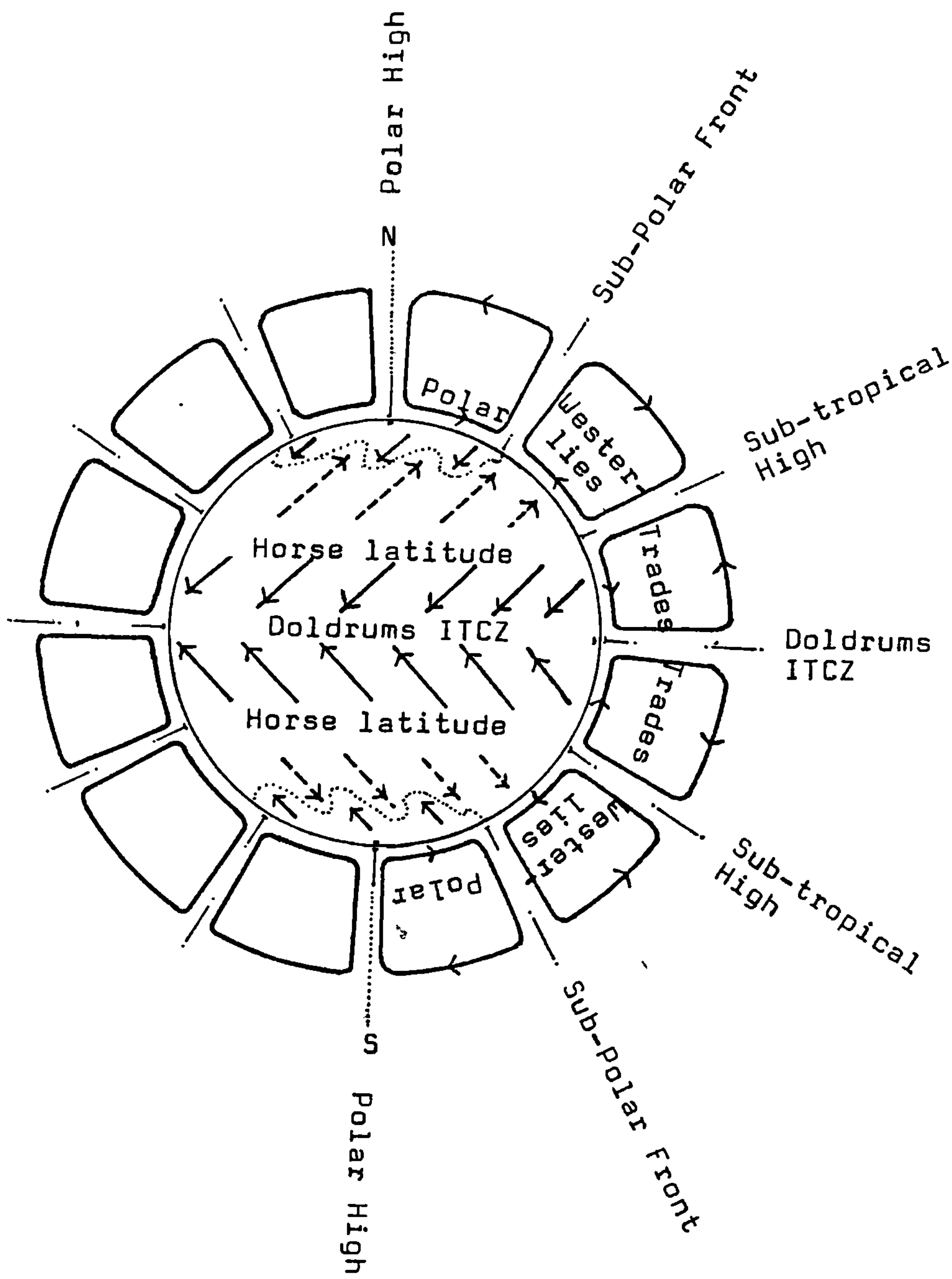


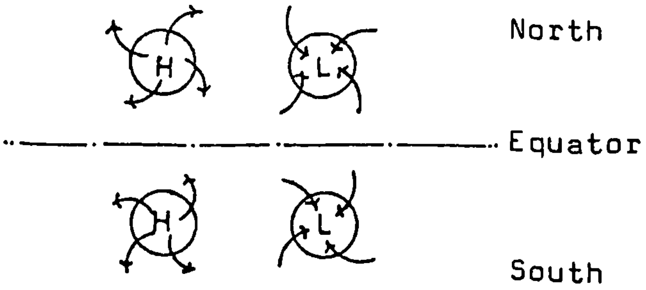
Figure (2.14) Global wind patterns

slippage at the boundary layer between the earth and its atmosphere results in what is known as the 'Coriolis Force'. This effect is experienced as a wind blowing in a direction opposite to that of the Earth's rotation. Therefore, the actual wind is the resultant of the thermal forces and the Coriolis Force; northeasterly winds to the north of the Equator, and southeasterly to the south.

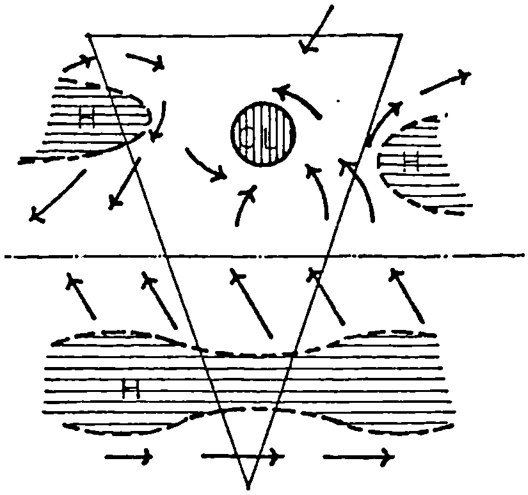
Around latitudes 30° N and S, there are two bands of continuously high barometric pressure (descending air). Between 30° and 60°, north and south, strong westerly winds prevail, blowing in the same direction as the earth's rotation. Further towards the Poles, from latitudes 60° north and south, the air flow pattern is similar to that near the equator. At the meeting point of the cold Polar winds and the mid-latitude westerlies, a band of low pressure, a sub-polar front, is formed with highly variable strong winds.

The influence of the continental masses upon the distribution of pressure, and upon the resultant air movements is illustrated in the diagrams of fig.(2.15). From the pressure distribution maps it is noticeable that in January, fig.(2.16) pattern of high pressure air masses dominating the continents, and low pressure systems dominating the oceans. In July, the pattern is reversed, fig.(2.17); high pressure systems dominate the oceans while continents are dominated by low pressure systems. A low pressure belt exists around the earth at the equator and in July it tends to shift northwards. This equatorial belt is known as 'The Belt of Calms' or 'Doldrums', fig.(2.15). The primary circulation patterns of the Earth's atmosphere are:

a) In the southern hemisphere:
   i) In subtropical areas, around 30°S, a broad high pressure exists throughout the year and is known as the subtropical high pressure belt. In



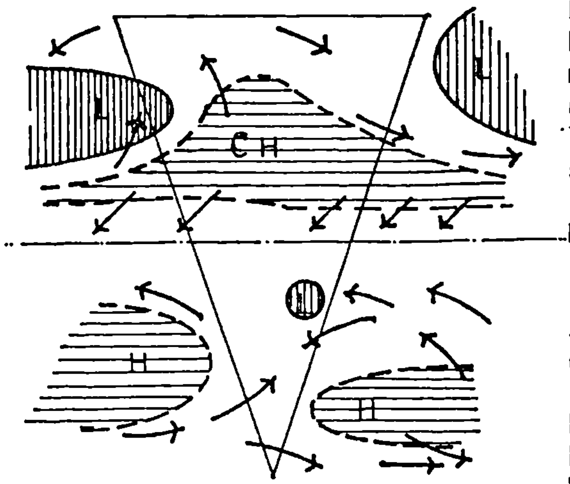
Wind flow around pressure systems



Northern summer; high pressure belt moves north and is broken by continental low. Trades apparent over oceans.

EQUATORIAL LOW MOVES (N) (DOLDRUM) JULY

Southern winter; trades over land and sea. Horse latitude high pressure continuous over land.



Northern winter; high pressure belt maintained and increased over continent. Trades over land and sea.

EQUATORIAL LOW MOVES (S) (DOLDRUMS) JAN

Southern summer; equatorial low slightly further south. High pressure belt broken over land low. Westerlies further S

Figure (2.15) The hypothetical continent influence on pressure and wind systems.

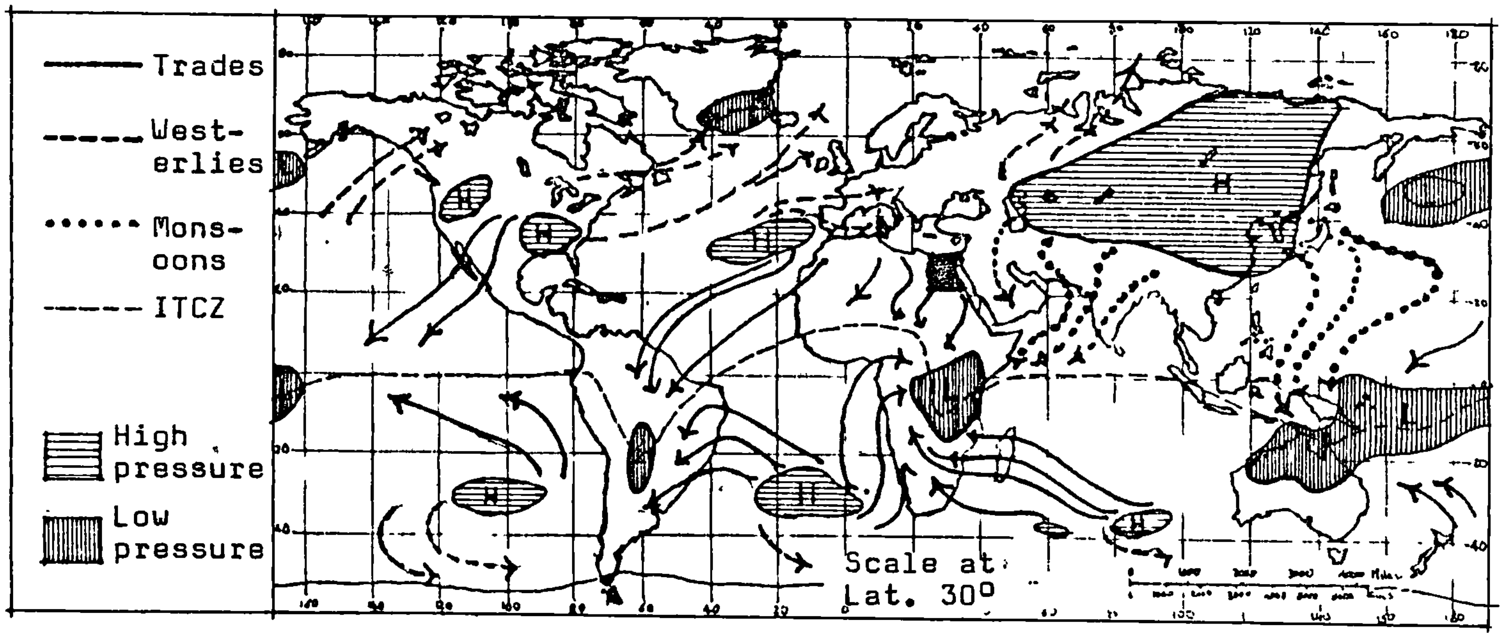


Figure (2.16) January sea level pressure distribution, and direction of mean surface resultant wind.

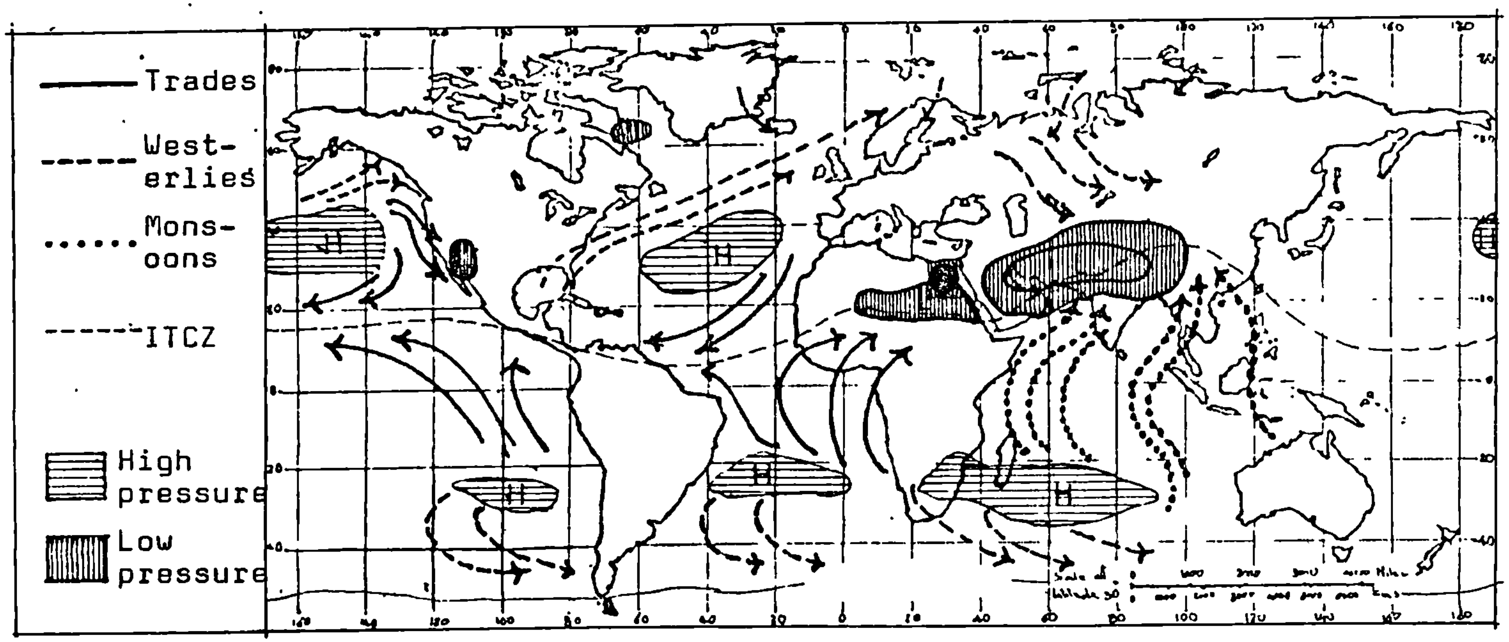


Figure (2.17) July sea level pressure distribution, and direction of mean surface resultant winds.

January it mixes with small low pressure systems over Australia and Africa.

ii) Throughout the temperate region, the pressure falls steadily towards the south and reaches a maximum over Antarctica.

b) In the northern hemisphere:

i) High pressure over the oceans in January in sub-tropical areas; connects up with more intense high pressure systems in higher latitudes over the continents. In July high pressure systems dominate over all the oceans.

ii) The subtropical low pressure dominates in January, while in July the low pressure systems are weaker with high pressure remaining over the pole.

iii) The pressure system of mid-latitude is very broken up compared with that of the southern hemisphere.

Thus, the pressure systems, along with heating by solar radiation and the rotation of the earth, determine the pattern of the winds. Air flows from regions of high pressure towards regions of low pressure, while near the ground winds will be influenced by the presence of surface features. Wind flow around high and low pressure zones is clockwise and counterclockwise respectively in the northern hemisphere, and the directions are reversed in the southern hemisphere.

The Earth's wind belts can generally be summarized as:

a) Doldrums; light and ascending currents of air near the Equator producing clouds with high precipitation; usually occur over oceans and around the ITCZ.

b) Trade winds; prevailing north and south of the Equator to about 30° latitudes. They blow from the north-east in the northern hemisphere, and from the south-east in the southern hemisphere. The ascending air near the

Equator cools and drops its moisture in the form of precipitation.

c) Westerlies; prevail on the poleward side of the subtropical high pressure system and are slightly variable; occur between 30^o and 60^o latitudes.

d) Easterlies; wind blowing from the east to latitude 60^o from the poles in both the northern and southern hemispheres.

Thus, the Earth's wind patterns, in January and July, vary in relation to the pressure zones and the Inter Tropical Conversion Zone. The shift in the ITCZ is the result of the seasonal change in the incoming solar radiation and the different heat capacities of land and water.

2.2.4 Precipitation

Heavy cloud formation and precipitation results from adiabatic cooling of large air masses and is generally affected by the vertical stability of air. At present the highest known annual average rainfall is $1{\cdot}199 \times 10^4$ mm (472 in) at Mt Waialeale in Hawaii, and the lowest is in the Sahara , in Chile and at Wadi-Halfa in Sudan where very little rain has fallen during tens of years of records.

For precipitation to occur the presence of moist air is essential. The visible trace of precipitation that does not reach the ground due to dryness of the air is called virge. Assuming a moist air mass exists, there can be four main causes of precipitation:

a) Orographic - due to high land the air mass is forced, at least in part, to ascend.

b) Convective - when differential heating takes place over a land or sea surface giving birth to warm areas, leading to a warm air parcel which starts to rise.

c) Convergence - when two air masses meet at an obtuse angle, such as the 'Doldrums', ascent of air must take place. This is found in the tropics.
d) Cyclonic - due to frontal precipitation, and may include the convergence of rain as is always found in the temperate zones. The difference is mainly between the two physical characteristics.

Precipitation can be considered the most important factor affecting roof shape in general and the slope of the pitched roof in particular. This slope is greatest in the wettest areas, while roofs are almost flat where precipitation is low. In Egypt precipitation is generally very low, and it is rare in most of the country.

Moisture content of the air, the presence of water vapour in it, can be established, and is measured either as relative humidity, as in fig.(2.18), or as water pressure of the air. For design purposes, relative humidity is one of the important climatic factors affecting human comfort and this will be considered in detail when dealing with 'human response to climate'.

2.2.5 Ocean Currents

Ocean currents are manifestations of an astronomical and geological nature for, in primary circulation, they are functions of the geometry of the solar system and the land-sea configuration. The main factors that give rise to ocean currents are:

a) velocity of the prevailing wind,
b) rotation of the earth,
c) variation in the water density due to difference in temperature and salinity. This factor is influenced by the radiation pattern that varies seasonally over the oceans.

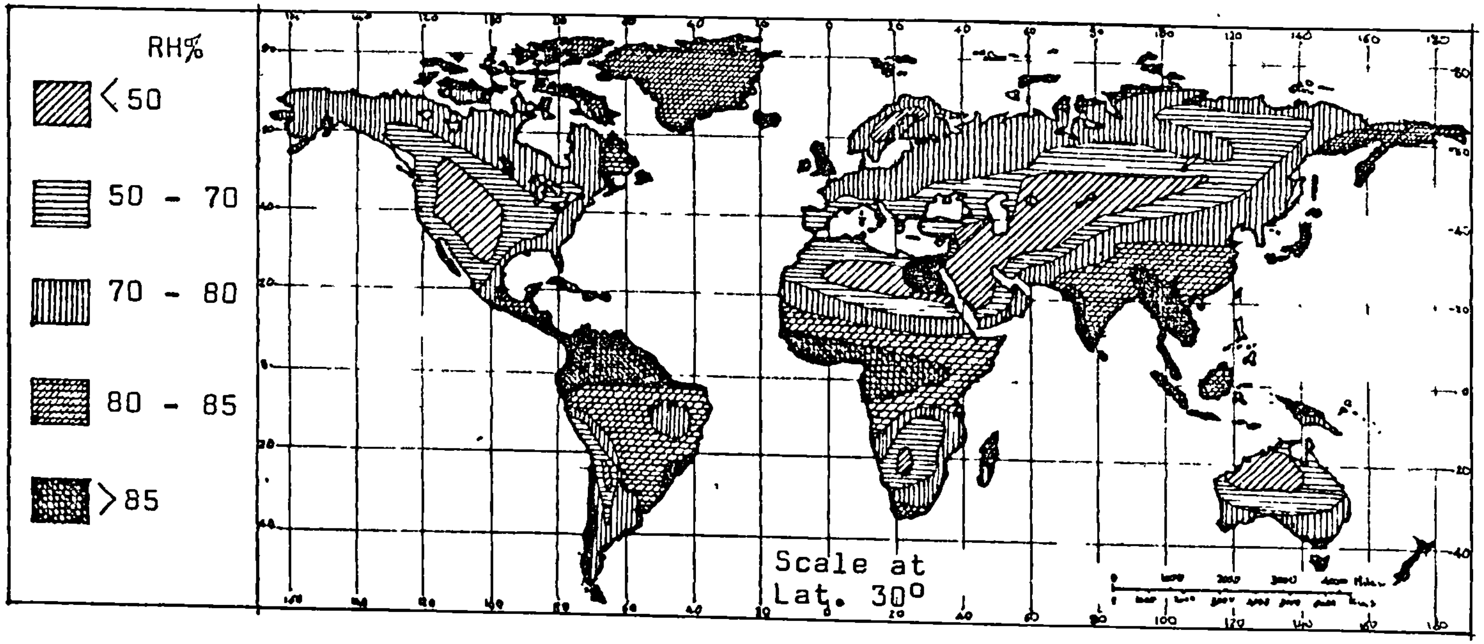
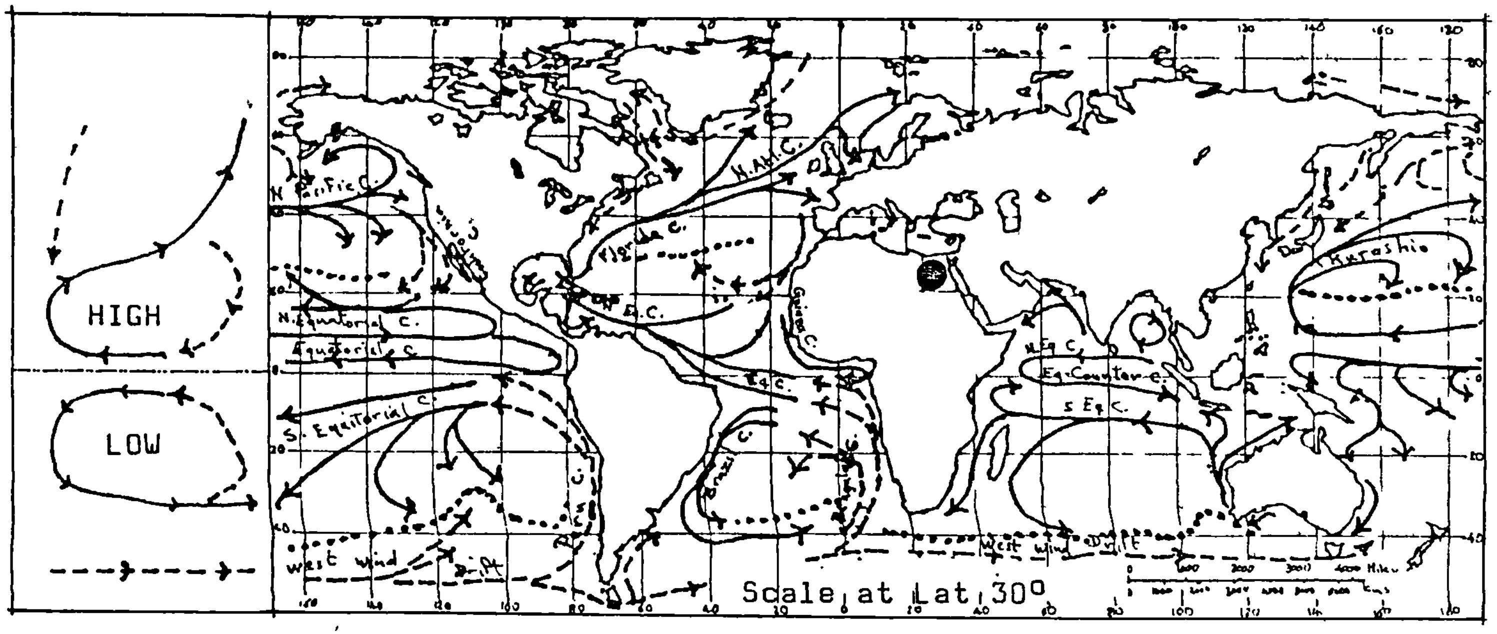


Figure (2.18) World distribution of average relative humidity for July.

The ocean currents are perforce influenced by the land-sea configuration, their direction also being subjected to the coriolis force which tends to impart a clockwise rotation in the northern hemisphere and counter-clockwise in the southern hemisphere. The general tendency is for cold water to be carried Equator-wards along the eastern margins of the oceans, or the western edges of the continents, and for the warm water to be moved polewards along the western margins of the oceans, or eastern edges of the continents. Along western edges of some continents the prevailing winds cause a frictional drag that tends to move the warmer upper layers of water away from the shore faster than the lower layer, causing the cold water to up-well to the surface, figure (2.19).

The influence of the ocean currents on climate may be summarised as follows:

a) They have a modifying effect on the climates of the adjacent land masses tending to make them more equable. Cold currents tend to keep down summer temperatures and warm currents tend to keep winter temperatures at a reasonable level.
b) A warm current will probably cause an increase in precipitation since the warm water tends to increase moisture content of the air above it. A cold current reduces the evaporation and thus the moisture content of air above it.
c) The air masses associated with different currents, in some cases, meet and partially mix causing the cooling of one mass and the precipitation of its moisture. Naturally, the presence of a cold current flowing along the edge of the continent tends to cool the coastal regions and warm currents tend to warm them. For example, the warm Gulf Stream comes to the west coast of the United Kingdom and tends to warm it. Glasgow, which is approximately at the same latitude as Moscow,



······· Subtropical currents —— Warm currents - - - Cool currents

Figure (2.19) Generalized scheme of ocean currents.

has a winter external design temperature (-1°C) higher than that of Moscow (-26°C) (148).

2.2.6 Air Masses and Fronts

An 'air mass' is a widespread body of air, the properties of which can be identified as:

a) having been established while that air was situated over a particular region of the earth's surface,
b) undergoing specific modifications while in transit away from the source region.

An air mass is often approximately homogeneous in its horizontal extent, particularly with reference to temperature and moisture distribution, since the source area itself is large in extent. Such regional sources are limited around the globe and give rise to the following types of air masses:

i) Arctic and Antarctic air masses; cold and extending to great heights; most develop in winter over ice and snow surfaces.
ii) Polar air masses; often develop within subpolar highs.
iii) Continental air masses; low surface temperature, low moisture content and great stability in lower layer.
iv) Maritime air masses; initially like continental but in passing over warmer water become unstable with higher moisture contents.
v) Tropical air masses; develop in low latitudes; they are either continental (iii above), which are hot and dry being produced over subtropical regions, or maritime (iv above), which are very warm and humid being produced over tropical and subtropical seas.
vi) Equatorial air masses; tropical air that stagnates in the Doldrums zone of the Equator.

Because of the definite characteristics shown by each type of air mass, advent over an area brings with it certain characteristics of climate. Thus, the overall image of climate will be generated by the frequency of occurrence of each of these air masses.

The interface or transition zone between two air masses of different densities, due to air temperature and moisture content, is defined as a 'front', and these are basically cold, warm or stationary. If a mass of cold air is advancing towards a mass of warm air, the cold air mass will push itself under the warm one and the zone of contact is recognized as a 'cold front'. As the wedge of warm air is pushed over the cold air, clouds form and precipitation usually occurs. If, on the other hand, a wedge of warm air advances over a wedge of cold air and the movement is one of warm air towards the cold, we have what is known as a 'warm front'. When either a warm or a cold front shows little movement, or wavers back and forth, it is called a 'stationary front', figure (2.20).

2.3 Classification of Climate

Air temperature, radiation, wind and moisture are the parameters we use to describe the weather and the daily climate. The earth's climate can be classified in many ways. The theory on which many climatic classifications are based deals with a hypothetical 'standard continent' as discussed in Appendix 1, however, these classifications depend on the purpose for which such categorization is necessary. The earliest division of the world into natural climatic regions was due to Supan (41) who used temperature values only. Such classification based on a single climatic element has obvious limitations, fig.(2.21). Another classification suggested by Rubrer (41) was dependant on

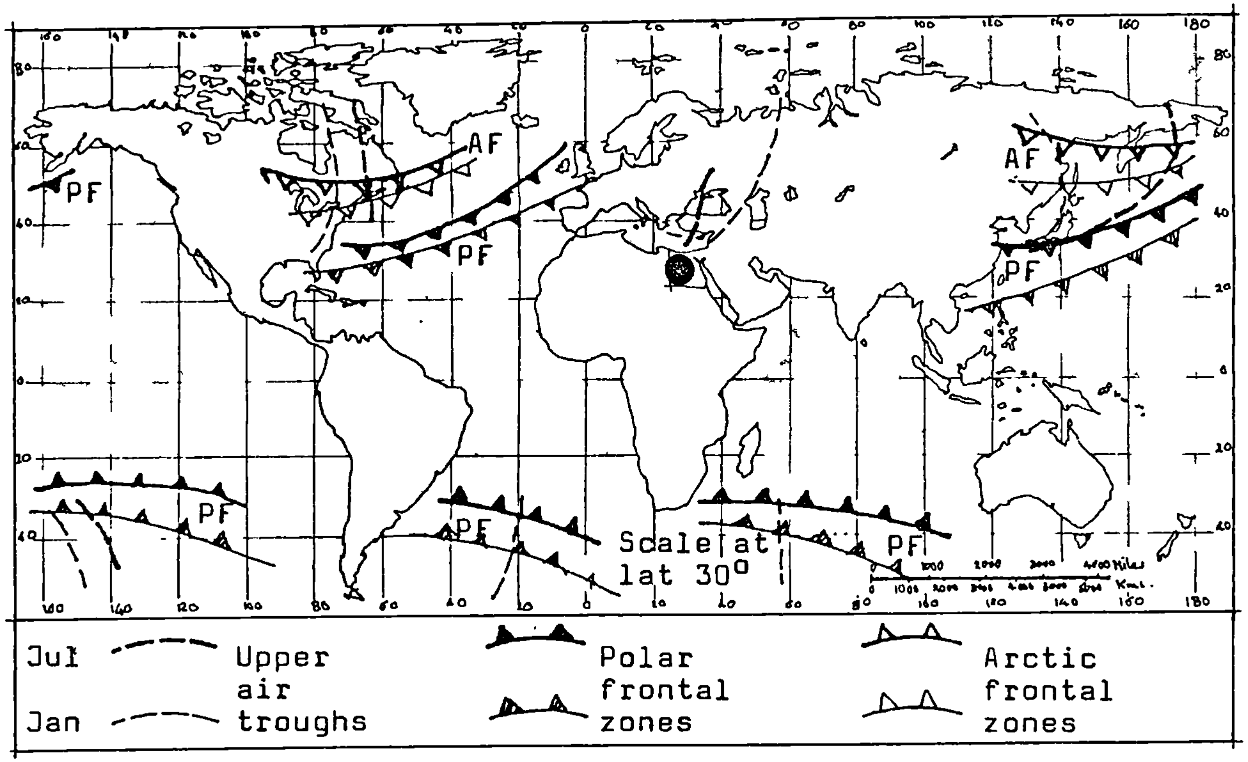


Figure (2.20) The close association of upper air troughs with the major frontal zones

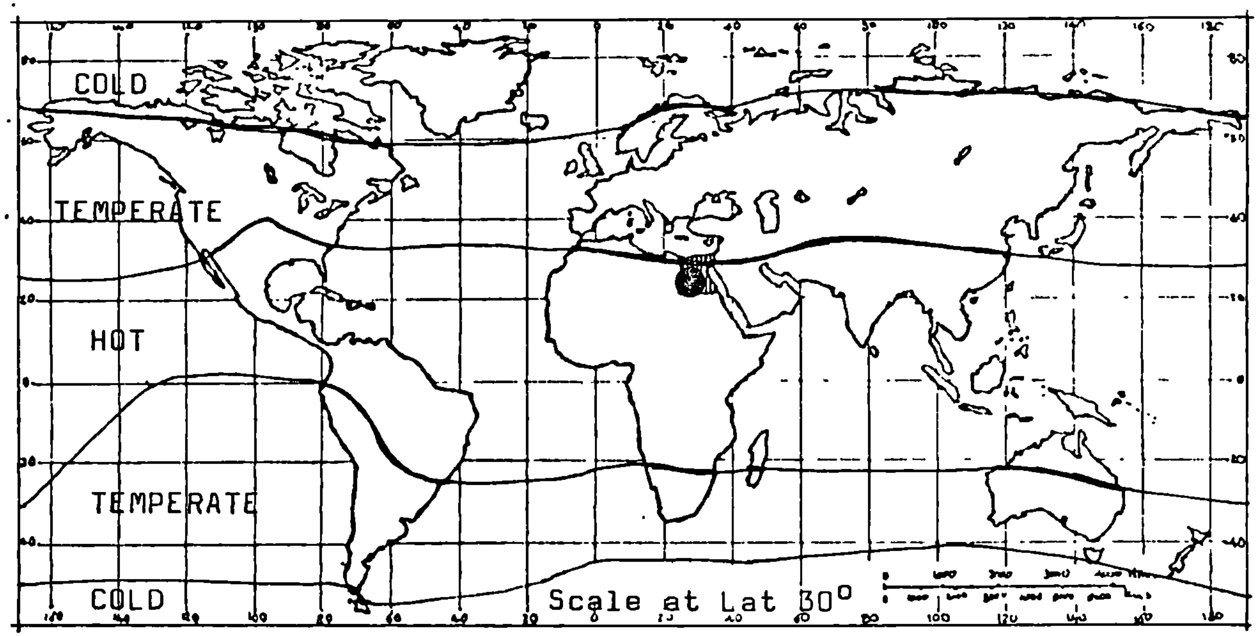


Figure (2.21) World climate classification as seen by Supan (41).

on the number of warm days; that is, on the number of days with mean temperature in excess of 10°C (50°F). The following divisions were recommended:

sub-arctic	1	-	60	warm days / year
cool	60	-	120	warm days / year
temperate	121	-	180	warm days / year
warm temperate	181	-	240	warm days / year
warm	241	-	300	warm days / year

<u>2.3.1 Appraisal of Classification Methods</u>

One of the more recent and the most generally accepted classification is that used by Koppen, fig.(2.22), in which the relation of climate to vegetation is used as a criterion. He divided the world into five sections, each identified by a letter, A, B, C, D or E. These are based on temperature considerations with the exception of B, which is dependant on the relationship between the mean annual precipitation measured in mm (or inches), and the seasonal annual temperature measured in °C (or °F). This classification does not take any account of the high-land regions and neglects the precipitation level.

Another classification, which is as widely accepted as Koppen's, is that of Miller, fig.(2.23). It divides the world into seven sectors, A to G, defined as follows:

A Hot climates - no month below 18°C (64°F) mean annual temperature

B Warm temperate - no cold season with all months over 6·5°C (43°F)

C Cool temperate - with cold season of 1 - 5 months below 6·5°C

D Cold climates - with long cold season of 6 - 9 months below 6·5°C

E Arctic - with very brief warm season and less than

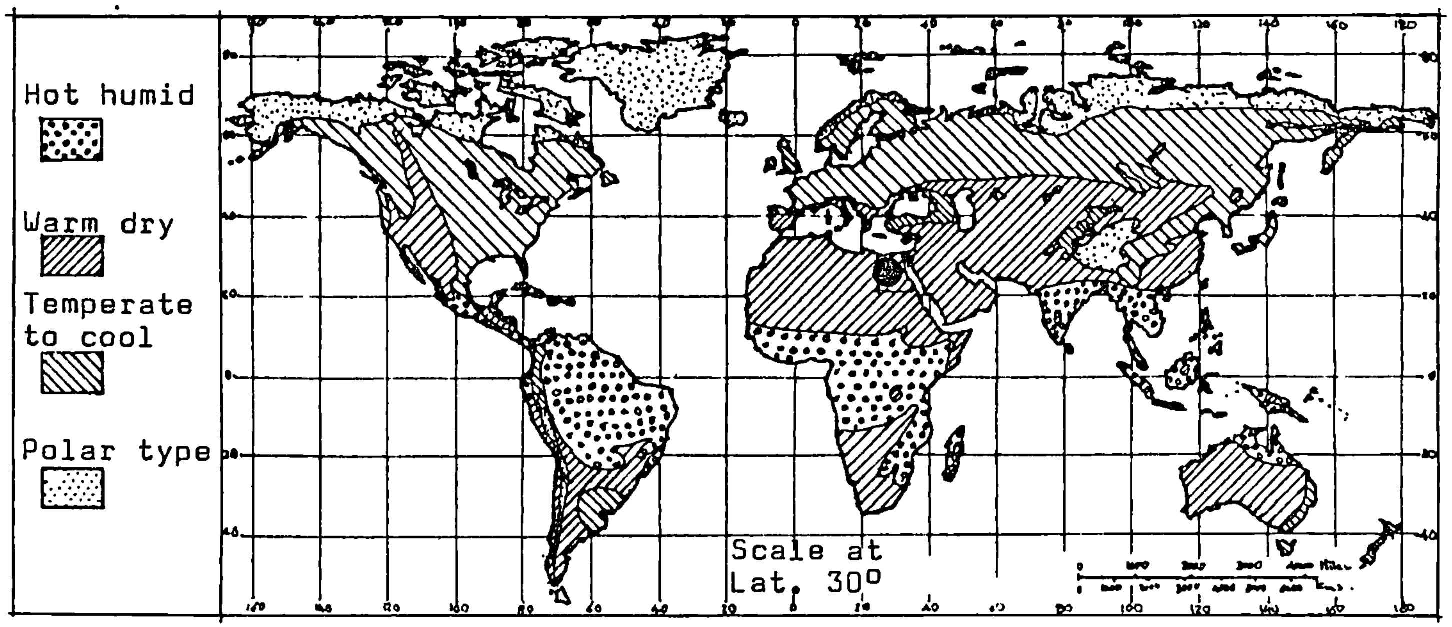


Figure (2.22) Simplified climate map of the earth based on Koppen's classification. After Straaten (249).

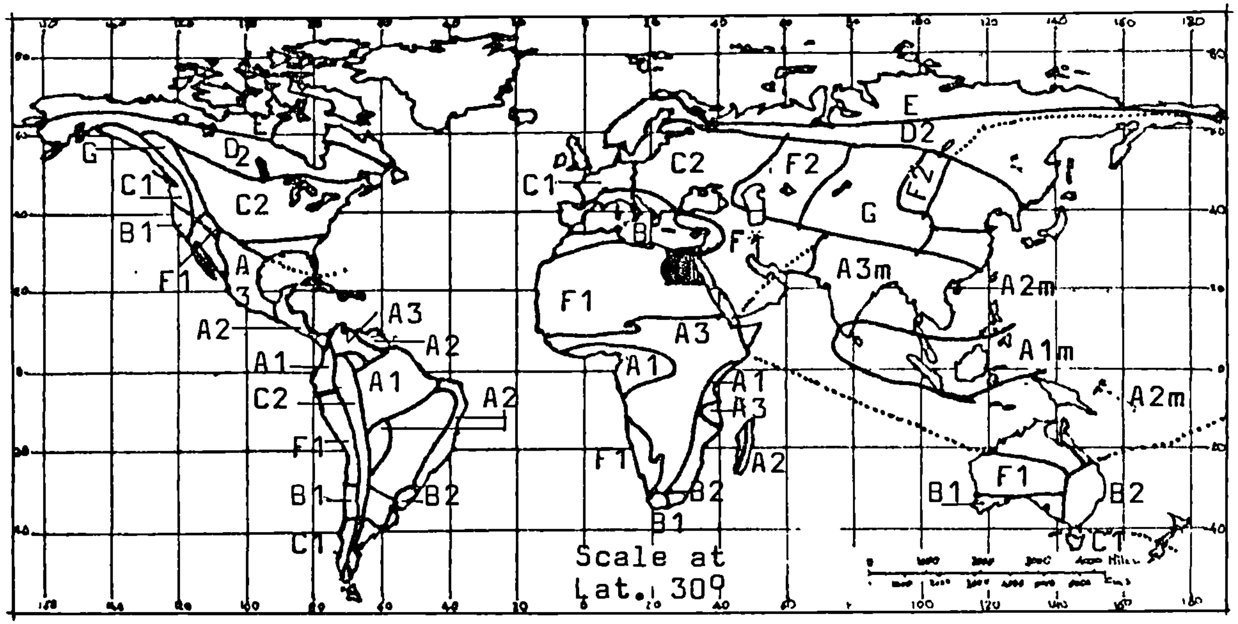


Figure (2.23) World climates as seen by Miller (189).

3 months above 6·5°C

F Desert climates - with rainfall measured in inches less than 1/5 the temperature in °F (approximately equal to rainfall in mm $<$ 14 times the temperature in °C)

G Mountain climates.

Inspecting the climatic classifications above, two main factors emerge as a basis for assessment, the climatic elements used as bases for classification, and the range of their sectors and subdivisions. Supan and Rubrer classifications used air temperature as the only climatic element defining their zones. Supan divided the world into three zones seperated by the isotherms of 10°C and 20°C, while Rubrer divided it into six zones depending on the number of warm days ($>$10°C). Classifications founded on one climatic factor have definite limitations when applying them to building design and town planning. For design purposes, what is needed is a classification which considers the four climatic elements affecting human comfort. This classification must also have a wider variety of sectors allowing for a better building adaptation to the prevailing climatic conditions.

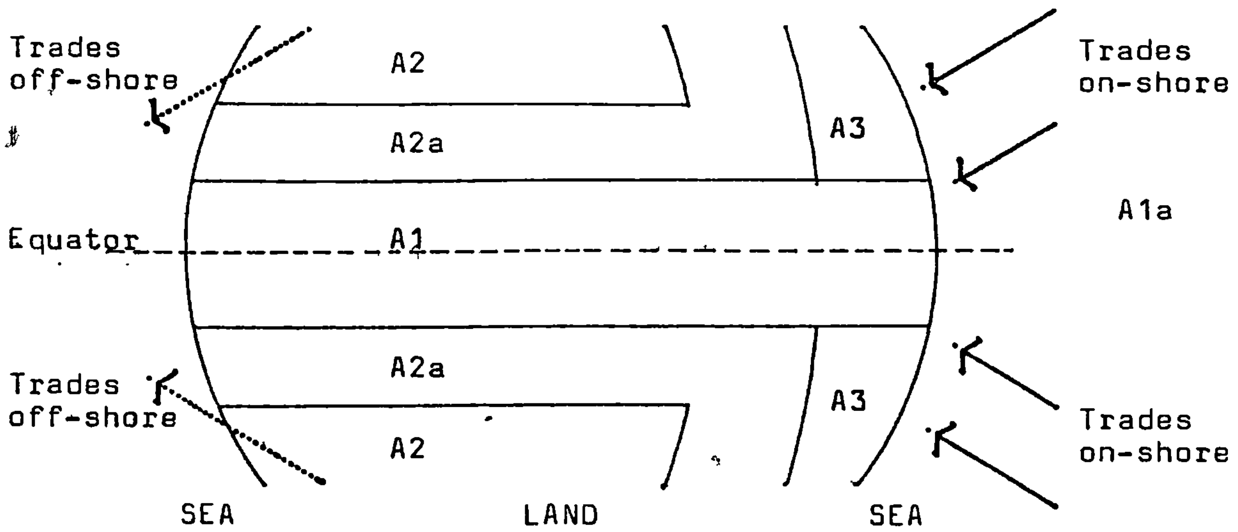
Koppen's classification depends mainly on vegetation regions which may be considered as indicators for two climatic factors, air temperature and precipitation. Millar's classification also depends on temperature and vegetation. These two classifications are the most widely used despite their complexity.

The need for classifying climates specifically in relation to building design has often been expressed, implying that this would offer a satisfactory solution to the problem of design for climate. Yet, any classification method can only serve to indicate the possible general forms that designers might assume. Detailed design requires further information on climate characteristics of the actual site, and this cannot be taken into account in any general classification. It is usually covered by the microclimatic studies which will differ within the one climatic division. The establishment of a scale for evaluating climate, from the architectural point of view, will be the aim of section 2.4.2. A climatic classification procedure, which may be generally used, will be suggested for the Egyptian climate in Chapter 3. To understand the climate of any region, the causes must first be studied before considering the detailed climatic zone characteristics. The hot and the warm temperate climatic zones will be considered in detail.

2.3.2 Characteristics of Hot Climates

In hot climates buildings serve to keep the occupants cool, rather than warm, for the greater part of the year. The dominant problem is the excessive heat stress and the high mean annual temperature which is not less than 20°C (68°F). The most suitable classification for hot climates, considering design applications, is that proposed by G A Atkinson (279). He divided the hot climates into four subdivisions fig.(2.24):

A_1 Warm humid equatorial climate - generally this is a narrow belt between 15°N and 15°S of the equator, with little seasonal variation throughout the year, and periods of heavy rain and electric storms. Usually the shaded air temperature ranges between 27°C and 32°C during the day and 21°C to 27°C at night, with very little annual variation. Relative humidity in this region is very high, over 70% for most of the time. This is accompanied by a very high precipitation which may exceed 500mm per month. The annual rainfall usually renges between 2000mm and 5000mm. The sky in this region is usually very cloudy all the year, causing a very high diffuse radiation near the ground which is likely to accumulate. With the Doldrums



A1 Warm-humid equatorial
A1a Warm-humid island

A2 Hot-dry desert or semi-desert
A2a Hot-dry maritime desert

A3 Composite or monsoon

A4 Tropical upland

Figure (2.24) Distribution of hot climates about the Equator.

dominating this region, wind velocities are very low. These conditions encourage quick growth of plants with the water table usually high. Risk of mould growth is also very likely, leading to rapid decay of building materials.

A_1a <u>Warm-humid island climate</u> - this type of climate is generally found on islands located on the Trade Wind zones within the Equatorial belt, and again shows very little seasonal variation, the temperature ranges within a limit of $8^{o}C$. This zone is very humid with relative humidity between 55% and 100%. The mean annual precipitation may be up to 1500 mm with about 250 mm in the wettest month. This region usually has very strong radiation, mainly direct because of clear skies. Being in the Trade Winds zone, winds at 6 and 7 m/s (13 - 15 mph) dominate, with much higher velocities during cyclones. During the cyclonic or hurricane times, wind speeds range from 45 to 70 m/s (100 to 150 mph). Corrosion and decay of building materials are likely to occur due to the high salt content of the atmosphere.

A_2 <u>Hot-dry desert or semi-desert climates</u> - these conditions exist in two belts between 15^{o} and 30^{o} north and south of the Equator. They are found in Africa (the Sah'-ra'a), central and western Asia, north-western America and in central and western Australia. In all of these regions the characteristic arid conditions are caused by the Trade Winds blowing towards the Equator losing most of their water vapour content over the vast continental areas. Griffiths (132) suggested the following boundaries for this region:

i) In the north the 125 mm isohyet.
ii) In the south the isopleth R in mm $< 14T^{o}C$
    (R in inches $< 5T^{o}F$)

where T is the mean annual temperature
and R is the mean annual rainfall.

These arid zones are characterized by the general absence of moist air masses. The air masses over the Sah'-ra'a for example, have low relative humidity ranging between 10% and 55%. The northern and southern edges of the Sah'-ra'a show very different annual distribution of their scanty rainfall. Winter period rains occur in the north, while the south has summer rains. Flash storms may occur over limited areas with up to 50 mm rain in a few hours. However, during the winter season, six important features can be identified, each of which plays a significant role in the weather over the northern Sah'-ra'a:

1. The Sah'-ra'a high; an extension of the Azores anti-cyclones.
2. The Arabian high; another part of the sub-tropical high pressure belt.
3. The Balkan high; in conjunction with the great anti-cyclone over central Asia.
4. Mediterranean low pressure area; over the central and eastern Mediterranean.
5. The Equatorial trough; over central Africa.
6. The movement of the ITCZ southwards, fig.(2.25).

During the summer there is an approximate inverse of winter conditions, the main features are:

1. A low over the Arabian Peninsula.
2. A low over the southern Sah'-ra'a.
3. A high pressure ridge over central Africa.
4. The ITCZ shifts northwards of the Equator, fig.(2.26).

The wind circulation is such that air masses reaching most of the Sah'-ra'a have experienced reasonably long trajectories over the sea, and the extremely high temperature over the land brings about a reduction in relative humidity. Thus the winter and summer seasons have many similarities with the shift of the ITCZ just north of the Equator.

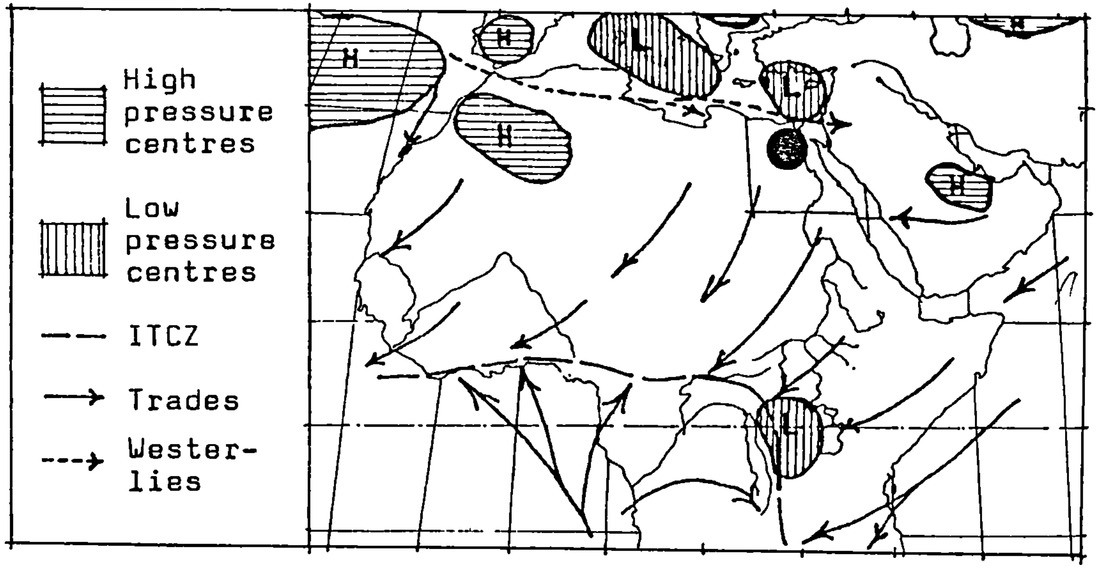


Figure (2.25) Mean daily pressure patterns and air flow (January).

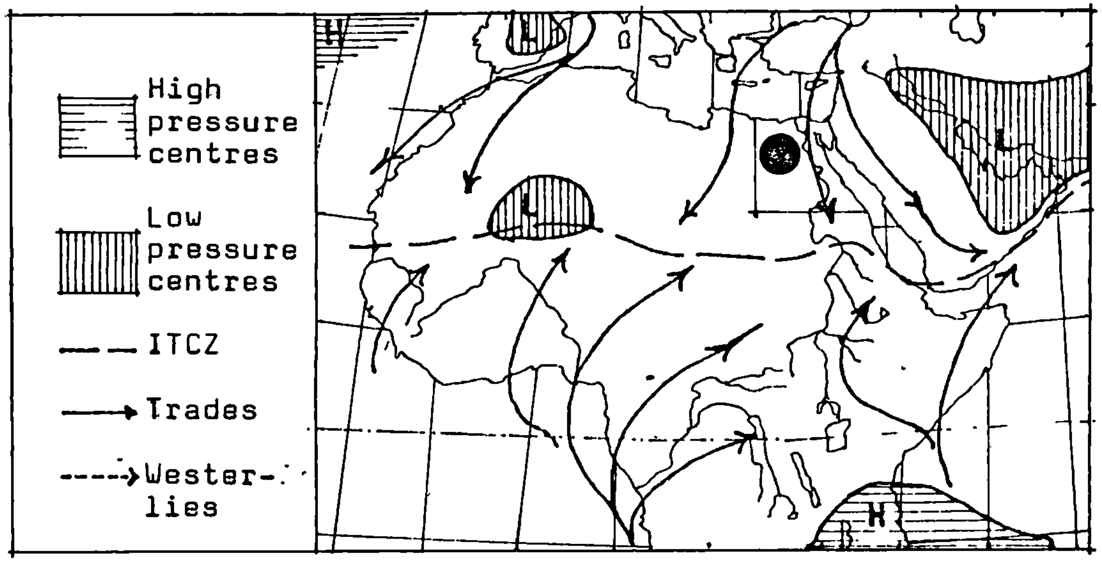


Figure (2.26) Mean daily pressure patterns and air flow (July).

A_2a Hot-dry maritime desert climate - these conditions occur in the coastal areas of the hot-dry desert regions and have very low precipitation, as in other desert regions. However, the arrival of the rainy season depresses the temperature and increases humidity to uncomfortable levels. Air temperature in these regions is very high, with a maximum during the dry season of about 38°C (100°F). The temperature range is between 9°C and 12°C, because of the high relative humidity of 50 to 90% occurring in this region. Solar radiation is very strong with very high diffused radiation. The prevailing wind is mostly local coastal.

A_3 Composite or Monsoon climate - This type of climatic conditions generally occurs in large land masses near the tropics, and is mainly a combination of two seasons - two thirds of the year is hot-dry, and the remaining third is warm-humid. Localities further north and south often have a third cool-dry season described as winter. During the hot season the mean maximum temperature may reach 43°C, with the warm season having a mean maximum temperature of 32°C, and the cold season 27°C as in New Delhi (155). The relative humidity during the dry period may be as low as 20% while 95% may be recorded during the wet period. The monsoon rains are intense and prolonged, up to 35 mm may fall in one hour. The annual mean precipitation varies between 500 mm and 1500 mm, with about 250 mm falling in the wettest month.

Solar radiation is either strong diffused during the rainy period, or strong beam in the dry season. The monsoon winds are fairly strong and steady, and in the dry period hot dusty winds prevail during the day. Soil in these regions is usually very dry without any vegetation cover during the dry season, but changes rapidly with rain, becoming fertile and green within a few days. Soil erosion during the monsoon season can cause considerable stability problems for buildings. The possibility of instability is not the only problem facing buildings in this climatic zone, as the seasonal changes in relative humidity cause rapid deterioration of building materials, also termite damage is of common concern . Moreover, dust and sand-storms during the dry season cause difficulties with the necessary ventilation for buildings.

The east coast of Africa is affected by the monsoon centre of India, by the south-east Trade Winds, and by the convectional rainfall belt. The alignment of the coast brings the wind on-shore of the Equator resulting in rainfall in January on the eastern side of Madagascar and along the coast of Mozambique. In July winds are less directly on-shore, and rainfall is considerably lower. North of the Equator the winds tend to be parallel to the coast, and even off-shore, for much of the year so that little precipitation occurs.

A_4 Tropical upland climate - these climatic conditions prevail in the mountainous regions and plateaux 900 to 1200 m above sea level. Seasonal variations are small near the Equator, but further away from it the seasons follow those of nearby lowlands. The mean maximum air temperature may reach 30^{o}C, while the mean minimum can be as low as 10^{o}C. This region is extremely humid with a relative humidity ranging between 45 and 99%. Precipitation on windward slopes may be as high as 80 mm/hr, with an annual average of not less than 1000 mm. Solar radiation is very strong and direct during clear periods, but more diffused as cloud cover increases. This climate is characterised by strong long wave radiation loss during clear nights of the dry season. Prevailing winds are variable, predominantly NE and SE with velocities rarely exceeding 15 m/s. Thunder storms, with the risk of electric discharges and hail, may occur during the rainy period.

2.3.3 Characteristics of Warm Temperate Climates

Polewards of the hot climate zones, and before reaching the cool-temperate climates with their distinct long cold season, lie the warm temperate regions of the world, where the climate shows marked differences between summer and winter, figure (2.27). Even so, the winter is not normally cold enough to check plant growth, as the mean monthly temperature is generally in excess of 6·1°C (43°F) in the coldest month. These regions are transitional ones where the seasonal shift of the pressure belt results in their being alternately under the influence of the Trade Winds in summer, and the Westerlies in winter. The winter months are affected by depression tracks over oceans or seas, as in the Mediterranean basin, fig.(2.28), bringing moist, windy conditions. The summer months are hot and arid due to the continental effects of the off-shore trades. Mean temperature for summer is usually between 21 and 26°C (70 to 80°F), and the winter mean temperature is above 6°C (43°F) and often higher than 10°C (50°F). Rainfall as high as 1500 mm (160 in) may occur, with an annual average of 750 mm (30 in) fig.(2.29). This usually occurs in the shape of heavy showers associated with bright and sunny intervals.

Relative humidity is not usually high except for the autumn months when some areas have damp spells of weather with mists and dew at night. In the spring the low pressure draws in winds from the south. These are hot, dry and often dust-bearing winds. In regions with this kind of climate, these winds may have local names such as the Sirocco of northwest Africa, and the Khamaseen of Egypt. They are damaging to crops and uncomfortable for man. During the Egyptian summer a high pressure zone extends across the Mediterranean, and winds are generally north-easterly.

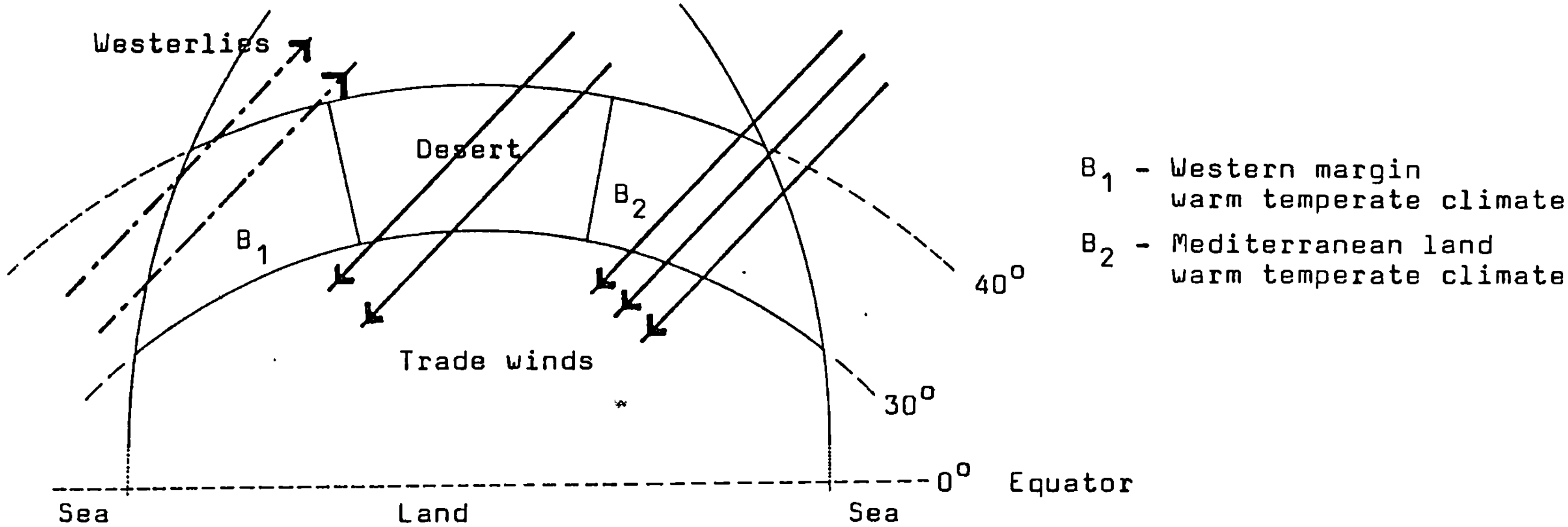


Figure (2.27) Distribution of warm temperate climates in the northern hemisphere.

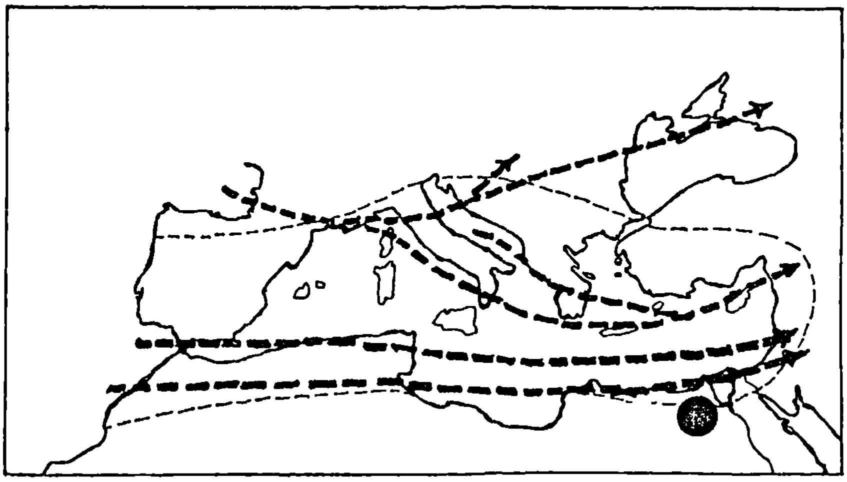


Figure (2.28) Main routes followed by cool-season cyclones in the Mediterranean Basin.

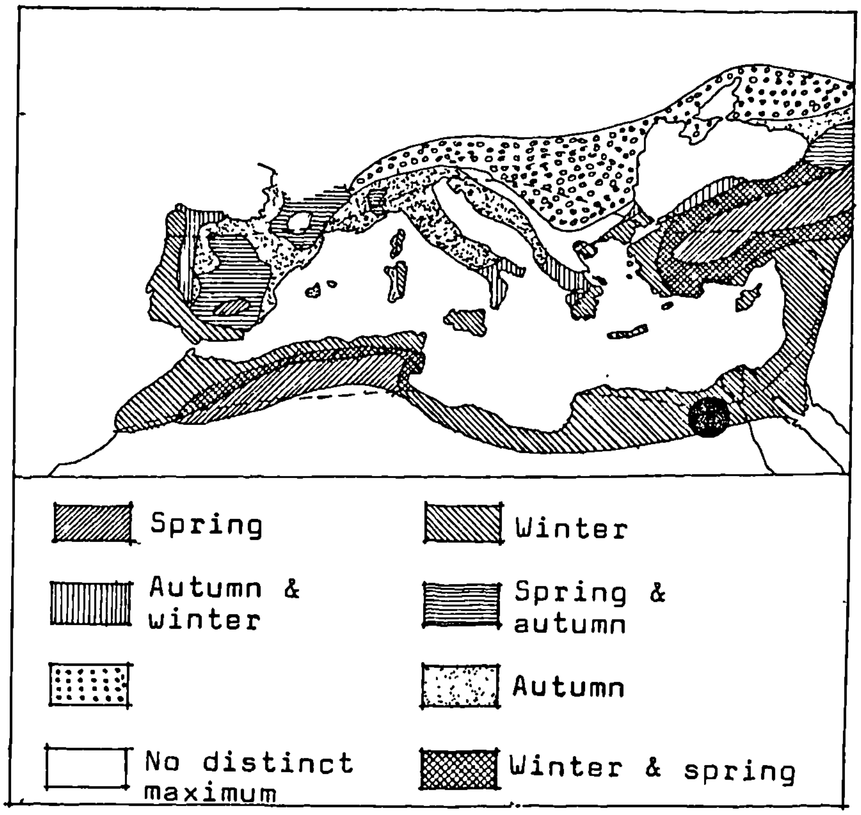


Figure (2.29) Seasons of maximum rainfall in the Mediterranean Basin borderland.

2.3.4 Comment on Classification

The various climatic classifications discussed above were established with consideration of one or two climatic elements only, yet they seem to include the effects of one or more other elements, such as vegetation, which may give a rough indication of solar radiation, precipitation and wind conditions. For example, in Egypt the Nile Delta is considered to have the same climatic conditions as any part of the Sah'-ra'a. Thus the Delta could have been classified as hot-dry climate, save for Atkinson's consideration of the amount of rainfall in determining the climatic characteristics of the region.

From the architectural design point of view, the main aim is to create an environment satisfying the aesthetic and functional aspects of human comfort. The functional aspect can be achieved by providing buildings which will modify the prevailing climatic conditions. In order to choose a suitable index the existing thermal indices will be evaluated, and any necessary modifications made. Then the index will be used as a base for defining the climatic zones. The next section (2.4) will deal with evaluation of thermal indices, and Chapter 3 with the modification of the chosen index, which will then be used to classify the climatic regions within Egypt.

2.4 Human Response to Climate

A comfort zone for human beings can be defined negatively as the situation where no feeling of discomfort is experienced. This is very similar to the zone of thermal neutrality, and differs with individuals, their type of clothing, and the nature of their activities. Moreover, it depends on sex as women generally prefer an effective temperature for comfort 1°C higher than men. Human comfort requirements depend on the conditions of the surrounding environment and the way man exchanges heat with it. The inner human body temperature is about 37°C and must remain so. Any increase or decrease from that 37°C will result in a heat stress situation causing discomfort. The range of conditions within which at least 80% of the people would feel comfortable can be termed as 'the optimum comfort zone'. This has been established by several research workers despite their different approaches and definitions.

Ellsworth Huntington (206) postulates that the optimum climatic conditions for human progress are as follows:

a) Average temperature ranges from somewhat below 17°C (62·6°F) in the coldest months to nearly 21·5°C (70°F) in the warmest months.
b) Frequent storms or winds to keep the relative humidity quite high, except in hot weather, and provide rain at at all seasons.
c) A constant succession of cyclonic storms which bring frequent moderate changes in temperature, but are not severe enough to be harmfull.

His study shows that the periods of highest and lowest rate of activity occur at different times due to different climatic conditions. At higher latitudes the most desirable period is from July to September with winter as an unfavourable season. In temperate regions spring and autumn are periods of high activity, while summer and winter are relatively poor. In low latitudes there are two climatic periods, a short favourable winter and a long summer with a decline in human activity. Thus, it is of unquestionable importance to understand the nature of the interactions between man and his environment.

2.4.1 Man/Environment Heat Exchange

Heat exchange between a human body and its surrounding environment depends basically of clothing, air temperature, humidity, air movement and solar radiation. This exchange occurs through four main processes, namely - radiation, conduction, convection and evaporation. D H K Lee (278) summarized the factors involved in the heat balance of the body in the following way, fig.(2.30):

Gains

a) Heat produced by:
   1) basal processes
   2) activity
   3) digestion
   4) muscle tensing and shivering in response to cold

b) Absorption of radiant energy:
   1) from the sun, directly or reflected
   2) from glowing radiators
   3) from non-glowing hot objects

c) Heat conduction towards the body:
   1) from air above skin temperature
   2) by contact with hotter objects

d) Condensation of atmospheric moisture

Losses

e) Outward radiation:
   1) to sky
   2) to colder surrounding

f) Heat conduction away from the body:
   1) to air below skin temperature (accelerated by air movement)
   2) by contact with cold objects

g) Evaporation:
   1) from respiratory tract
   2) from skin

Therefore, the thermal balance of the body's heat gains

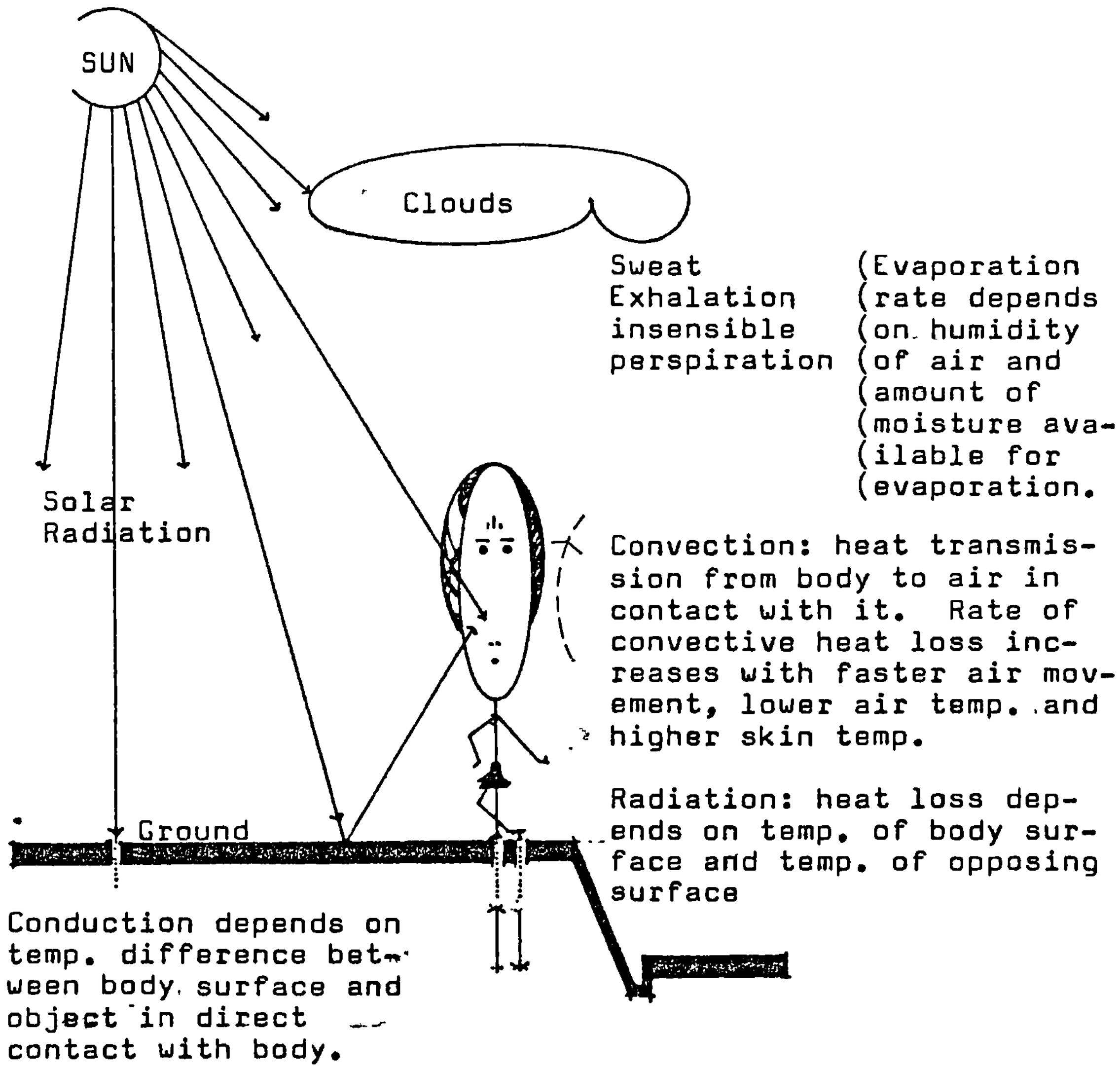


Figure (2.30) Heat exchange between man and environment, (196).

and losses may be expressed as:

$$M - E \pm C_d \pm C_v \pm R = 0$$

where: M = metabolism of all energy produced in the body; only about 20% is utilised and the surplus 80% must be dissipated as heat. The rate of excess heat output varies with activity from about 50 Watts when sleeping, 150 Watts for moderate movement, 300 to 400 Watts for walking and moderate lifting, and up to 800 Watts for sustained hard work.

E = evaporation of moisture and sweat; as latent heat of water is 2400 kJ/kg, the evaporation of water at the rate of 1·0 kg/h will produce a heat loss of $24 \times 10^5/3600$ = 666 Watts.

C_d = the conductive heat exchange; negative when the body is in contact with cold bodies, and positive when in contact with warmer bodies.

C_v = convection heat exchange; negative if air is cooler than the skin, and positive if it is warmer.

R = radiant heat exchange; negative to the night sky and cold surfaces, and positive from the sun and hot bodies.

If the result of the above summation is greater than zero over heating will be experienced by man, and if it continues sweating will start.

Inhabitants of warmer climates prefer somewhat higher temperature than those living in cooler regions. Full adjustment and re-acclimatization is reached in a period varying from one to six months, depending on individuals. In hot climates two different types of thermal discomfort can be differentiated:

a) Thermal sensation of hotness which is closely associated with dry heat exchange with the environment by convection and radiation.
b) Wetness of skin in the form of sensible perspiration which is experienced on the warm side of the comfort zone and is a specific combination of temperature, relative humidity, air velocity and metabolic rate.

Air movement affects body cooling, though it does not decrease the air temperature. The cooling sensation is due to increased evaporation from the body and to heat loss by convection. As air velocity increases, the upper comfort limit is raised, however this rise slows as higher air temperatures or velocities are reached.

Clothing, though not a part of building design considerations, is a factor which cannot be ignored when considering the thermal design of the building. To make valid thermal predictions, it is necessary to make some qualification of the thermal effect of clothing. Scales for clothing effectiveness were developed in Britain and the United States of America. The American scale of units, called clo-values is the one which has gained widest acceptance and use. The scale varies from zero for nude, to a maximum of 4 which represents heavy Polar dress. The unit is defined in terms of heat transfer resistance from the skin to the outer surface of the clothed body (insulation). Typical ranges of combinations of clothing, together with their appropriate clo-value and typical temperatures at which sedentary subjects would be thermally comfortable are shown in table (2.3).

2.4.2 The Thermal Indices

It is impossible to express human comfort as a function of a single environmental factor, since these affect the human body simultaneously and the influence of any one depends

Table (2.3) Thermal effect of clothing.
After Fanger (103) and Burberry (58).

Clo Value	Clothing Ensemble	Sedentary Max Comfort Temp
0	Nude	28•5°C
0•1	Shorts	
0•3 - 0•4	Typical tropical clothing ensemble: shorts, open-neck shirt with short sleeves, light socks and sandals.	
0•5	Light summer clothing: long light-weight trousers, open-neck shirt with short sleeves.	25•0°C
1•0	Typical business suit, short under-wear and a waistcoat.	22•0°C
1•5	Typical business suit plus cotton coat (or long underwear plus heavy tweed business suit, waistcoat and wool socks).	18•0°C
2•0	Typical cold clothing ensemble: heavy tweed suit, waistcoat, wool socks, heavy shoes, heavy woollen overcoat, gloves and hat.	14•5°C
4•0	Heavy wool pile ensemble (Polar weather suit).	

on the level of the others. Therefore, it is important to evaluate the combined effect of environmental factors on the physiological and sensory responses of the body and to express any combination of them in terms of a single parameter. Thus, attempts have been made to develop a single formula or scale combining the effects of all these factors and this is known as the 'Thermal Index'. At first the purpose of the indices was limited to estimation of the combined effect of air temperature and humidity on human comfort at rest and/or engaged in sedentary activity. Later, the effect of radiant temperature, air velocity, metabolic rate, clothing and finally solar radiation were also taken into account. As a result of this effort, a large number of thermal indices were developed. While the early ones were concerned mainly with thermal sensation, the later indices estimated the physiological responses to the combined effect of climatic and human factors.

The thermal indices may differ in the following ways:

i) their basic approach to the problems
ii) the units used as the basis for expressing the combined effect of the various factors
iii) the range of conditions of their application
iv) the relative importance attributed to each factor

The thermal indices which will be described and discussed in this part are:

a) Effective temperature (ET) and corrected effective temperature (CET)
b) Resultant temperature (RT)
c) Predicted 4 hour sweat rate (P_4SR)
d) Heat stress index (HSI)
e) Index of thermal stress (ITS)
f) Standard effective temperature (SET)

Tables (2.4 a to f) describe these indices. Inspecting these tables, two factors may be taken as a basis for comparison. They are a) the index unit, and b) the range of applicability.

a) <u>The index unit</u>: includes at least one climatic factor. The unit of the ET index and the RT is the temperature of still saturated air. The unit of the P_4SR and the ITS is the expected sweat rate under given environmental and metabolic conditions. The unit of the HSI is the ratio of the evaporative cooling required by the body to the maximum capacity of air. The unit of the SET is the degree of discomfort with reference to skin wetness and temperature of humid air under given environmental and metabolic conditions.

The choice of units has directly determined the properties of the indices. Saturated air temperature is inherently a factor of inconsistant physiological significance, because an increase in the temperature of saturated air is accompanied by an elevation of the vapour pressure. Moreover, the physiological effect of vapour pressure is not linear but progressively increases with the vapour pressure. Consequently, when the saturated air temperature is used as a unit the relation between the index and the physiological and sensory responses is also non-linear. For example, varying the effective temperature from 25° to 27°C has little effect, while an increase from 35° to 37°C makes the difference between conditions tolerable for several hours, and conditions which may result in a heat stroke after only a short time (122). In these circumstances there is no possibility of evaluating directly the difference between two climatic conditions differing in their ET, RT or the value of any other index based on the same unit. It is also impossible to evaluate directly the physiological effects of changes in air motion and humidity expressed by changes in the value of the index, since this

Table (2.4 a) The Effective Temperature (ET)
American Society of Heating and Airconditioning Engineers
1923 - 25

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Air temp Humidity Air velocity	Instantaneous thermal sensation on semi-nude and customary indoor clothing	The temp of saturated, still air, of average velocity 0•12 m/s (25 ft/min)	Dry bulb temp Wet bulb temp Air speed	Air temp: 1-43°C (30-110°F) Wet bulb temp: 1-43°C (30-110°F) Air speed: 0•12-3•50 m/s (20-700 ft/min)

<u>Evaluation</u> The index overestimates the effect of humidity, (Givoni; Yaglou)

It does not make allowance for the deleterious effect of low air speeds in hot and humid conditions, (Smith)

At high air temperature, it exaggerates the stress imposed by air speeds of about 0•5 m/s to 1•5 m/s (100 to 300 ft/min), (Smith)

Table (2.4 b) The Resultant Temperature (RT)

A Missenard

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Air temp Humidity Air speed	The thermal equilibrium between body and environment (exposure of subjects greater than used in ET) Subjects clothed and unclothed.	The temp of saturated still air with average velocity of 0·12 m/s (25 ft/min)	Dry bulb temp Wet bulb temp Air speed	Air temp: 20-45^{o}C (68-120^{o}F) Wet bulb temp: 18-40^{o}C (64-104^{o}F) Wind speed: still air to 3·0 m/s (600 ft/min)

<u>Evaluation</u> Below 30^{o}C there was slight overestimation of the effect of humidity with respect to both sweat rate and thermal sensation, (Givoni).

At higher range of air velocity the index underestimated the cooling effect of air motion while in lower range, the effect of wind was overestimated.

Table (2.4 c) The Predicted Four Hour Sweat Rate (P_4SR)
Royal Naval Research Establishment, England. (McArdle *et al*)

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Global air temp Humidity Wind speed Metabolic level Clothing	Subjects exposed 4 hours dressed in 2 types of clothing under rest conditions (av. metabolic level:63 W, 54 kcal/hr) and alternate rest/work (av. met. level: 129 W, 111 kcal/hr).	Expected sweat rate in 4 hour period under different combinations of climatic factors under rest and rest/work conditions.	Globe temp Wet bulb temp Wind speed Metabolic level Clothing	Globe temp t_g: 27-54°C (80-150°F) Wet bulb temp: 16-36°C (60-97°F) Metabolic level: 115-440 W 100-360 kcal/hr

<u>Evaluation</u> The P_4SR agrees with the thermal sensation in the index range up to 1·2 (above this range thermal sensation is not sensitive enough),(Givoni).

The effect of air velocity agreed with the experimental results. The effect attributed to humidity was found to be slightly less than experimentally observed.

It seems that the P_4SR enables reliable estimation of the overall thermal stress, manifested in the sweat rate, within the given range of thermal sensation, under a variety of matabolic, climatic and clothing conditions.

Table (2.4 d) The Heat Stress Index (HSI)

Belding and Hatch (Univ of Pittsburgh)

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Metabolic rate Radiation and convection Evaporative capacity of the environment The required evaporative capacity for cooling.	The theoretical calculation of: external heat stress acting on man exposed to a given thermal environment; metabolic heat produced for various activity levels; evaporative cap. of environment.	The numerical value of the index is presented by the ratio E/E_{max} Heat stress = required evaporation/max evaporative capacity of the environment x 100 (zero = comfort zone).	Globe, or dry bulb temp Vapour pressure Air velocity Metabolic level	Dry bulb, or Globe temp: 21-49^{o}C (70-140^{o}F) Vapour pres: 3•42 mm Hg Air velocity: 0•25-10•0 m/s (50-2000 ft/min) Metabolic rate: 100-500 kcal/hr 115-600 W

<u>Evaluation</u> The effect attributed to metabolic rate was lower than observed in sweat rate measurements. The cooling effect of wind is overestimated. The warming effect of humidity is overestimated, (Givoni).

Despite the great importance of the HSI, permitting isolation of the different factors resulting in a given heat stress, it is doubtful whether it could be regarded as adequate for quantitative evaluation of severity of thermal stress.

Table (2.4 e) The Index of Thermal Stress (ITS) Givoni.

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Total thermal stress on body (metabolic and environmental) Air temp Vapour pres. Air velocity Solar radiation Metabolic rate Clothing	Theoretical calculation of the thermal equilibrium between meta-bolic heat production and heat exchange with environment.	Required sweat rate to achieve thermal balance under given environmental and metabolic conditions.	Metabolic rate Air velocity Air temp or globe temp Normal solar intensity Vapour pres. Clothing type Posture	Air temp: 20-50°C (70-120°F) Vapour pres: 5-40 mm Hg Air velocity: 0·1-3·5 m/s (20-700 ft/min) Met. rate: 115-700 W 100-600 kcal/h SR up to 700 W (600 kcal/h) Clo. 0·1-2·0

Evaluation Givoni suggests that the ITS provides an analytical method to determine the combined effect of metabolic rate, environmental conditions and clothing on physiological strain manifested by sweat rate within the limits stated.
The upper limit of application to predict expected sweat rate is defined by the environmental and metabolic conditions yielding either a sweat rate of 1200 g/h, or an E/E_{max} ratio of 2·2, when the cooling efficiency of sweating falls to about 0·285. The lower limit is set by an air temperature of 20°C.

Table (2.4 f) The Standard Effective Temperature (SET)
Gagge *et al*.

Factors Included	Thermal Effect Determination	Unit	Data Required	Range
Air temp Radiation Relative humidity (or skin wetness) Air velocity Metabolic rate Clothing	The discomfort level (DISC) with reference to skin wetness and SET.	The degree of discomfort (DISC) or skin wetness or SET.	Air temp Mean radiant temp Relative humidity or vapour pressure Air velocity Activity level	Shivering to failure of free skin evaporation Lower to upper limits of clothing, metabolic rate, and environmental variables.

<u>Evaluation</u> SET is the most comprehensive index described in this chapter. It has a single scale with equal intervals, based on the human physiological response to heat stress.

is also dependant on the existing index level when these changes take place.

The expected sweat rate seems to be a suitable basis for the assessment of stress imposed by a given environment, or a combination of work and heat load, for the whole range between the comfort zone and the limit of thermal equilibrium. Thus the indices using sweat rate as a base unit have a direct physiological significance. However, these indices do not give reliable predictions of discomfort due to skin wetness, and care should be taken if they are used to evaluate conditions of high humidity and low air velocity, when skin wetness results in a primary sensory stress. The E/E_{max}[1] ratio, in spite of its significance in relation to the cooling efficiency of sweating and skin wetness, has not proved adequate for predicting either physiological response or thermal sensation.

b) <u>The range of applicability</u>: In comparing ranges of thermal indices, a distinction should be made between the range of conditions covered and the zone in which physiological significance is retained. In assessing the reliability of the thermal indices, inferred from correlation observed between their predictions and experimental results, the following conclusions are made:

1) Effective temperature (ET) and corrected effective temperature (CET), of all the indices reviewed, appear to be the least reliable in predicting the expected physiological and sensory responses in comfort conditions.

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1 E/E_{max} = the cooling efficiency of sweating - the ratio between the required evaporative cooling (E) and the potential evaporative cooling of the environment (E_{max}). This is discussed in further detail in part (4.2.2).

2) The Resultant Temperature (RT) - reliability is satisfactory in predicting responses of people at rest or engaged in sedentary activity.
3) Predicted Four-hour Sweat Rate (P_4SR) - reliability is satisfactory under light to medium heat stress conditions for people at rest or engaged in light to medium work. Under severe heat stress it is still reliable in predicting sweat rate, but this response alone is not so important and under these conditions the index is less satisfactory for predicting strain.
4) The Heat Stress Index (HSI) - this is suitable for analysing the relative contribution of the various factors resulting in thermal stress, but is not suitable for predicting quantitative physiological responses to the stress.
5) The Index of Thermal Stress (ITS) - this is claimed to be suitable for analysing the individual contributions of the metabolic and environmental factors within the range covered. The very hot dry conditions are covered but the cooler part of the comfort zone is ignored, as well as the cool, cold and night times of the hot arid zones. In very hot conditions the index covers neither the effect of diffused radiation (the major radiant heat source in hot, humid climates), nor the high intensities of beam radiation in the hot, arid zones. The cloth coefficients considered in this index cover clothing conditions in common use in hot to moderate climates only, ignoring the clothing type used in cold climates. Therefore, this index cannot be used for comparing different environmental and metabolic conditions, except for those cases falling within its narrow range.
6) Standard Effective Temperature (SET) - this index is suitable for analysing the individual contribution of metabolic and environmental factors, as well as predicting the physiological strain imposed on man

during rest and working conditions. It has a single scale for comparing different conditions, the discomfort scale, with equal intervals depending on the human physiological responses to heat stress. This allows for comparison of a wide range of environmental and metabolic conditions. However, this index was devised to consider radiant heat in internal spaces and not external ones. It is important to extend the index to cover the external radiant heat load, if it is to be used for comparing the external climatic conditions. This has been achieved by means of the computer programme reproduced in Appendix A2.

The SET index has been used to establish the Egyptian climatic regions as discussed in Chapter 3. It also seems possible that this index may be used in the future as a basis for devising a general architectural climatic classification system relating directly to human comfort.

2.5 Design Considerations for Thermal Comfort

The thermo-regulatory mechanism of a healthy person is constantly responding to changes in the environment. An increase in metabolic heat production or a change in the environmental conditions may result in a higher heat production than the dissipating capacity of the enclosing surface. Blood vessels near the skin surface dilate (vasodilation) resulting in an increase in the volume of blood transported to the surface, and skin temperature is elevated so that losses by radiation and convection are increased. When vasodilation is insufficient to restore or maintain the thermal balance, the sweat glands are activated, bringing an evaporative cooling mechanism into action. Sweat can be produced for short periods at a rate of up to 4 litres per hour, but the mechanism is fatiguable.

The evaporation of moisture gives a cooling effect of some 2400 kJ per kilogram of moisture evaporated. Short-term adjustment is achieved in about 30 minutes, while the complete acclimatization process may take up to six months. In hot climates the volume of blood circulating can be increased by up to 20% to maintain constant vasodilation and thus accelerate heat transport to the skin. The sweat secretion rate also increases over a period of several weeks. When the body-environment system fails to restore thermal balance, hyperthermia (inevitable body heating) occurs, with inner body temperature rising to about 40°C and heat stroke may develop.

When the heat dissipation rate exceeds the heat production rate, under cold conditions, the first physiological response is vasoconstriction. Blood vessels near the skin surface contract, heat transport from deep tissues is reduced, the skin temperature is lowered and so both radiant and convective heat dissipation are diminished. Vasoconstriction may also be accompanied by the phenomenon known as 'goose pimples' (the erection of hairs as in most furry animals), an atavistic mechanism. Beyond that, shivering will occur, increasing muscular metabolism. For short periods violent shivering can produce a tenfold increase in metabolic heat production. Acclimatization to cold conditions is achieved in about 21 days. When the body-environment system fails to restore thermal balance, hypothermia occurs, and deep body temperature can fall below 35°C (253).

Since external conditions will be outside the comfort limits for most of the time, it is necessary to know the degree of discomfort in order to find out how uncomfortable conditions can be improved. This will indicate which particular method of modifying the surrounding environment will be the most suitable to achieve comfort level. Body heat loss can be controlled by clothing, posture, choice of location and activity. Man can tolerate a much wider variation of environmental conditions when active than when at rest. However, activity as well as the other factors mentioned above, are individual voluntary control mechanisms. Thus, the adaptation of the surrounding thermal environment by the physical built environment is a necessity. This extends beyond the simple building element encompassing the built environment up to the scale of a city region, which can also modify the thermal environment (172). Therefore, in this research the built environment is considered as part of a total control system extending from the body core to the natural climate.

As mentioned earlier, builders in each climatic zone have been trying to adapt their buildings to the prevailing climatic conditions. In each zone, certain techniques were developed to cope with the specific climatic design requirements. The two hot extreme climatic conditions where environmental modification can be considered as a matter of survival are (A_1) the warm, humid zone and (A_2) the hot-dry and semi-desert climates. The general building design characteristics in each of them are as follows:

A_1 The warm, humid zone has very little if any seasonal climatic variation and the main cause of discomfort is the subjective feeling of skin wetness. The sweat evaporation rate in this zone is very low due to the high relative humidity of the air. Maximum solar radiation of about 2100 $J/cm^2 \cdot day$, and annual mean air temperature of about 27^oC means that it is impossible to ensure thermal equilibrium with the building techniques of the temperate zone.

Continuous ventilation is the most effective method of ensuring a sweat evaporation rate sufficient to maintain thermal equilibrium and minimum sweat accumulation on the skin. At the same time, radiant solar heat gain should be prevented. The town plan, the house layout and its interior design should allow for the maximum cross ventilation by orientation towards the prevailing breeze. Building, in these areas, should be located on high ground if possible. Use of raised building on stilts is favourable, allowing air passage under the floor for cooling, figure (2.31).

The avoidance of totally enclosed courtyards is of special importance. External spaces should allow for shade and provide free passage of air. Heat reflection and glare can be considerably reduced by planting, which provides additional shade. Roofs and walls should be of low thermal capacity, with reflective outside surfaces. Openings should be as large as possible and fully openable walls placed to permit natural air flow through the internal spaces at living level.

A_2 <u>The hot-dry desert or semi-desert zones</u> have intensive solar radiation by day, requiring a building system capable of ensuring the total exclusion of solar radiation and radiant heat. These regions have two main seasons, a warm moderate winter and a very hot, dry summer. Buildings are adapted to summer conditions, which always satisfies the winter requirements. Walls and roofs maintain the interior surface temperature at a level less than skin temperature by day. Breezes can only be used if carefully controlled and if the dust is filtered out.

In Upper Egypt, the villagers, with their own experience on the one hand, and with the help of some native architects on the other, have developed some very efficient methods for taking advantage of the cool breezes prevailing in these climatic conditions figs.(2.1a to c). Fathy (105) made an attempt to

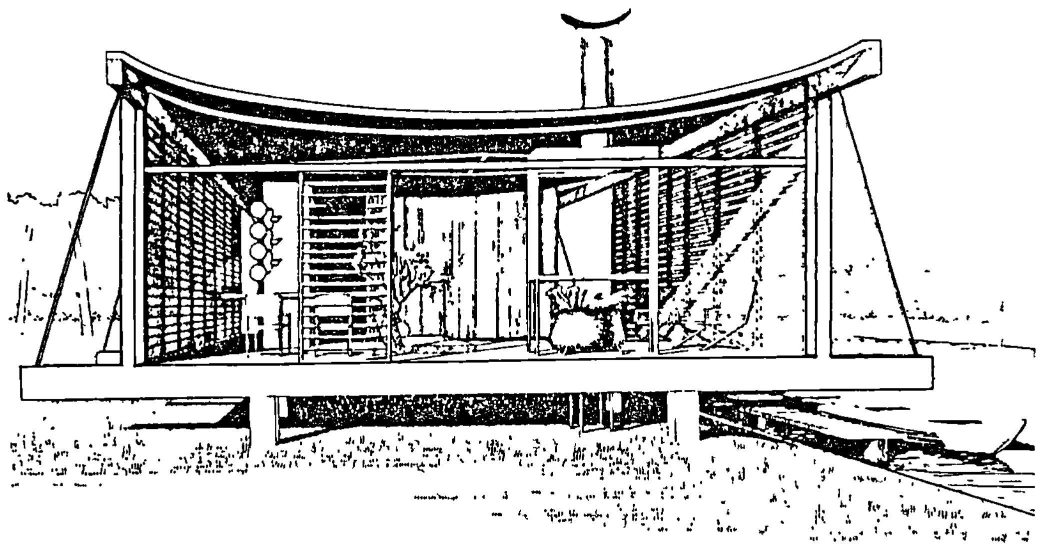

Figure (2.31) Cacoon House, Florida, USA. By Twitchell & Rudolph, (111).

combine these systems in his designs for New Gourna and the oasis of Bariz[1], fig.(2.32a & b) (104).

The urban form should aim for the protection of buildings and external living spaces from solar radiation and hot dusty winds. It should also allow for cool breezes to penetrate, and provide shaded areas for external use. An enclosed compact and inward-looking plan, such as the closed courtyard buildings, with seperate rooms for day and night use, can satisfy human comfort even in the very hot conditions.

Because of the intensity of the solar radiation, on average 2510 $J/cm^2/day$, the west is considered to be the most unfavourable orientation. The use of narrow roads and streets, arcades, colonades and enclosed courtyards are most desirable, providing for maximum shading and coolness. The landscape of external spaces should provide for shading of verandahs and courtyards. The use of trees, loggias, pools and water fountains within the courts and open spaces will cool and, more important, humidify the air. The use of water fountains and shade plants in the interiors is also recommended.

Walls and roofs should be constructed of materials of high thermal capacity, to utilise the large diurnal temperature range which may reach 20^oC. Roofs must be constructed of heavy massive materials with outside applied insulation. Sloping the roof plane towards the courtyard increases the benifit from the inversion cooling during the night. External surfaces of light colours will reflect a large part of the incident

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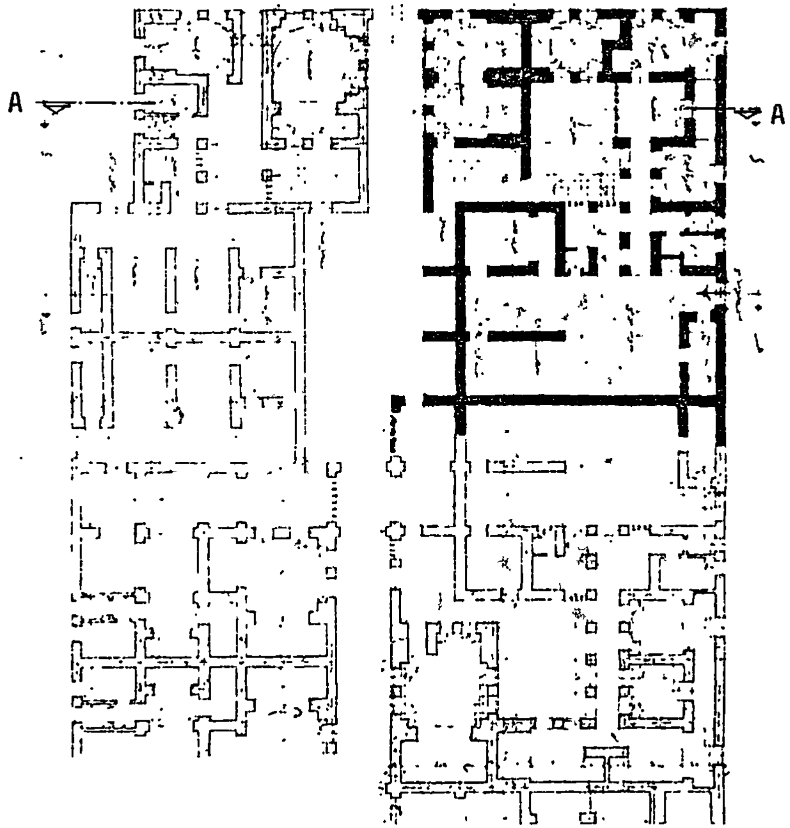
1 'Bariz' is the Arabic pronounciation for Paris - the Ptolomic Paris.



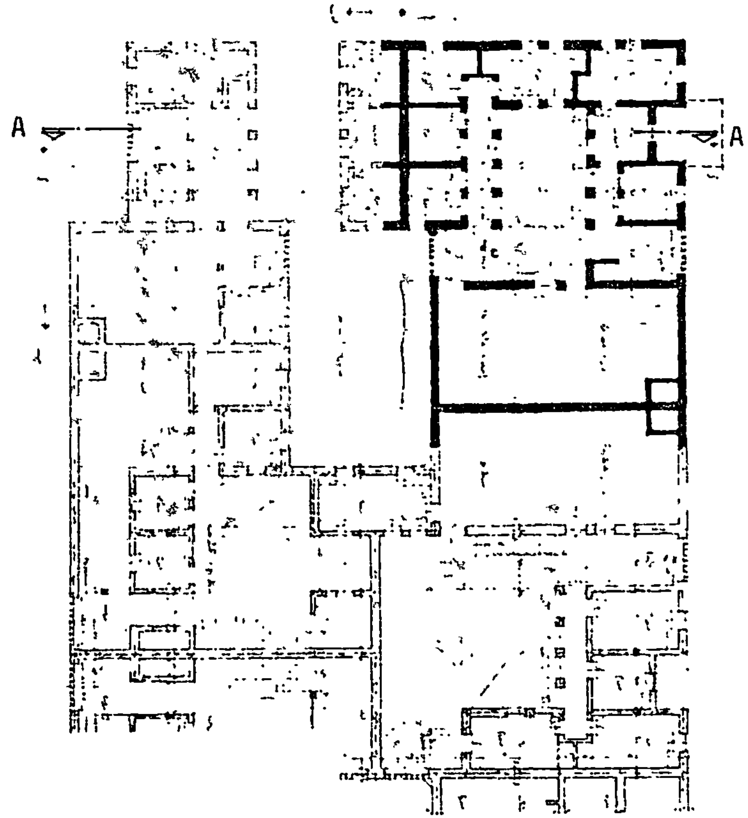


Figure (2.32a) Bariz Centre, Western Desert, Egypt. Architect H Fathy, (104).

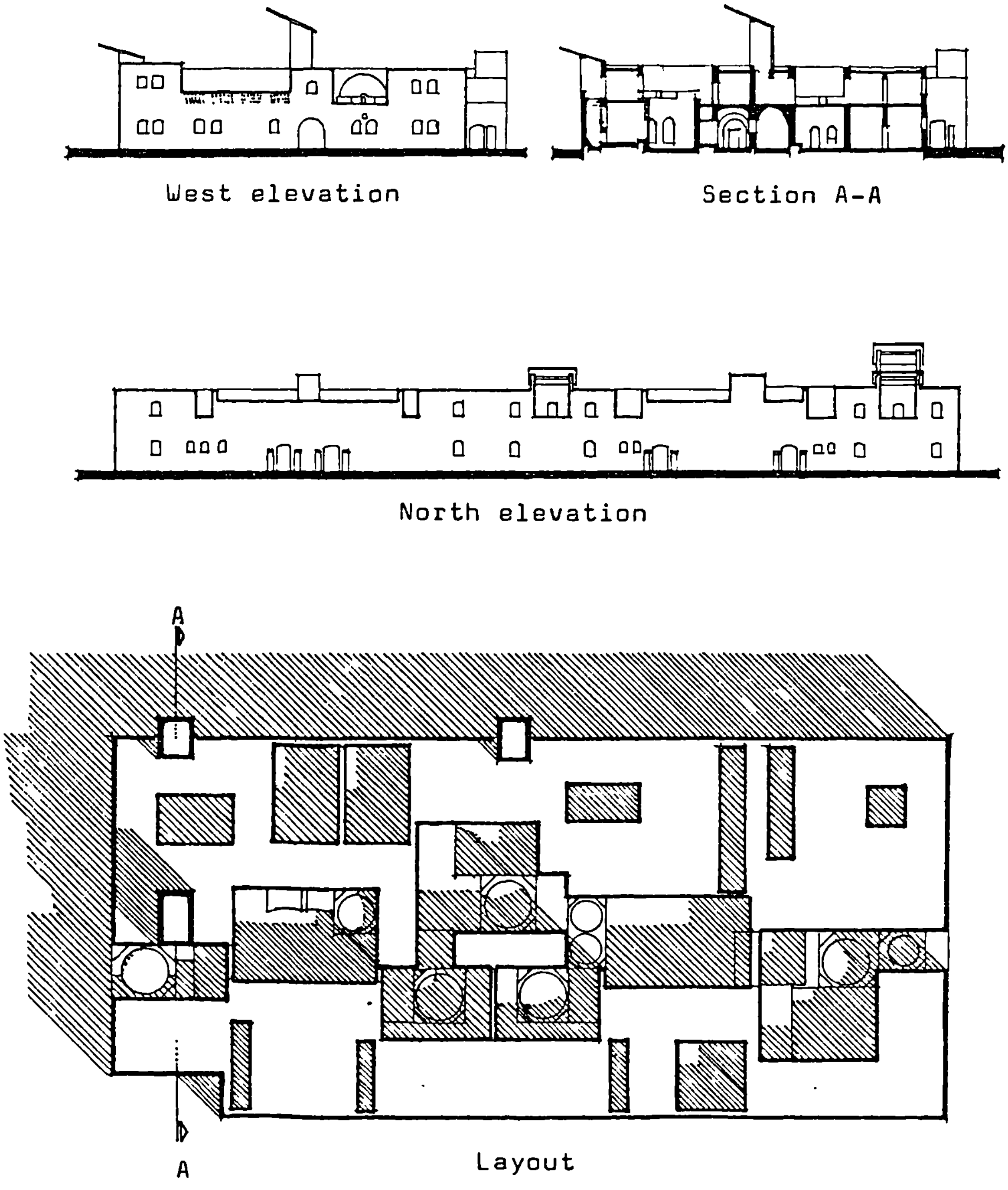


Figure (2.32b) Bariz Centre, by Fathy (104).

solar radiation and reduce the heat gain of fabric. Dark coloured surfaces should be avoided. Openings should be small towards the outside, and large towards the inner courtyard. The building forms should help to minimize the heat gain, the use of vaultd and domes can show a significant reduction of heat gain through the roofs.

In conclusion, it can be stated that the impact of climate on human comfort may be modified through man's efforts in controlling the built environment. Considerations for the the design of building form, planning layout, interior design, choice of materials and colours, are of great importance. A detailed investigation of the climatic effects on building design in Egypt will be undertaken in Chapter 3.

Chapter 3 : CLIMATE AND HUMAN COMFORT : Analysis of the Egyptian Climate

3.1 Climate in Egypt

Egypt occupies the extreme north-eastern corner of Africa, has the continent's only border with Asia, and has coast-lines stretching along the Mediterranean and the Red Sea. The country covers about one million km^2 [1], but a large part is uninhabited, the cultivated territory being approximately 4% of the total area. The population is approximately 42 million[2], and the country has the two largest cities in Africa - the capital Cairo, and the main port Alexandria, which lies on the Mediterranean coast (132). The Nile, the longest river in the world, passes through Egypt, and in many aspects is its making. The Nile valley consists of two main parts, Upper Egypt -'Alwadi' - the most southerly 800 km (500 miles), and Lower Egypt comprising the 'Delta'. The Delta is an almost equilateral triangle of alluvium with a northern base of about 160 km (100 miles) along the Mediterranean shore, and the apex at Cairo. Egypt is situated approximately between longitudes 25^o and 35^oE and latitudes 22^o and 31^oN, figure (3.1).

Geologically, Egypt consists of four different regions; the Nile valley, the Western Desert, the Eastern Desert, and Sinai (26). These regions are flat for the most part except for the Southern Hills near the Sudanese border; a mountainous area in the Eastern Desert; and the Sinai mountains which, at around 2000 m, are considered the

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1 The area of Egypt is approximately 4 times that of the UK
2 It has been stated that the Egyptian population was 37·870 million in 1976, and 38·745 million in 1977 (63).

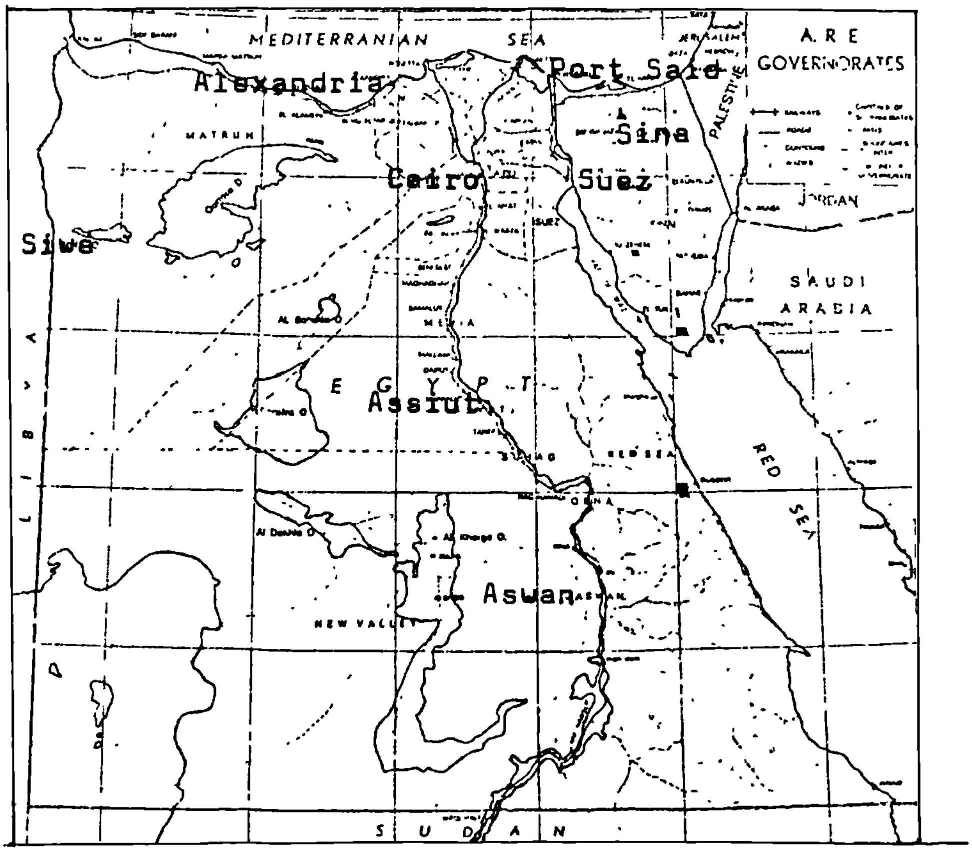

Figure (3.1) The Egyptian regions, governorates and major cities.

highest in Egypt. The lowest area of the country is the Quatara Depression in the Western Desert, which is about 200 metres below sea level.

A recent soil survey of Egypt has been carried out for the World Soil Map project[1]. This showed that a large portion of the country, about 17%, is covered by lithosols, especially in the Eastern Desert, southern Sinai and on the El-Gilf El-Kebir plateau in the south-western part of the Western Desert. This material is usually the basement complex consisting of Pre-Cambrian[2] igneous and metamorphic[3] rocks with some more recent volcanic rocks. Soil profiles are shallow and stony, possessing only a weakly developed A horizon. Rock outcrops are common and slopes nearly always steep.

Limestone soils, which account for 25% of all the soils of the country, predominate in the central and northern parts of the Western Desert. Thin crusts of physical weathering which have been smoothed and poliched by aeolian activity are developed on limestone plateaux. Some fine material occurs beneath the weathered stones, making the surface very level.

Sandstone lithic ermolithosols are developed on the Nubian[4] sandstone and cover some 20% of the country, mainly in the southern part of the Western Desert. These soils produce a very bare and smooth form of desert pavement which has

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1 A soil classification established by FAO/UNESCO as the basis for their 1:5,000,000 soil map of the world. The FAO/UNESCO approach is utilised in most of the recent work in soil mapping (26).
2 Pre-Cambrian igneous includes basalt, granites, delerites, grits, conglomerates, sandstones and rocks made up of small stones.
3 Metamorphic rocks include schists and gneisses.
4 Nubia is the southernmost part of the river Nile in Upper Egypt.

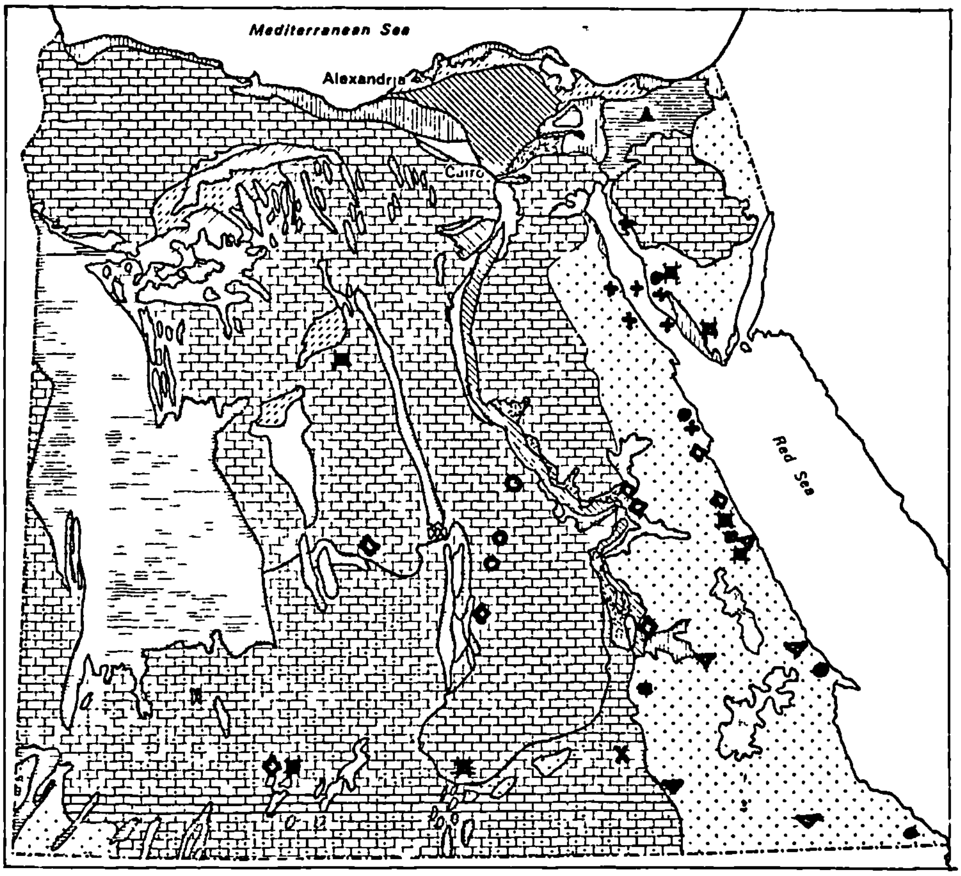
been intensely affected by wind action. Again no profile development is seen.

Shifting sand dunes (dynamic ergosols) cover 15% of the country in a series of scattered zones throughout the main plateau region. The best-known occurrence of these soils is undoubtedly the great sand sea of the Western Desert.

All other soil types cover only very small areas of the country. Beaumont et al (26) stated that most of the cultivated area is restricted to one of these groups, namely fluviosols (alluvium), which occur extensively throughout the Nile valley and Delta region. These soils, which cover only 4% of Egypt, are developed on Nile silt, and as a consequence are heavy textured.

Afiah (5), Dardeer (83), and Moursy (198) indicate the availability of fluviosols, fine sand and phosphates in considerable quantities in the New Valley area, fig.(3.2), which covers a large proportion of the Western Desert. Most of these areas have a thin covering of sand ranging from less than 1 cm to over 10 cm. This region has substantial reserves of phosphates, kaolin, white silica and marble, as well as iron ore. It is interesting to note that the New Valley was cultivated and mined during the Pharoanic, Roman and Islamic periods in Egypt. Another region of the same importance to the country is Sinai where there are mining areas for iron ore, coal and magnesium. The Gulf of Suez is especially valuable because of its oil-fields which help support Egyptian industry. Gold is mined in the Red Sea area and the Eastern Desert, also magnesium phosphate and iron ore, fig.(3.2). Throughout Egypt's history the building materials used have been more or less in accordance with the geological pattern.

Nowadays traditional building materials may differ from one region to another, however the alluvial mud of the



- lithosols
- limestone
- sandstone
- gravelly ermolithosols
- argillic ermolithosols
- fluviosols alluvium
- solonchaks
- dynamic ergosols
- other types

- ▲ coal
- ■ iron ore
- ◊ phosphate
- ▼ gold
- ✚ oil
- X kaolin
- O marble
- ● magnesium

Figure (3.2) Mineral resources and soil map of Egypt (26).

Nile valley is, even today, the most commonly used material in the rural areas. It is usually used in the form of sun-baked brick, finished with mud plaster. Mud walls of 0•5 m average thickness have a high heat capacity. The time lag for such a wall is about 8 hours, rendering the interior cool for most of the day, while allowing radiant heat to warm it through the night; during the hot season some of the rural Egyptians find it necessary to sleep on the roofs. Limestone was frequently used, not only in rural areas but also in Cairo's old houses. This was due mainly to its availability from the Mukkattam Hills and other neighbouring quarries. Stone was usually used for the ground floor construction, where wall thickness could vary greatly and in most cases exceeded 0•5 m. Limestone has a higher thermal capacity than mud brick, a wall of 0•5 m thickness and 1920 kg/m^3 specific gravity has a time lag of 15 hours, and is therefore advantageous in keeping the interior of the building cool for most of the day. In some areas of the country other building materials may be found. In the northern part of Upper Egypt sandstone is more common, while in the south near Aswan granite is available, and is used for decoration and surface finishes. West of Asyut there are sufficient deposits of limestone, sand and clay for cement manufacturing. In the Western Desert limestone, sandstone, sand, gravel and clay are found, and these can be used for brick making[1].

The climate of a given region may be assumed to have remained constant throughout its human history. The revolution of the globe gives the rhythmic occurrence of day and night, regulating both human activity and natural life. The tilted rotation of the Earth around the sun sets the

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1 The Egyptian Survey and Mining Authority Centre in Al-Kharga Oasis supplies information as well as technical advice in the fields of land reclaimation, water supply and construction (5).

rhythm of the seasons, while the regularity of the sun's radiation sets the patterns of temperature, humidity, pressure and wind movement that sweep over the Earth. The main climatic elements affecting human comfort can be summarised as follows:

a) Solar radiation, which is usually measured as the intensity of incident energy on a horizontal plane in Joules per square metre of surface per second (J/m^2s = N/m^2 $=W/m^2$). The quantity and quality of solar radiation depends on the presence or absence of cloud.

b) Air temperature, which is mainly the expression of the thermal characteristecs of the solar radiation, and measured in the continental system (international) in degrees Centigrade. Generally, air temperature needs to be lower than skin temperature to help keep an individual cool in hot climates.

c) Air movement (wind) in open terrain it is usually measured by its speed and direction 10 m above ground level.

d) Humidity, which may be measured as:
   1. Absolute humidity (AH), the absolute amount of water present in unit mass or unit volume of air, g/kg or g/m^3 respectively.
   2. Relative humidity (RH), which indicates the evaporation potential.

      RH = (AH/amount of moisture air can hold) x 100

e) Precipitation, for all forms of water deposited from the atmosphere - rain, snow, hail, dew and frost - expressed in mm/h, mm/day, mm/month, or mm/year.

f) Topography and vegetation, characteristics of the site that will influence building design.

In fact, the thermal and visual aspects of climate are among the most important elements to be considered in building design and town planning, where modifications of environmental conditions are needed. Neglecting these factors could adversely affect the comfort level of the inhabitants, and may even cause physiological damage.

3.1.1 Determinants of the Egyptian Climate

To understand the Egyptian climate, it is important to be aware of its causes. Soliman (132) summarises the determinants in the following four factors:

a) The semi-permanent pressure air mass systems in each season, namely the cold Siberian anti-cyclone in winter, the hot low pressure zones of Africa in spring and autumn, and the huge low pressure area over south-west Asia in summer.
b) The travelling depressions and associated weather in winter and transitional seasons.
c) The Mediterranean, and to a lesser extent the Red Sea, as sources of water vapour, in addition to their being positive or negative thermal sources, as they act as warm surfaces to cold Polar air masses and cool surfaces to tropical masses. The Mediterranean has a pronounced influence on the northern area (Lower Egypt) but the effect diminishes towards the south (Upper Egypt).
d) Topography plays a small role in the general climate but has some local effects.

The Egyptian climate can be divided into four seasons: winter from December to February; spring from March to May; summer from June to September; autumn from October to November. In winter time the climate of Lower Egypt is mild (17^{o} to 20^{o}C daily mean) with some rain showers (mean monthly 45 mm) mainly over coastal areas. Upper Egypt is particularly rainless with warm sunny days but rather cool nights (mean max. daily 21^{o}C, mean min. daily 7^{o}C). The coldest spells experienced in Egypt are on the arrival of the Siberian anticyclone Polar continental (Pc) air masses, occurring about the second week of January when temperatures can fall as low as 2·4^{o}C. The conditions that favour the invasion of this Pc air occur when a deep depression with a steep pressure gradient covers the Mediterranean, reaching Egypt as a cold north-westerly wind. When the Balkans are covered in snow for a long period conditions may become favourable for snow to fall. This situation arises perhaps once in ten years (132), figure (3.3).

The source of hot Tropical continental air mass (Tc) is the thermal low above the land mass of Africa, but it lies too far south to be drawn northwards by the Mediterranean depressions, and therefore rarely affects Egypt in winter. On the other hand, the Mediterrenean becomes the theatre for the consecutive passage of depressions, some of which are single-centred and others complex. They are the main causes of the weather in this season. In front of these depressions south-southwesterly winds blow across Egypt with clear skies, except for patches of high cloud. Low relative humidity is experienced with the approach of the depressions towards the eastern Mediterranean. The winds are modified Polar air, originally from a north-northwesterly direction, turned round the centre of the low to blow as southwesterlies over Egypt. This fact makes for a differentiation between the structure of these depressions and those of the middle latitudes, where the southwesterlies are warm. When the depression reaches the eastern Mediterranean cold, moist northwesterly winds blow over Egypt, and convection clouds appear during the daytime. When an upper cold low pressure or steep trough exists above the depression, more clouds result over Lower Egypt and rain may occur. This rain is sometimes heavy and may be accompanied by thunder. On average the depressions remain for two or three days over the eastern Mediterranean during which time Egypt can experience its worst winter weather.

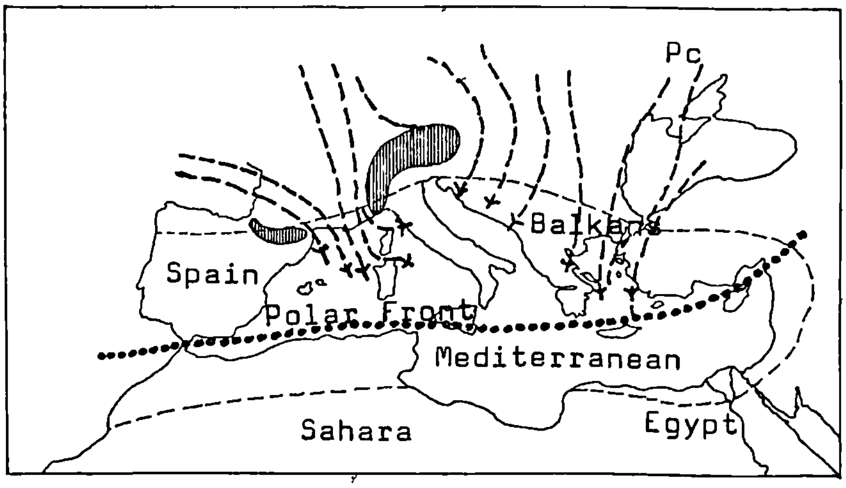
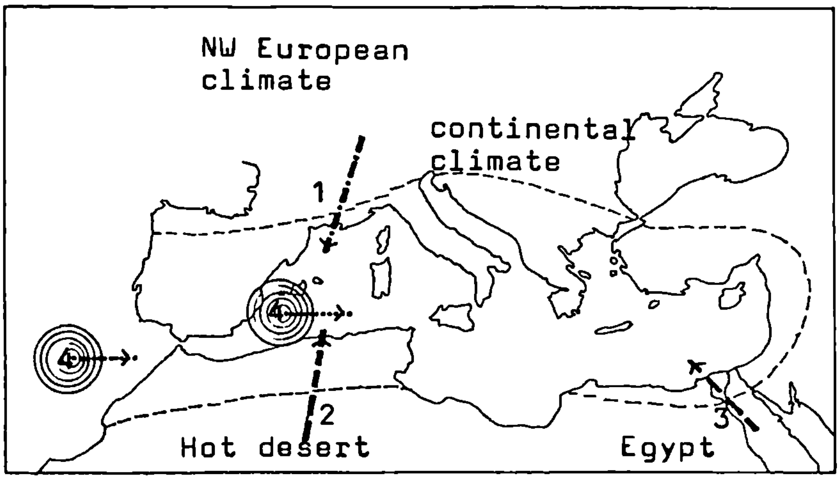


Figure (3.3) Mediterranean Polar front and routes of cold northerly air.



1 - Mistral
2 - Sirocco
3 - Khamaseen
4 - Depressions

Figure (3.4) Local winds in the Mediterranean Basin (due to the Mediterranean depression), in winter and transitional seasons.

The warm Mediterranean water plays an important part in supplying enormous amounts of water vapour to the Polar air masses moving south towards Egypt. When the depressions are deep, the southwest winds may reach gale force and cause severe sandstorms. The north-northwesterly winds in the rear of these depressions may also reach gale force especially at the coast, but the dust raised is much less than with southwesterly winds. Mediterranean depressions mainly affect Lower Egypt, while Upper Egypt remains unaffected. However, the cold northwesterly winds in the rear of depressions over the eastern Mediterranean continue their journey southwards to Upper Egypt, causing both a reduction in temperature and the raising of sand, but they are not associated with any precipitation. Between the passage of consecutive depressions, high pressure zones cover the eastern Mediterranean and cause the flow of northeasterly winds over Lower Egypt. This condition favours the formation of fog in the early morning, dispersing a few hours after sunrise. In the extreme southern parts of Upper Egypt the dryness of the air does not favour such fog formation.

In the spring months, March to May, the main feature is the southward shift in the tracks of the depressions. The centres of the depressions move either along the coastline of Africa, or further south where they are known as desert or Khamaseen depressions. The frequency of Khamaseen depressions varies from two to six per month. Khamaseen conditions occurring in front of the depressions can be summarised as warm, dry, dust-laden, southerly winds. The depressions are smaller in area than those of winter, and may be associated with more high and medium clouds, but much less rain, and with severe sandstorms. The sand is raised by the strong southerly winds ahead of the depressions. When these depressions become cold upper lows (cut off from troughs further north) they are often associated with large amounts of high and medium cloud, also thunder storms which can give very heavy showers of rain and hail. Some of the rain showers are characterised by very large drops which are actually melted hail, originating from the mid-tropospheric instability clouds, figure (3.4).

The Red Sea, except in its immediate area, does not play a role in the formation of thunderstorms over Egypt, as it is enclosed by a high chain of mountains. These mountains cause the lifting of air masses as well as being a high level heat source. Hot, southeasterly currents from Arabia turn northeastwards over Egypt, and moderate to severe heatwaves are then experienced. The air is hot and dry except for the surface layer where it picks up moisture from the Mediterranean, a feature that sometimes leads to the formation of early morning fog over Lower Egypt. In spring therefore, the sub-tropical discontinuity (STD) is located appreciably north of its winter position, and comes within the field of interaction of the Khamaseen depressions. After the formation of a depression, the STD moves northwards so that very hot (Tc_h) air forms the warm sector of the depressions. Severe heat waves are then experienced in regions affected by these hot winds. All record maximum temperatures are caused by this Tc_h air, which is also the causative agent of record low relative humidities. When the depression is west of Egypt, the eastern Mediterranean is covered by high pressure, thereby causing frequent northeasterly winds over Lower Egypt. The spring conditions may extend a week to ten days into June, but afterwards, practically till the end of September, summer conditions prevail.

The summer climate is generally hot and dry, clear skies prevailing except for cumulus or early morning stratus clouds which form over Lower Egypt and disperse a few hours after sunrise. In this season depressions cease to move across Egypt and the weather becomes settled. The steady north or northwest winds blow persistently for they are part of the circulation around the huge Asiatic low centred over northwest India. The climate of Lower and Middle Egypt, being affected by the cool Mediterranean waters, is warm during the daytime and cool at night. The maximum effect is in coastal areas where the weather is pleasant. As the STD moves further north in summer, extreme Upper Egypt lying to the south of it experiences a hot and very dry climate. Heat waves in this season are mostly caused by the westward oscillation of the STD, however, very high temperatures may also be experienced when the Tc_h of western Syria and Iraq moves over the country. While moving over the Mediterranean this air picks up moisture and becomes most oppressive. Although the temperature may not be so high, the increased humidity makes the heat seem worse than that of spring. Northeasterly winds in the summer again favour the formation of early morning fog or very low stratus in Lower Egypt.

The autumn climate is similar to that of spring, for it is another transitional season. Khamaseen-like depressions begin to move across Egypt during late October, and cause a breakdown of the settled summer regime. Early depressions in September are infrequent and usually die out on arriving over Egypt from the west. Autumn depressions tend to be stormier than those of spring, and are slower in their eastward movement. The higher humidity in this season favours a greater frequency of thunderstorms and heavier precipitation, especially in November. Northeast winds and early morning fog are frequent, as in spring, while heatwaves are less common and less severe (132).

The broad climate of the country as a whole leads to marked differences in the climate of the Egyptian regions. For the purposes of this chapter the author will consider Egypt under six regions with assumed definite boundaries. However this is not in fact the case; it is important to note these boundaries are merely transitional, not defined.

3.2 The Climatic Regions of Egypt

The six climatic regions of Egypt are categorised as follows:

i) Lower Egypt, comprising the Mediterranean coast and the Nile Delta.
ii) Greater Cairo.
iii) The Red Sea coastal region (excluding Sinai).
iv) Upper Egypt, comprising the last 800 kilmetres of the Nile valley.
v) The Desert region, comprising both the Western and Eastern Deserts.
vi) Sinai, which is the only high land in Egypt.

The regional characteristics of the country will be defined with respect to values of air temperature, relative humidity, sunshine and wind, fig.(3.5). Because of the very low precipitation rate, and its similarity in the different regions, precipitation will be considered of little significance to human comfort.

3.2.1 Activity Patterns and Elements of the Egyptian Climate

The presentation of any climatic information depends on the problem being considered. The problem must first be identified and described, and for this research it is the way in which climate and other external factors affect the process of architectural design for human comfort. When the problem is thus identified, then the relevant climatic data may be extracted from the available climatic information covering the region or locale under consideration.

In Chapter 2 the way in which climate influences the design process, and to what extent it affects human comfort, has

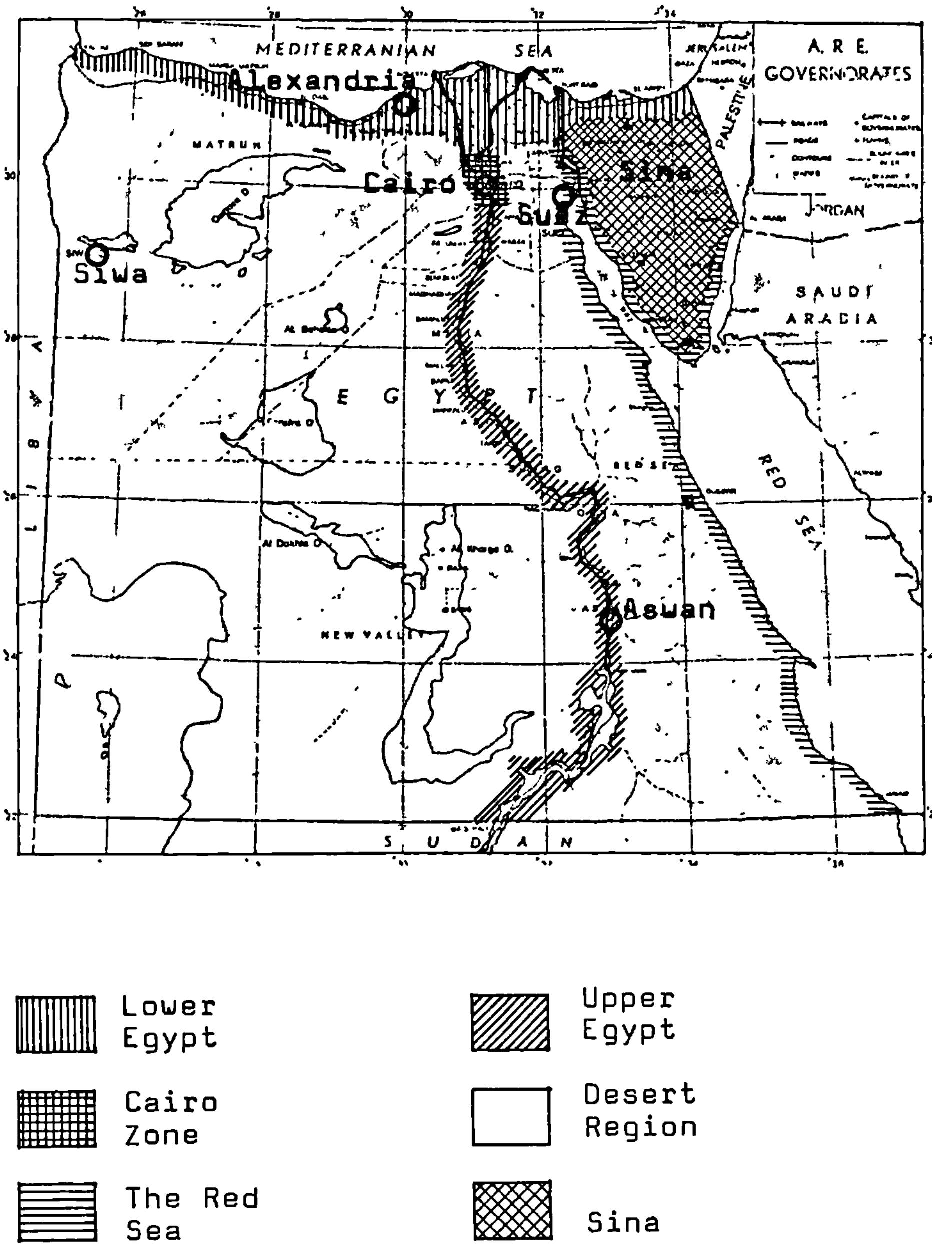


Figure (3.5) The proposed six climatic regions of Egypt.

been discussed. The thermal indices available to architectural design were examined, and the Standard Effective Temperature (SET) index (178,112, 113, 180) of Gagge et al was presented as the most suitable for evaluating the climatic effects on human comfort for the internal and external environments. The SET takes into consideration air temperature, radiation, relative humidity, air velocity as well as activity levels and clothing. The intention in this section is to use this index to find the modifications needed in the climatic conditions to satisfy human comfort in each of the Egyptian regions. This requires a knowledge of the relevant climatological data pertaining to these regions, and to analyse the climatic elements within the different regions in order to obtain the lower and upper limits for each. These limits are to be taken as a basis for the design process, bearing in mind the pattern of life and the comfort zone suitable in each of them.

Activity in any region corresponds to a great extent to the climate. In Egypt the sun is the main regulatory element for human activity; its rise means the beginning of a new day, and by sunset the day's work has usually come to an end. This is particularly true in rural Egypt, however, in the large towns and cities activities usually extend for several hours after sunset. Other factors which can modify the activity pattern, such as business hours and working patterns, must also be considered. In Egyptian cities the working day is divided into two parts, the first starts between 06.00 and 08.00, and ends around 14.00. The second lasts from 16.00 till 19.00, and between these two periods people have their lunch, the main meal of the day, and most take a siesta. It is important to point out here that siesta time corresponds to the period when discomfort due to heat is highest. After a day's work the city people usually spend the evening enjoying their leisure and social activities. Most of these stop by midnight, to start again in the early morning. fig.(3.6).

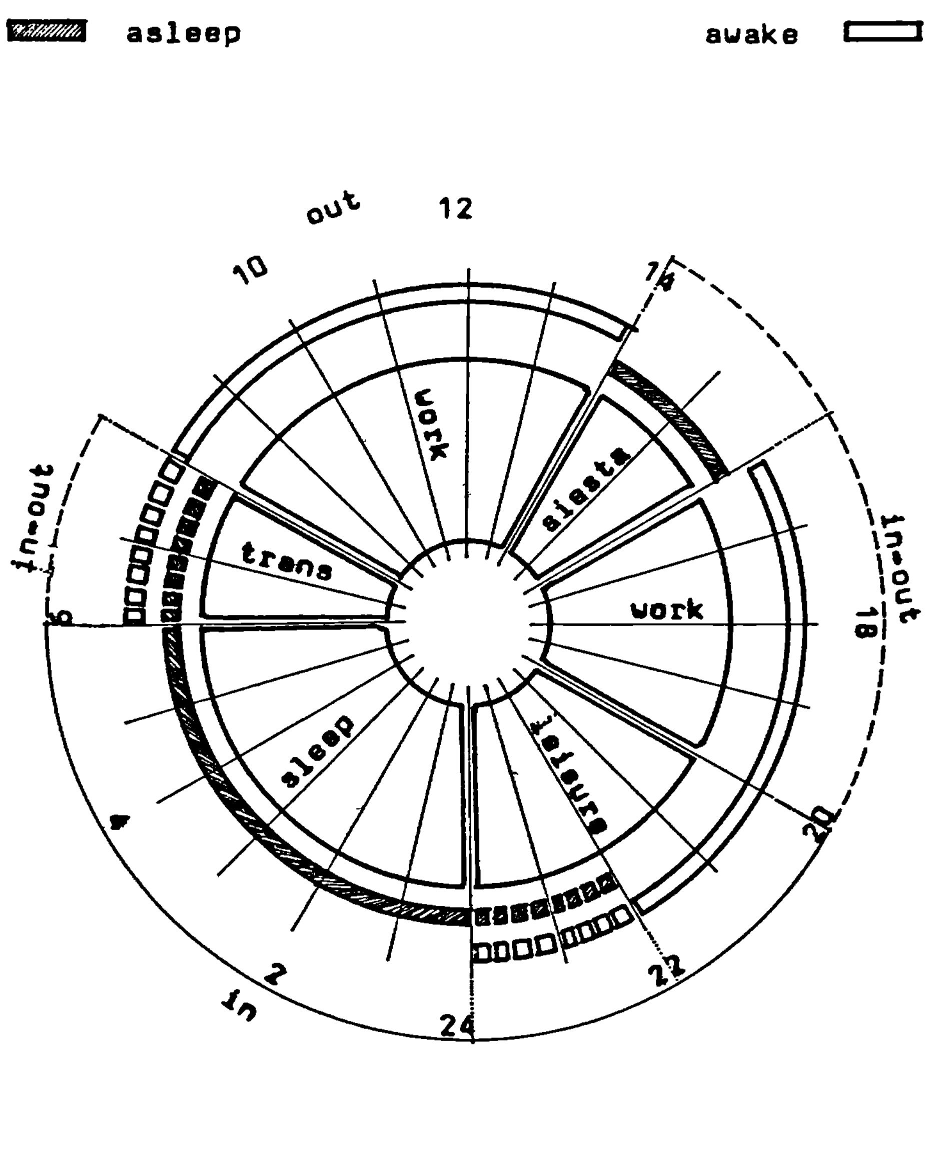


Figure (3.6) The activity pattern diagram for the Egyptian urban life in relation to time spent in or out of the home.

Individual human feelings of comfort differ, and optimum comfort conditions are dependent on the balance of heat exchange between the body and its surrounding environment, the type of clothing, and the activity level. In this section comfort in the internal environment will be taken as that environment in which conditions satisfy comfort requirements of at least 80% of the occupants wearing customary Egyptian indoor clothing[1], and engaged in light muscular activity.

The SET chart, fig.(3.7), is for occupants wearing customary indoor clothing at 0·6 clo and engaged in light muscular activity at 1·0 MET, in still air, velocity 0·10 m/s, and at an elevation not in excess of 300 m (1000 ft) above sea level. The optimum comfort conditions for 80% of the occupants are expressed in the DISC scale of the SET, and are taken at ±0·5 DISC, while the desirable comfort conditions accepted by 70% of the occupants will be taken at ±1·0 DISC. The upper and lower limits of the optimum and desirable comfort zones for Egyptian people inside buildings, shown in table (3.1), have been calculated from the SET charts (see Appendix 3) for use in the following section.

3.2.2 Air Temperature in the Egyptian Regions

Air temperature in the shallow layer in which humans function is the most important single climatic element for the purpose of building design. The changes of air temperature with height are not of great significance except for tall buildings. In the following paragraphs, and for usual cases of 4 to 5 storey housing design, temperature

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1 The customary Egyptian type of clothing worn in the home is the light-coloured cotton gallabiya or pyjama. This may be assumed equivalent to light summer clothes having clo value 0·6 in summer and 0·9 in winter.

is measured at 1·6 m for maximum and minimum, and at 1·4 m for monthly mean unless otherwise noted (254). It is further assumed, for the purpose of this section, that the comfort zone for the Egyptian inhabitants will be at 50% relative humidity with air temperatures between 21·5°C and 27°C. As air temperature varies with time, hourly variations must be considered as they would affect the building design significantly, however, variations over short intervals of a few minutes may be ignored.

Table (3.1) The comfort levels within buildings for people wearing customary Egyptian indoor clothes, engaged in light activity.

Comfort Zones	Relative Humidity	Minimum Ambient Temp °C	Maximum Ambient Temp °C
The desirable comfort zone (70% of occupants)	30%	19	32
	50%	19	30
	70%	19	29
The optimum comfort zone (80% of occupants)	30%	21·5	28
	50%	21·5	27
	70%	22	26

For building design purposes the monthly mean maximum and minimum air temperatures should be obtained, then the mean monthly range can be found. This will help to determine the seasonal climatic conditions. The highest of the 12 maxima will determine the hottest month, while the lowest will be considered as the coldest from the ambient temperature point of view. Finding the difference between the lowest monthly mean minimum and the highest monthly mean maximum establishes the annual mean temperature range. Table (3.2) gives the monthly mean maxima amd minima, and the highest and lowest temperatures for 5 of the 6 Egyptian

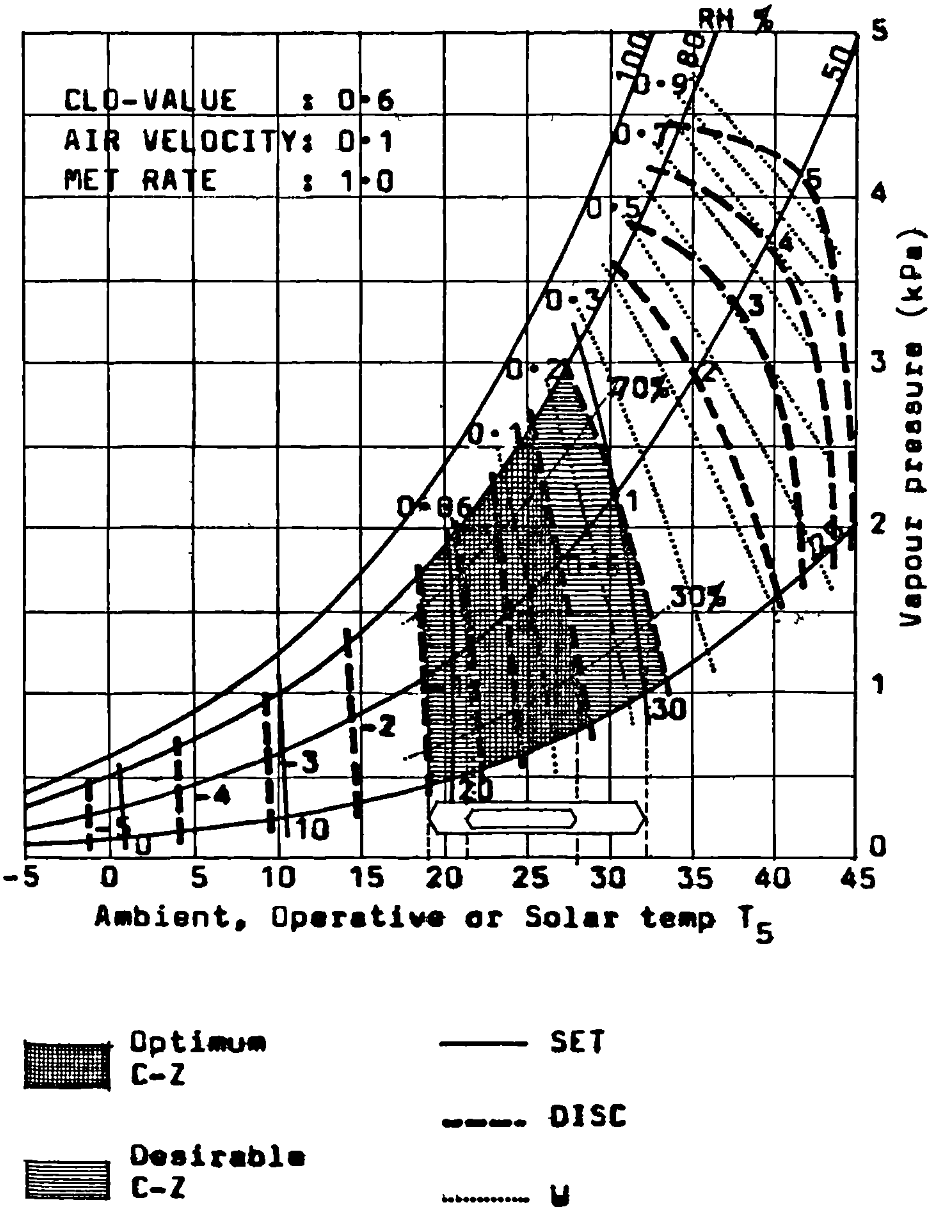


Figure (3.7) The Standard Effective Temperature (SET) as an outdoor thermal index (178) where:

T_S = the sum of the dry bulb temperature and the solar radiation contribution to ambient air temperature computed as in Appendix A2.

Table (3.2) Air temperature data for the Egyptian Regions in °C.
Data from "Climatological Normals for UAR" [1] after Taha (254)

Region		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
LOWER EGYPT (1)	monthly mean max	18·5	19·0	21·0	23·5	26·5	28·0	29·5	30·5	29·5	27·5	24·5	20·5	30·5
	monthly mean min	9·5	9·5	11·0	13·5	16·5	20·0	22·5	23·0	21·5	18·0	15·0	11·0	9·5
	monthly mean range	9·0	9·5	10·0	10·0	10·0	8·0	7·0	7·5	8·0	9·5	9·5	9·5	21*
CAIRO (2)	monthly mean max	19·0	20·5	23·5	28·0	32·5	34·5	35·5	35·0	32·5	30·0	25·0	20·5	35·5
	monthly mean min	8·5	9·0	11·5	14·0	17·5	20·0	21·5	21·5	20·0	18·0	14·0	10·5	8·5
	monthly mean range	10·5	11·5	12·0	14·0	15·0	14·5	14·0	13·5	12·5	12·0	11·0	10·0	27*
RED SEA (3)	monthly mean max	20·5	21·5	24·5	28·0	32·5	35·0	36·5	36·5	33·5	31·0	26·5	22·0	36·5
	monthly mean min	8·5	9·5	11·5	14·5	18·0	20·5	22·5	22·5	20·5	18·5	14·5	10·5	8·5
	monthly mean range	12·0	12·0	13·0	13·5	14·5	14·5	14·0	14·0	13·0	12·5	12·0	11·5	28*
UPPER EGYPT (4)	monthly mean max	24·0	26·5	30·5	35·5	40·5	42·0	42·0	42·0	40·0	37·5	31·5	26·5	42
	monthly mean min	9·5	10·5	14·0	18·5	23·5	25·0	26·0	26·5	24·0	21·5	16·5	13·0	9·5
	monthly mean range	14·5	16·0	16·5	17·0	17·0	17·0	16·0	15·5	16·0	16·0	15·0	13·5	32·5*
THE DESERT (5)	monthly mean max	19·5	22·0	28·0	30·0	34·5	37·0	38·0	38·0	35·0	32·5	26·5	24·5	38
	monthly mean min	4·0	5·5	8·0	12·0	17·0	19·0	20·5	20·5	18·5	15·0	10·0	6·0	4·0
	monthly mean range	15·5	16·5	20·0	18·0	17·5	18·0	17·5	17·5	16·5	17·5	16·5	18·5	34*
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

1 UAR is the formal name of the Arab Republic of Egypt.
* The yearly range in °C.

regions. Due to the fact that the data available for the 'Sina' region is incomplete, this region will be dropped from the climatological analysis.

Ambient air temperature, for the purpose of this section, is plotted against time. The monthly mean maxima and minima for the 5 main regional cities in Egypt are shown in fig.(3.8), as well as the monthly mean for the whole year, and the optimum comfort temperature for each region. Considering this optimum comfort air temperature, one can detect those periods where maximum air temperature is above the optimum comfort upper level, indicating that the inhabitants will experience thermal stresses in summer. The periods when mean maximum air temperature is below the lower limit of the comfort zone will be taken as winter time. Thus, the lengths of the seasons will differ from one region to another, fig.(3.9).

In Lower Egypt (Region 1 - Alexandria) summer conditions prevail from June till mid October, while autumn ends by the beginning of December. Winter conditions start at the beginning of December and end by the second week of March. In the Cairo (2) and the Red Sea (3 - Suez) regions summer starts around the beginning of April and finishes by the end of October. Autumn in Cairo lasts for only one month and winter conditions start by the beginning of December, ending by late February or early March. Spring in the Cairo zone is, like autumn, very short, only lasting till the beginning of April by which time the Khamaseen wind starts blowing from the southwest bringing high air temperatures. Autumn in the Red Sea region is about two weeks longer than in Cairo. It starts at the end of October and ends by the second week of December when winter conditions start. Winter finishes by the second week of February, while spring ends by the beginning of April. In Upper Egypt (4 - Aswan) the year is composed of two seasons - a long hot summer prevailing from the third week of

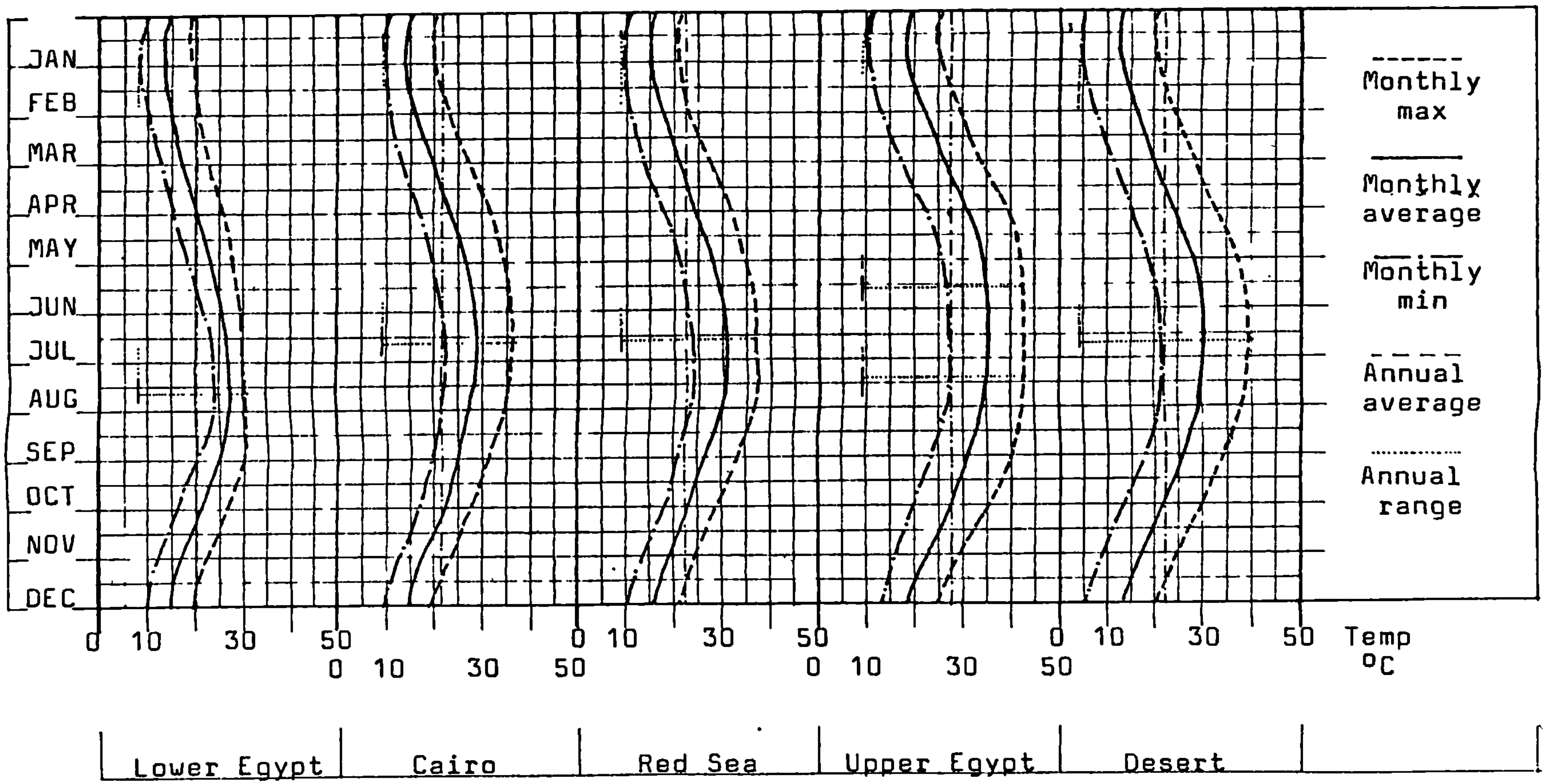


Figure (3.8) , Air temperature for the Egyptian regions

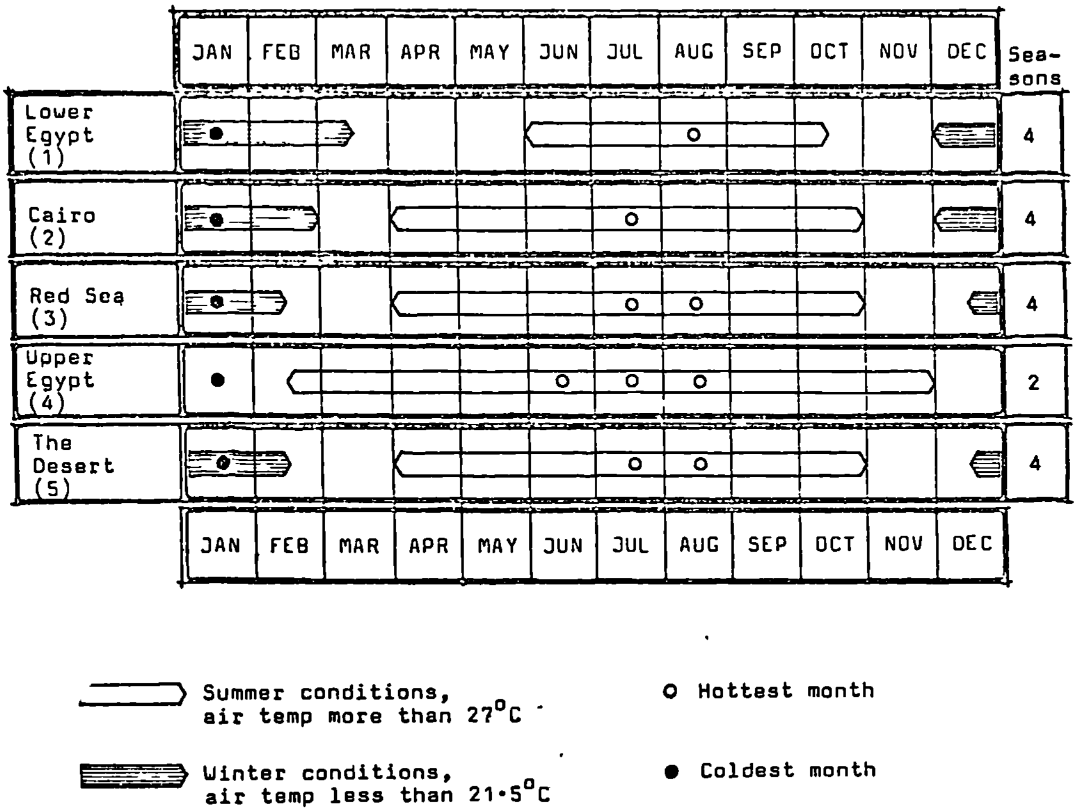


Figure (3.9) The seasonal chart for the Egyptian regions due to the air temperature and dependant on the optimum comfort conditions with 21•5°C as the lower limit and 27°C as the upper limit.

February till the end of November, and a short spring. In the Desert region (5 - Siwa), the seasons are similar to those of the Red Sea region.

On inspection of the air temperature figures for the different regions as shown in fig.(3.9), it can be seen that the highest monthly mean maximum differs from one region to another. This variation is not only in magnitude, but also in the time of its occurrence, illustrating the influence of relative humidity and wind on air temperature.

3.2.3 Humidity in the Egyptian Regions

The humidity of the air does not directly affect the heat load operating on the body, but it determines the evaporative capacity of air and hence the cooling efficiency of sweating. In extremely hot conditions the humidity level determines the limits of endurance time by restricting the total evaporation. The boundaries of these thermal regions determining the effect of humidity depend on the overall requirements for evaporative cooling, on air velocity, and also on the clothing type. At air temperatures in the range 20 - 25°C (68 - 77°F) the humidity level does not affect physiological and sensory responses, and variations in relative humidity between 30% and 85% are barely perceptible. This can be seen from the SET charts, fig.(3.7), where wetness and DISC curves approximate to perpendicular lines on the temperature axis. Only when the air is almost saturated are sensations of clamminess and dampness noticeable. At temperatures above 25°C the effects of humidity become gradually more apparent, especially the effects on skin wetness, skin temperature, and at even higher temperatures, sweat rate.

The humidity of the air can be expressed in various ways, in terms of relative humidity, specific humidity, or vapour pressure. In this section humidity will be expressed in terms of relative humidity (RH). In order to give an indication of the prevailing humidity conditions it is sufficient, for the purpose of this section, to consider the monthly mean maximum and minimum RH values. The maxima are usually measured just before sunrise and are fairly high in any climate. The minima are usually measured at noon giving far lower values than for the rest of the day. RH values for the hours when air temperature is at its highest are almost the same as the monthly mean average. Thus it is sufficient to consider the monthly mean average as an indication of the humidity conditions, yet the hourly changes do have a special importance in determining the upper and lower design values.

The mean monthly maximum, minimum and average for the five city regions in Egypt are given in table (3.3). By plotting monthly mean average against time as in fig.(3.10) it is possible to compare the relative humidity in all five regions, and relate it to temperature values given in fig. (3.8). The highest relative humidities seem to occur in winter, particularly during December, in all the regions, whereas the second highest values might differ. In Lower Egypt the second highest is in summer during June, July and August, at the same time as the highest temperature. In the vicinity of the Mediterranean this encourages evaporation and raises the RH. In Cairo the second highest occur around the end of summer in August and September.

In Lower Egypt RH ranges between 67% and 74% with an annual average of 70%, while in Cairo it ranges between 44% and 64% with an annual average of 55%. It falls below 50% only in the period from March till June. In the Red Sea region RH fluctuates between 45% and 61% with an annual average of around 53%. However, from the third week of March till the first week of July it is below 50%. In Upper Egypt RH is very low, ranging between 18% and 41% with an annual average of 27%. For the whole period from

Table (3.3) Relative humidity data for the Egyptian regions.
Data from Taha (254).

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
LOWER EGYPT (1)	monthly mean max	79	78	77	80	82	82	82	82	79	80	82	81	82
	monthly mean min	54	51	50	50	53	58	61	61	57	53	54	55	50
	monthly mean average	71	70	67	68	70	72	73	73	69	68	72	74	70
CAIRO (2)	monthly mean max	70	68	69	66	64	70	76	79	80	78	76	71	80
	monthly mean min	43	38	32	27	24	25	31	34	35	35	41	45	24
	monthly mean average	59	58	52	48	44	48	52	56	58	58	61	64	55
RED SEA (3)	monthly mean max	70	68	64	61	58	62	67	70	70	71	73	72	73
	monthly mean min	46	42	36	31	30	30	32	33	37	39	45	48	30
	monthly mean average	59	56	51	47	45	47	50	52	55	56	60	61	53
UPPER EGYPT (4)	monthly mean max	52	45	36	30	26	28	29	32	37	41	49	53	53
	monthly mean min	27	21	16	14	13	14	16	18	19	21	27	30	13
	monthly mean average	38	31	24	20	18	19	21	23	26	29	36	41	27
THE DESERT (5)	monthly mean max	73	69	64	60	55	58	66	68	68	66	69	73	73
	monthly mean min	47	42	37	34	32	31	34	34	38	40	45	49	31
	monthly mean average	60	55	49	45	42	43	46	48	51	52	57	61	51
		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

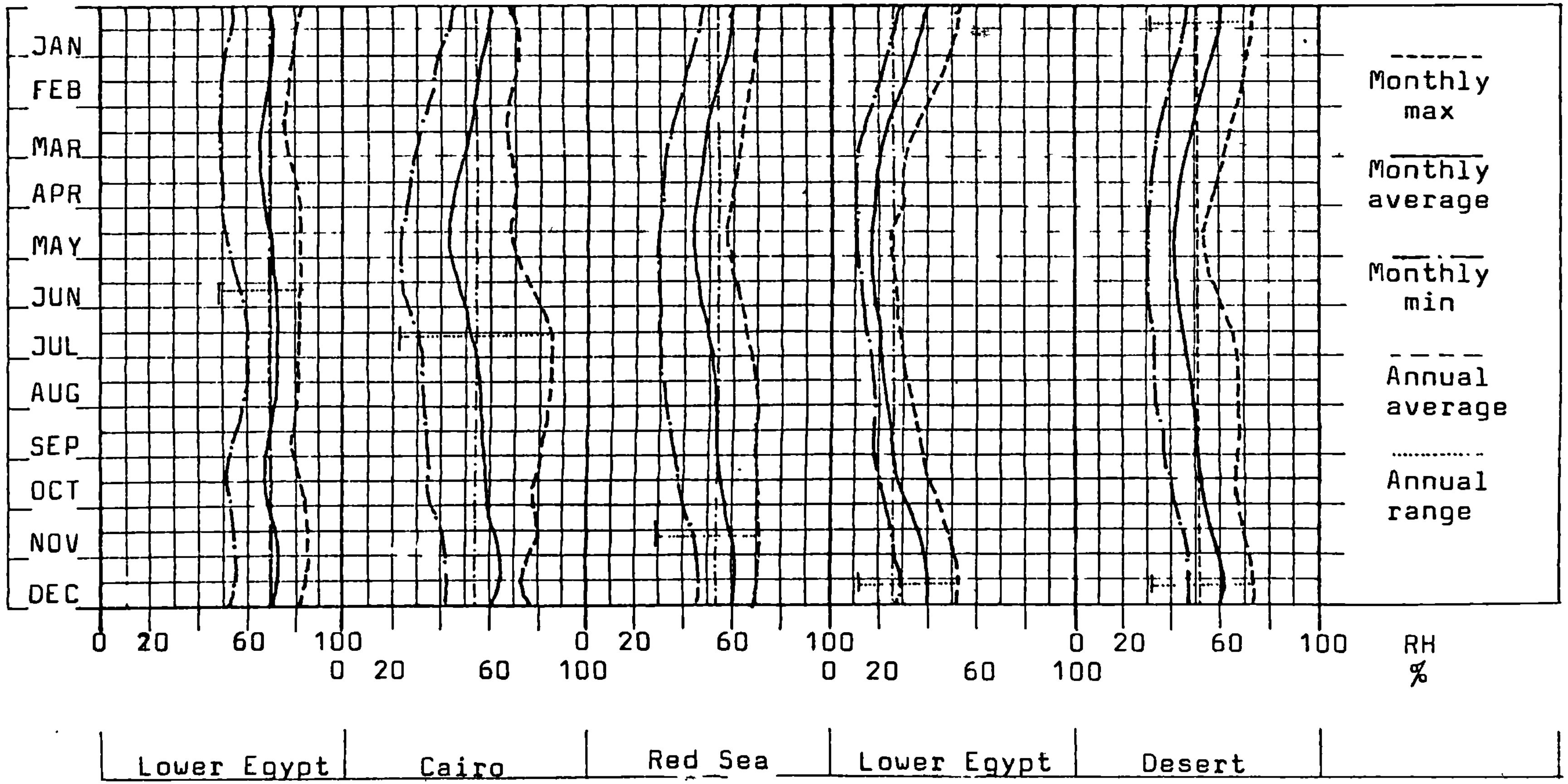


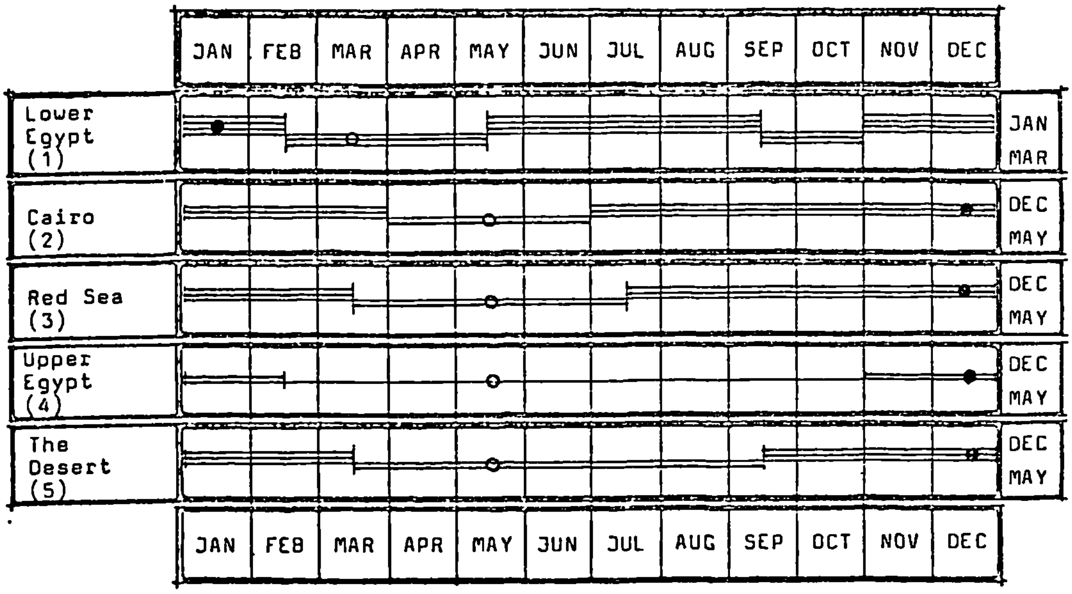
Figure (3.10) Relative humidity for the Egyptian regions, February till October it is below 30%. Siwa is the biggest town in the Desert region, yet its average annual is as high as 51% with the highest value of 61% in December and the lowest, 42%, in May. In this region the period from March till August has RH lower than 50%.

Considering the humidity grouping established by Mahoney (259) the Egyptian regions may be classified due to RH as in fig.(3.11). The effect of air movement is very significant, as an increase in air velocity counterbalances the effect of humidity. Thus the lower limit of physiological and sensory response to humidity elevation is raised as air velocity increases.

3.2.4 Wind Patterns Over the Egyptian Regions

Wind movement near the ground affects the human body in two different ways. Firstly it determines the convective heat exchange of the body, and secondly it affects the evaporative capacity of the air and consequently the cooling efficiency of sweating. The effect of the ambient air velocity on the convective heat exchange is customarily assumed to be proportional to the square root of the velocity (ie $V^{0\cdot5}$). The exact relationship however may depend on the type of clothing, and it has been suggested that a power of 0·33 would be more applicable (122, 272, 200).

The effect of air velocity on the evaporative capacity is interrelated with the effect of humidity, and an increase in air velocity raises evaporative capacity and may thus offset the effect of high humidity. This will occur even in the case of saturated air associated with a temperature lower than skin temperature. In this case the air film around the skin increases in temperature, and its evaporative capacity is raised allowing sweat evaporation to occur by moving the air film. When the air temperature is below that of the skin, the two effects of air velocity combined - convective and evaporative - result in a cooling



o Lowest month ● Highest month

HUMIDITY GROUP	RH VALUES %	SYMBOL
1	below 30	——— (single line)
2	30 - 50	double line
3	50 - 70	triple line
4	above 70	quadruple line

The Humidity Groups (after C Mahoney).

Figure (3.11) The humidity groups in the five Egyptian regions.

sensation. Thus an increase in air velocity will always produce a cooling effect, which increases as the air temperature decreases. When the air temperature is above that of the skin, the two effects of air movement work in different directions. On the one hand an increase in air velocity causes a higher convective heat gain, while on the other, this increase raises the evaporative capacity and consequently the cooling efficiency. When the skin is wet and the cooling efficiency of sweating is below 100%, an increase in air velocity has a greater effect on sweat evaporation efficiency than on the convective heat gain. The net result is a cooling effect which is reflected by a reduction in the sweat rate. At the same time, the higher air velocity reduces the subjective discomfort due to wet skin, but this effect only continues until the skin is dry, a further increase does not affect the cooling efficiency of sweating although the convective heating continues. Therefore, at high air temperatures there is an optimum value of air velocity at which the air motion produces the greatest cooling effect. Reduction of air velocity below this level causes discomfort and heat stress, due to reduced efficiency of sweat evaporation. Increasing air velocity beyond this optimum level will cause heating by convection. Optimum velocity is not constant, but is dependent on air temperature, humidity, metabolic rate and clothing.

Wind velocity can be measured by a cup-type or propeller anemometer, or by a Pitot tube, while wind direction can be measured with a wind vane. An anemograph can produce continuous recordings of wind velocity and directional changes. In Egypt wind measurements are made using the cup-type anemometer. In flat, open countryside free wind velocities are normally recorded at a height of 10 m above the ground. In urban areas measurements are taken at a height of between 10 and 20 m to avoid obstructions. velocities near the ground are a good deal lower than the free wind speed. Wind velocity is measured in metres per second (m/s) while the Beaufort wind-force scale, table (3.5), will be used to describe wind categories. For wind calculations several factors have to be considered. First, the decrease in measured wind speeds close to ground level; second, the modification of the operative wind pattern by topography and the immediate surroundings; and third, the physiological effect of the wind, rated as desirable or undesirable breezes. The wind effects of the free atmosphere are modified and slowed down in the lower levels, and at the ground surface the air is almost at rest. Wind velocities in the Earth's boundary layer take different profiles depending on the type of terrain and the strength of the wind. In Egypt winds rarely exceed 6 m/s, and for this velocity range, the power law (18) is sufficient to describe the velocity profile.

The effects of wind movement on housing have to be considered in both the external and internal environments. For comfort conditions, air movements have to be evaluated as both positive and negative. They should be blocked as much as possible during underheated periods, but admitted and utilized at overheated times. In Egypt, wind speed and direction characteristics can differ from one place to another. Speed and direction of wind, both prevailing and secondary (if any), for the five Egyptian regional cities are shown in table (3.4). The monthly mean average, plotted against time, fig.(3.12), shows the highest wind speed period in each region. In Lower Egypt (Alexandria) the annual average is about 4 m/s with the highest velocity recorded in March. This is described according to the Beaufort scale as slight wind. The second highest occurs during July, while the lowest of 3·1 m/s (slight breeze) is recorded in October. The annual average in Cairo zone is 3·2 m/s with the maximum of 4 m/s (slight wind) in April. The lowest record of 2·5 m/s falls in the category of slight breeze. In the Red Sea area the highest average is 3 m/s and the lowest record is 1·8 m/s. Both of these

Table (3.4) Wind data for the Egyptian regions.
Data from Taha (254) and Soliman (132).

Region		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
LOWER EGYPT (1)	monthly mean average	4·4	4·4	4·7	4·3	4·1	4·2	4·4	4·0	3·5	3·1	3·4	3·9	4·7
	prev. wind	NW	NW	NW	NW	NW	NW	NW	NW	NW	N	N	SW	NW
	sec. wind	SW	W		N		N	N	N	N	W	W	NW	N
CAIRO (2)	monthly mean average	3·4	3·6	3·8	4·0	3·9	3·5	2·5	2·6	2·9	2·9	3·1	3·0	4·0
	prev. wind	NE	NW	SW	NW	N	NW	SW	SW	NW	NW	NW	NW	NW
	sec. wind	E	SW	NW	SW	NW	SW	W	W	W	SW	N	E	SW
RED SEA (3)	monthly mean average	1·8	2·1	2·3	2·5	2·5	2·7	2·7	3·0	2·9	2·6	2·0	1·8	3·0
	prev. wind	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW
	sec. wind	S	S	S	S	S	N	N	N	N			S	N
UPPER EGYPT (4)	monthly mean average	1·8	2·2	2·6	2·6	3·0	2·4	1·9	2·2	2·0	2·2	1·5	1·9	3·0
	prev. wind	N	N	N	N	N	N	N	N	N	N	N	N	N
	sec. wind													
THE DESERT (5)	monthly mean average	2·0	2·0	2·5	2·4	2·3	2·1	2·0	1·8	1·5	1·3	1·3	1·5	2·5
	prev. wind	W	W	W	NW	NE	N	NW	NW	NW	NW	W	W	W
	sec. wind					NW	NE		N					N

JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC

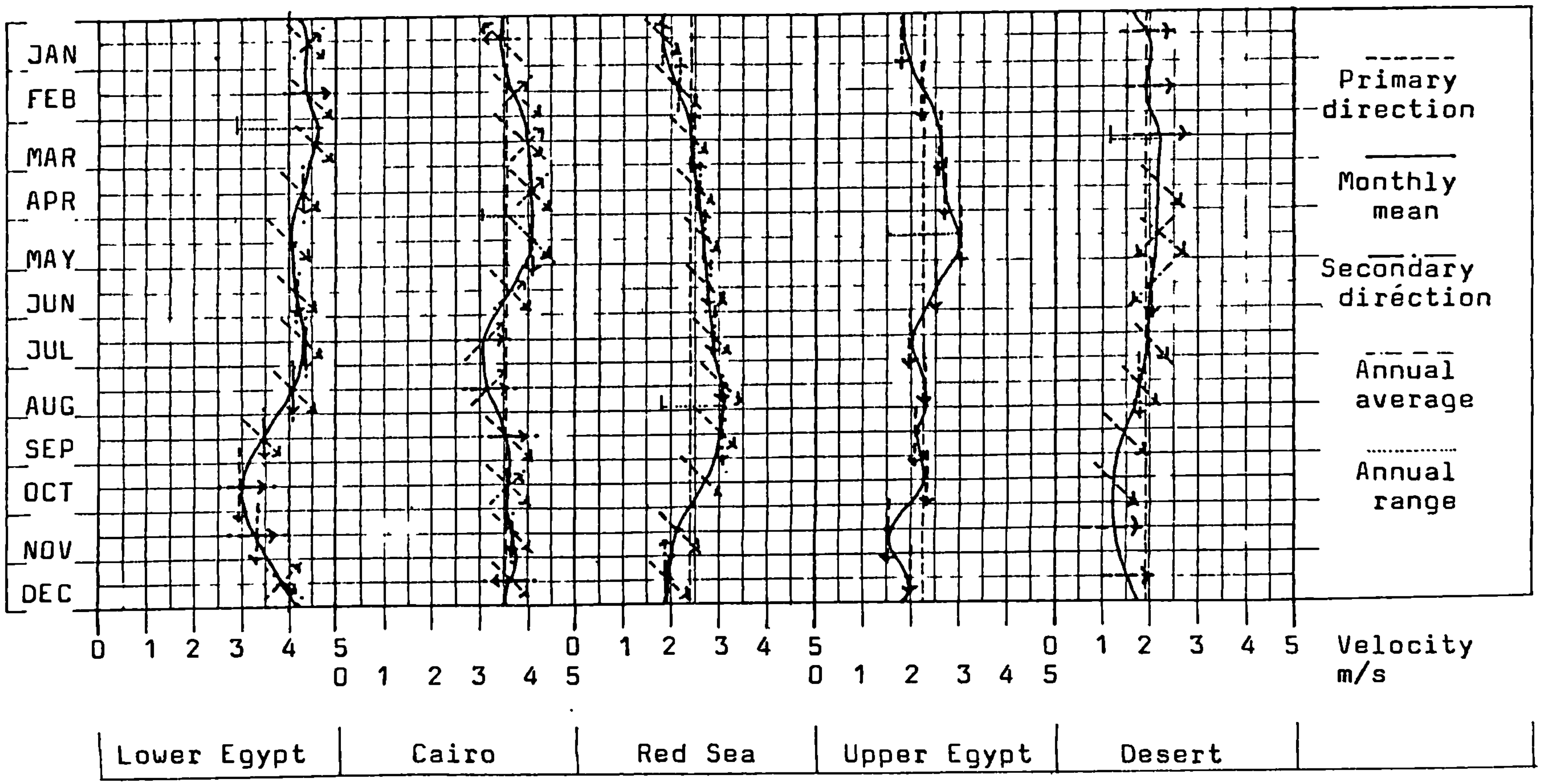


Figure (3.12) Wind velocity and direction for the Egyptian regions

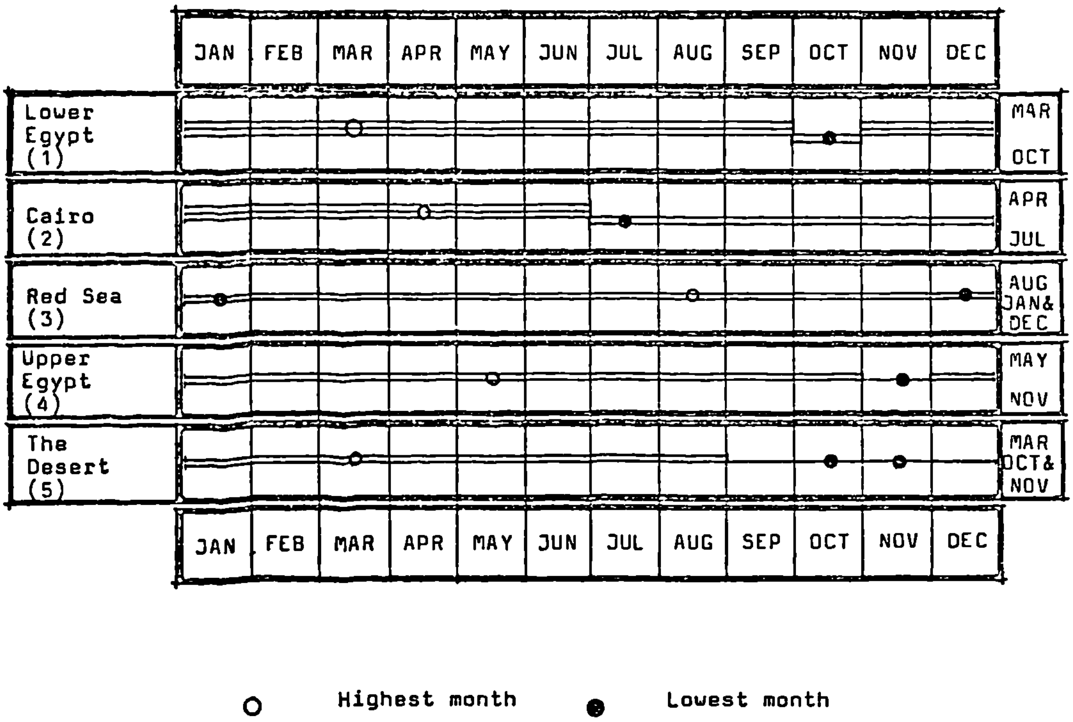


Figure (3.13) The wind force in the five Egyptian regions.

Force	Observable effects	Speed m/s	Symbol
0	Complete calm, smoke rises straight vertically, lake surface smooth.	up to 0·5	
1	Slight movement, smoke slightly inclined.	0·5 - 1·7	
2	Slight breeze, leaves rustling.	1·7 - 3·3	
3	Slight wind, twigs moved, small ripples on water.	3·3 - 5·2	
4	Moderate wind, small branches moved.	5·2 - 7·4	

Table (3.5) A summary of the Beaufort wind force scale.

records fall within the slight breeze category . Within Upper Egypt the wind blows from the north throughout the year as a slight breeze with a maximum monthly average of 2·6 m/s. During October and November the average is as low as 1·3 m/s, which may be considered as a slight movement. In the Desert region the highest monthly mean average is 2·5 m/s in March, while the lowest is 1·3 m/s. Fig.(3.13) gives a summary of wind forces in the five Egyptian regions. When the wind diagram, and the air temperature and humidity diagrams are superimposed, the desirable breezes can be distinguished from the undesirable ones, table (3.10).

In Alexandria, in Lower Egypt, cold discomfort due to low air temperature is experienced from the beginning of December until the second week of March. During this time the monthly mean average wind velocity is at its highest, and as this cold slight wind is not desirable, natural ventilation should be kept to a minimum. For the period starting in June and ending by the second week of October wind is desirable and natural ventilation should be kept at maximum. In the Cairo zone summer conditions with overheated periods start from April and end at the beginning of November. Wind speed is relatively high until July, when it suddenly falls to a light breeze. This, with good design can help modify the living conditions to within the comfort zone. In winter, when there is an underheated period from December to February natural ventilation should be kept to a minimum. In the Red Sea region the summer is as long as in Cairo, with the maximum monthly mean average for wind in August. This calls for making the most use of wind movement to bring the temperature effect within the comfort limits. In the region of Upper Egypt summer conditions start by the third week of February and end by the last week of November, and natural ventilation is of great importance particularly when the sum of radiant and ambient air temperatures exceeds the skin temperature. This excess occurs from the third week of April till the end of October, and the air should be cooled before allowing it indoors. This may be achieved by means of evaporation since the relative humidity during this period is below 30%. In the Desert region (Siwa) ventilation is very desirable during summer conditions when there is no dust, however if dusty winds prevail filtration should take place before allowing the air indoors.

3.2.5 Solar Radiation and Sunshine in Egypt

The sun affects man's life on Earth with its cantinuous radiation. This radiation affects the human body in two ways - thermally and biologically. The ultra-violet portion of the spectrum has a biological effect, while the thermal effects are due to the visible and infra-red rays. The thermal effects of solar radiation depend on the body posture with respect to the sun, clothing, reflectivity of the surrounding terrain, and air velocity. Around the 30° latitude the intemsity of direct radiation falling on a man wearing a hat and sitting with his back to the sun is greater than that falling on him if he were in a standing or walkimg position. This is explained by the high altitude angle of the sun during most of the daytime hours in summer. Table (3.6) illustrates the increase in weight loss[1] due to exposure to solar radiation according to wind conditions.

Clothing intercepts the sun's rays at some distance from the skin and part of the heat is dissipated into the environment. The proportion of dissipated heat depends on the material and the colour of clothing, as well as the air velocity. Wind speed reduces the heat gain due to solar

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1 In this context weight loss is due to perspiration, respiration, and other metabolic processes.

radiation, and the magnitude of this effect depends on the clothing porosity. Their interaction can be explained by the effect of wind speed on the surface coefficient of the body-clothing system, which determines the fraction of the absorbed radiation dissipated into the ambient air. Even for a nude body, a higher wind velocity increases the fraction of absorbed radiation lost to the external environment. For a clothed body this effect is further increased. The interaction between the effects of solar radiation, clothing and wind velocity is shown in table (3.7) which gives the average increase in weight loss due to solar radiation, in relation to clothing and wind conditions.

Table (3.6) The effect of posture on increase in weight loss due to solar radiation, in relation to activity. After Givoni (122).

Wind speed (m/s)	Weight loss (g/h) Sitting	Walking
1•0	341	259
2•5	306	220

As solar radiation raises the temperature of building fabric, the radiation effect of the inside surface of the fabric can be used, to some extent, to balance the lower internal temperature. This means that we can be comfortable at low air temperatures if the heat loss of the body can be balanced by the gain from solar radiation.

In Egypt, radiation measurements began only recently, and there are only two stations taking this kind of measurement, one in Giza, just south of Cairo, ten years in operation, the other in Tahrir, west of the Nile Delta, in existence for three years. Table (3.8) gives the mean maximum and minimum daily global radiation at these two stations. Unfortunately, the stations are only about 100 km apart, and are in the same climatic region so the differences between the mean values is small.

Table (3.7) Increase in weight-loss due to solar radiation in relation to clothing and wind speed. After Givoni (122).

Wind Speed (m/s)	Weight Loss (g/h) Semi-nude	Light Summer Clothing
1•0	300	191
2•5	263	122
Difference:	37	69

The daily total radiation incident on a horizontal plane can be estimated on the basis of sunshine duration (124) by equation (3-1) given below:

$$Q/Q_s = 0{\cdot}29 \cos\theta + 0{\cdot}52\, n/N \qquad (3\text{-}1)$$

Where Q = radiation on horizontal plane, MJ/m^2 day

Q_s = same, at upper limit of atmosphere; the solar constant per day, which can be taken as a constant = 36 MJ/m^2 day.

n = actual hours of sunshine per day

N = possible hours of sunshine per day

0•29 = empirical constant depending on transmission proportion of air mass.

θ = geographical latitude

The term n/N is the ratio between the actual hours and the possible hours of sunshine per day. This can be established by using the percentage of the total actual to the total possible (Np). Hence, equation (3-1) can be rewritten as follows:

Table (3.8) Global radiation for Giza and Tahrir (Ly/day). After Soliman _et al_ (132)

Region		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Giza	mean	290	375	498	576	635	667	663	610	533	420	319	266
	max daily	417	510	662	722	754	743	751	714	632	543	410	365
	min daily	46	85	172	185	109	410	564	457	183	156	123	48
Tahrir	mean	293	401	489	568	659	684	682	627	538	413	325	282
	max daily	404	513	628	715	742	755	747	692	602	497	405	380
	min daily	52	136	261	196	366	378	606	541	337	231	99	96

The length of record is 10 years at Giza and 3 years at Tahrir.

$$Q/Q_s = 0{\cdot}29 \cos\theta + 0{\cdot}52\ Np \qquad (3\text{-}2)$$

Solar radiation in the different Egyptian regions has been computed on the basis of the regression equation (3-2) of Angstrom type, and quantitative analysis is made at the end of this section. However, as sunshine records are much more common in Egypt than radiation records, the author has used the sunshine records in comparing quality of solar radiation within the different climatic regions. Table (3.9a) gives the percentage of total actual to total possible daily sunshine, while fig.(3.14) shows the sunshine hours in each region plotted against time.

In Lower Egypt, the annual average of the total actual to total possible hours of sunshine is 78%, with the highest record of 88•5% occurring during August. This makes August one of the hottest months in this region. At the same time the coastal areas of this region enjoy the pleasant sea-land breezes which modify the effect of this radiation and reduce the air temperature in the afternoons. The lowest record in this region is in December , which with consideration to air temperature, is the beginning of winter. The second lowest sunshine record is in February with the second strongest wind and the lowest air temperature. All these factors combined make February a very cold month in Lower Egypt.

In the Cairo zone June has the highest record of sunshine hours, with July, August and September over 80%, while the least sunshine in this region occurs in December. In the Red Sea region the sky is clearer than in either Lower Egypt or Cairo. Thus, during June, July, August and September the total actual to total possible sunshine hours is over 90% while January is the only month with sunshine lower than 60%. In Upper Egypt the sky is very clear all the year round and the lowest total actual to total possible sunshine hours is 84% recorded during November,

Table (3.9a) The hours of bright sunshine in the Egyptian regions.
(Percentage total actual to total possible hours).
Data after Taha, (254).

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
Lower Egypt (1)	72•0	68•5	72•5	75•0	81•0	86•0	87•0	88•5	84•5	81•5	75•5	62•5	88•5
Cairo (2)	65•0	64•0	62•0	74•0	73•0	89•0	88•0	86•0	85•0	78•0	68•0	59•0	89•0
Red Sea (3)	59•0	73•0	75•0	80•0	81•0	95•0	95•0	94•0	93•0	84•0	76•0	70•0	95•0
Upper Egypt (4)	84•0	86•0	85•0	88•0	86•0	96•0	95•0	94•0	95•0	91•0	84•0	84•0	96•0
The Desert (5)	81•0	80•0	84•0	88•0	84•0	98•0	98•0	98•0	98•0	91•0	83•0	78•0	98•0
	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

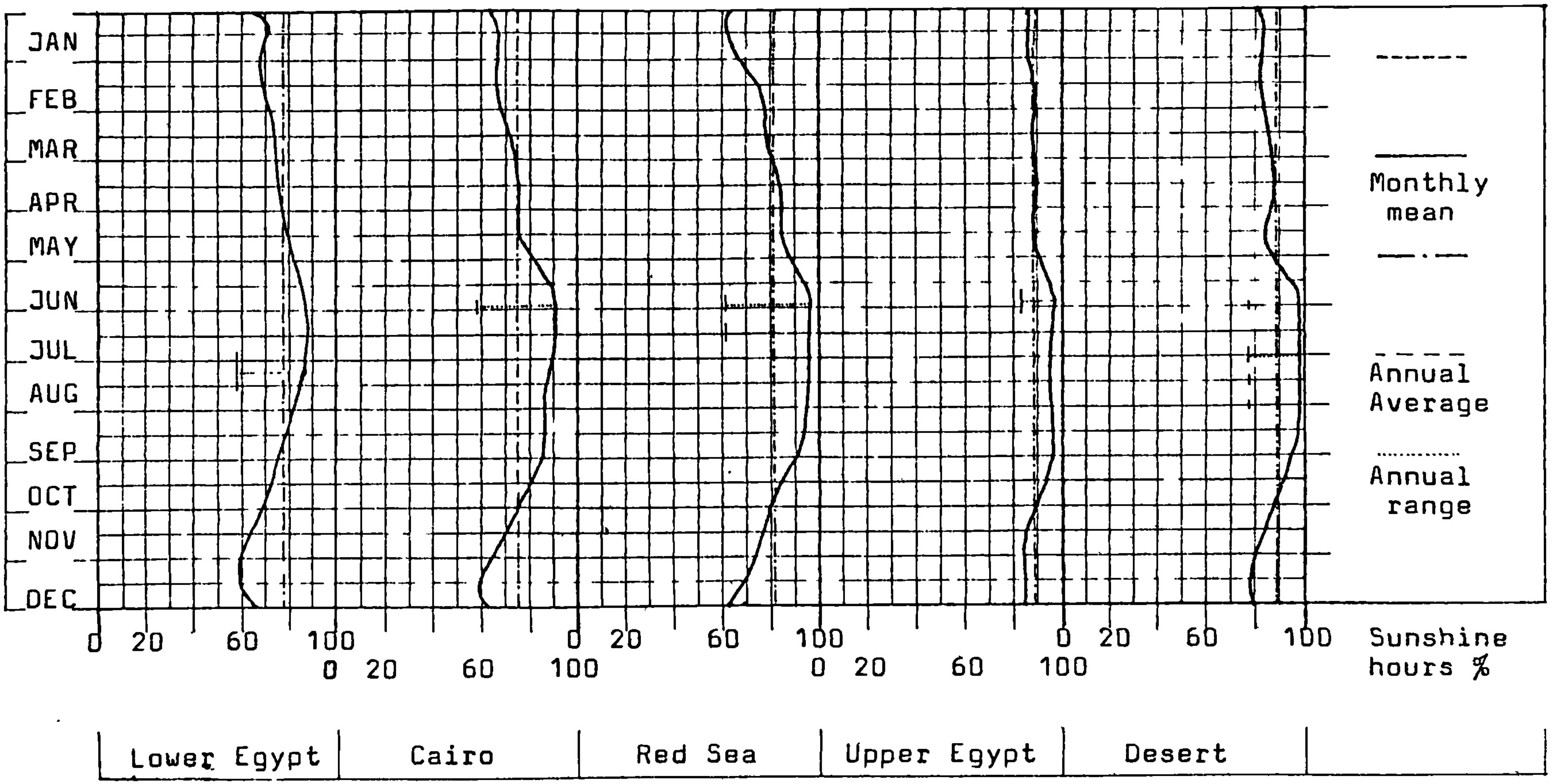

Figure (3.14), Hours of bright sunshine in the Egyptian regions.

December and January. This rises to over 90% during the period from June till the end of October. These clear sky conditions are responsible for the very wide temperature range in this region. The annual range is 32·5^{o}C with a monthly average range of 16^{o}C. In the Desert region the sky is the clearest of all the Egyptian regions with maximum sunshine of 98% for June, July, August and September. For most of the year the actual to possible sunshine hours is above 80% except during December when it falls to 78%. The annual average of 89% is considered the highest of all the Egyptian regions.

Generally, sunshine in Egypt is very high, but by comparing the monthly percentage with the annual average, it is possible to detect the periods of highest and lowest sunshine. In Lower Egypt the period from May till September is above the annual average with the maximum in August. The Cairo zone has a period of four months, starting from June and ending in September, with sunshine more than the annual average. In the Red Sea region the period from the middle of April till the middle of October is above the annual average, with the maximum occurring in May and June. In Upper Egypt the period with the maximum sunshine hours is from June till October, with the highest in June and July. In the Desert region the period from June till October has the highest sunshine in Egypt, with a peak of 98% in the period from June till September, figure (3.15).

Solar radiation quantities have been calculated using a computer program devised for that purpose. A sample of the results as well as the computer program are included in Appendix 2. In this program computation of the contribution of solar radiation as a source of radiant heat to the air temperature has been made. Quantitative values of the solar radiation acting on man standing in the outside environment have been computed in terms of the air temperature which will cause the same physiological

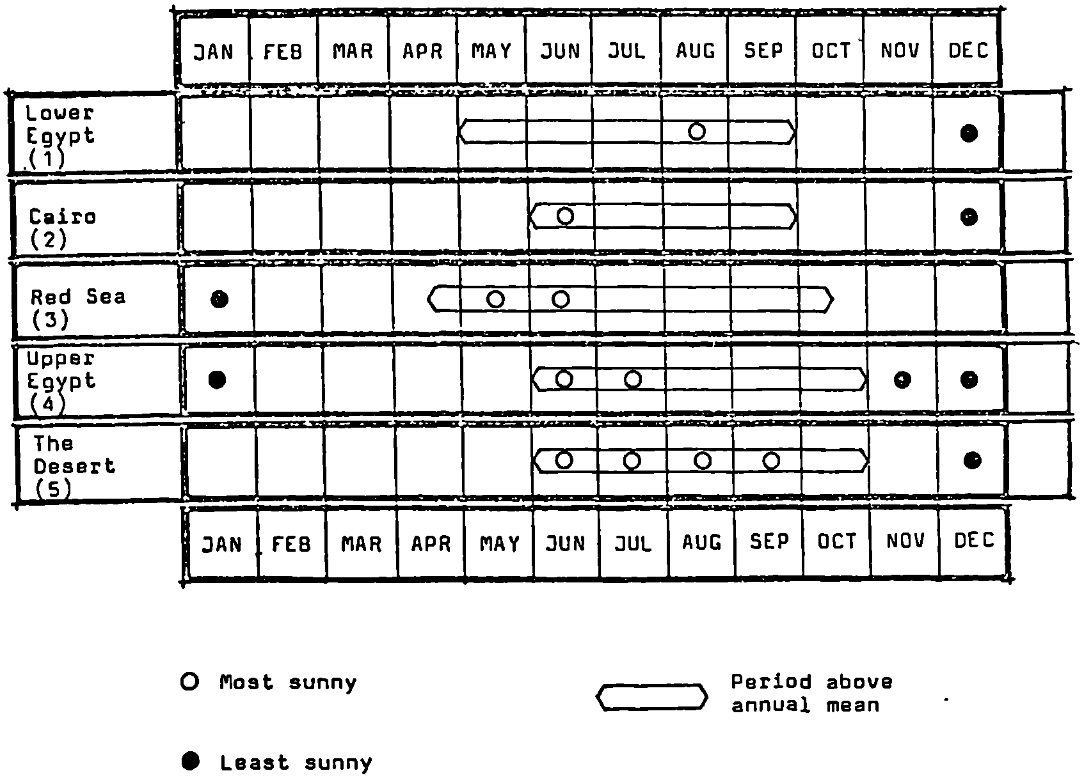

Figure (3.15) Annual variation in radiation for the Egyptian regions.

response as that caused by the radiation. Tables (3.9b) to (3.9e) give solar radiation falling on a horizontal plane at two seperate times, first at 12.00 when the maximum solar radiation is expected, and second at 14.00 when the maximum air temperature occurs.

In Lower Egypt, as well as in the Red Sea region, the maximum solar radiation occurs during the period from April to August where at 12.00 it is usually over 800 W/m^2 and at 14.00 it is over 650 W/m^2. At 12.00 it contributes over 7^oC to air temperature, while at 14.00 the contribution is about 6^oC.

The Cairo zone has a maximum solar radiation period extending from April to September when at 12.00 it is over 800 W/m^2 and at 14.00 it is about 700 W/m^2, except during September when it falls to just over 500 W/m^2. This may contribute up to 7^oC increase in air temperature.

Upper Egypt has a solar radiation intensity of over 800 W/m^2 at 12.00 from March till September, and over 650 W/m^2 from April till August, while it is over 500 W/m^2 in both March and September. In this region the solar radiation contribution to air temperature is over 7^oC at 12.00, coming down to $6{\cdot}4^oC$ at 14.00.

The highest solar radiation intensity falling on a horizontal plane in any of the Egyptian regions is that occurring in the Desert region. At 12.00 it is higher than 600 W/m^2 all the year through. This is due to the very low precipitation and relative humidity, as well as the clear sky conditions of this region. This also explains the very high temperature range and the aridity in the Desert. All the year through, even during the coldest days, the solar radiation intensity at 14.00 is over 480 W/m^2. Solar radiation of over 1000 W/m^2 at 14.00 occurs during the period from April to August and can add up to

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	284	508	734	935	1034	1063	1047	950	791	547	317	290
2	379	518	748	931	1042	1037	1027	944	773	556	338	272
3	394	587	801	964	1059	1055	1057	1003	845	644	445	332
4	642	823	1015	1193	1313	1321	1306	1230	1081	893	702	612
5	343	556	772	951	1070	1058	1050	970	802	582	377	328
6	319	525	750	933	1046	1051	1059	990	809	554	323	268
7	336	530	751	947	1053	1068	1076	1008	824	573	335	274
8	311	509	749	952	1053	1078	1067	974	802	560	316	265
9	355	558	782	953	1064	1055	1047	971	804	629	376	331
10	358	561	773	948	1066	1040	1031	948	783	565	395	323

1 Lower Egypt (Alexandria)
2 Red Sea (Suez)
3 Upper Egypt (Aswan)
4 Desert* (Siwa)
5 Cairo (Cairo)
6 El Khanka
7 Delta Barrage
8 Almaza
9 Giza
10 Helwan

(All regions considered as urban sites except for the Desert* region which has been considered as open site).

Table (3.9b) Total instantaneous solar radiation falling on horizontal plane in the Egyptian regions (W/m^2) at 12.00 hours on day 15 of each month.

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3·41	5·11	6·34	7·17	7·66	7·87	7·76	7·23	6·60	5·35	3·70	3·47
2	4·20	5·17	6·48	7·16	7·72	7·68	7·61	7·21	6·52	5·40	3·87	3·30
3	4·32	5·58	6·64	7·28	7·85	7·81	7·83	7·43	6·83	5·89	4·69	3·82
4	5·88	6·74	7·52	8·37	9·73	9·79	9·63	9·11	8·61	7·02	6·18	5·72
5	3·92	5·40	6·51	7·24	7·92	7·84	7·73	7·30	6·64	5·55	4·19	3·80
6	3·72	5·21	6·41	7·17	7·75	7·79	7·85	7·37	6·67	5·39	3·76	3·26
7	3·86	5·25	6·42	7·22	7·80	7·91	7·97	7·46	6·74	5·50	3·85	3·32
8	3·65	5·11	6·41	7·24	7·80	7·99	7·90	7·32	6·65	5·43	3·69	3·23
9	4·02	5·41	6·56	7·24	7·88	7·82	7·76	7·31	6·65	5·81	4·18	3·82
10	4·04	5·43	6·52	7·22	7·89	7·78	7·64	7·22	6·56	5·46	4·33	4·75

Table (3.9c) Solar radiation contribution to ambient air temperature in outer spaces in the Egyptian regions (^oC) at 12.00 hours on day 15 of each month.

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	147	335	539	708	787	819	821	734	534	263	111	108
2	211	302	508	657	749	751	760	680	467	231	94	57
3	167	339	539	658	730	733	752	701	516	270	133	87
4	549	730	967	1043	1127	1143	1151	1064	918	701	529	483
5	186	258	553	696	795	787	798	726	518	273	147	136
6	167	329	534	681	774	784	814	754	532	246	97	71
7	184	336	536	699	783	804	833	775	552	268	109	78
8	156	308	528	700	780	811	819	733	522	250	86	66
9	202	364	569	703	793	788	799	732	525	331	143	135
10	203	365	556	694	792	768	780	704	498	254	165	126

Table (3.9d) Total instantaneous solar radiation falling on horizontal plane in the Egyptian regions (W/m^2) at 14.00 hours on day 15 of each month.

Region	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2•00	3•86	5•30	6•22	6•58	6•72	6•73	6•34	5•27	3•21	1•56	1•53
2	2•71	3•57	5•11	5•96	6•41	6•42	6•46	6•08	4•84	2•90	1•34	0•82
3	2•23	3•89	5•30	5•96	6•32	6•33	6•42	6•18	5•16	3•28	1•83	1•25
4	5•36	6•82	7•67	7•78	8•34	8•47	8•52	8•08	7•11	6•15	5•24	4•95
5	2•44	4•04	5•38	6•16	6•62	6•58	6•63	6•30	5•17	3•31	2•01	1•78
6	2•23	3•80	5•27	6•08	6•52	6•57	6•78	6•48	5•26	3•05	1•39	1•10
7	2•42	3•86	5•28	6•17	6•56	6•65	6•78	6•53	5•38	3•26	1•55	1•12
8	2•11	3•62	5•24	6•18	6•55	6•68	6•72	6•34	5•19	3•09	1•23	0•94
9	2•61	4•08	5•48	6•19	6•61	6•58	6•63	6•33	5•21	3•82	2•01	1•87
10	2•62	4•09	5•40	6•15	6•60	6•49	6•55	6•20	5•64	3•13	2•20	1•76

Table (3.9e) Solar radiation contribution to ambient air temperature in outer spaces in the Egyptian regions (^{o}C) at 14.00 hours on day 15 of each month.

9·5^{o}C to the air temperature. In this region one may say that the solar radiation is the most important climatic factor. If it can be utilised in the right way, solar radiation energy could be the most important life support element. However, if it is uncontrolled, or the effects on human comfort and building design are under-estimated, solar radiation can be the most oppressive climatological element.

3.3 Climatic Seasons of the Egyptian Regions

Summer time in Upper Egypt is longer than in Lower Egypt while winter, if there is any, is very short. In everyday life a person may not distinguish the exact time of the beginning of summer or winter due to the Equinox, but he feels it by the effect of the weather conditions on his sensory system. Thus, the beginning of summer or winter is practically established by changing the type of clothing. This change is usually influenced by the combined effects of all the climatic elements mentioned above, ie air temperature, relative humidity, wind and solar radiation. The human sense of comfort will form the basis for distinguishing the seasons and the hottest and coldest months in each of the Egyptian regions. Summer time will be assumed as the time when the human body experiences discomfort due to excess heat stress, while winter will be the time when discomfort due to cold conditions is experienced. The evaluation of each of the main climatic elements in the five regions was discussed before, but it is within this section that the combined effects of all elements on human comfort will be considered, and for this purpose Standard Effective Temperature (SET) will be used (113, 178).

The elements of climate for each of the five regions are described in detail in table (3.10) with their combined

Table (3.10) The effect of the climatic elements in the Egyptian regions. Data from Taha (254). Solar radiation is estimated by a computer programme developed by the author.

Region	Element		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
LOWER EGYPT (1)	AIR TEMP	6	9·5	9·5	11·0	13·5	16·5	20·0	22·5	23·0	21·5	18·0	15·0	11·0	9·5
		14	18·5	19·0	21·0	23·5	26·5	28·0	29·5	30·5	29·5	27·5	24·5	20·5	30·5
	RH	6	79	78	77	80	82	82	82	82	79	80	82	81	82
		14	54	51	50	50	53	58	61	61	57	53	54	55	50
	WIND	$\overline{V}$	4·4	4·4	4·7	4·3	4·1	4·2	4·4	4·0	3·5	3·1	3·4	3·9	4·7
		D	NW	NW	NW	NW	NW	NW	NW	NW	NW	N	N	SW	NW
	SR	°C	2·00	3·86	5·30	6·22	6·58	6·72	6·73	6·34	5·27	3·21	1·56	1·53	6·73
		W/m²	147	335	539	708	787	819	821	734	534	263	111	108	821
	DISC	14	-1·8	-1·0	-0·1	+0·2	+0·6	+0·8	+1·1	+1·3	+1·0	+0·5	0·0	-1·0	+1·3
		6	-4·2	-4·3	-4·0	-3·2	-2·5	-1·8	-1·0	-0·5	-0·9	-1·8	-2·6	-3·9	-4·3
CAIRO (2)	AIR TEMP	6	8·5	9·0	11·5	14·0	17·5	20·0	21·5	21·5	20·0	18·0	14·0	10·5	8·5
		14	19·0	20·5	23·5	28·0	32·5	34·5	35·5	35·0	32·5	30·0	25·0	20·5	35·5
	RH	6	70	68	69	66	64	70	76	79	80	78	76	71	80
		14	43	38	32	27	24	25	31	34	35	35	41	45	24
	WIND	$\overline{V}$	3·4	3·6	3·8	4·0	3·9	3·5	2·5	2·6	2·9	2·9	3·1	3·0	4·0
		D	NE	NW	SW	NW	N	NW	SW	SW	NW	NW	NW	NW	NW
	SR	°C	2·44	4·04	5·38	6·16	6·62	6·56	6·63	6·30	5·17	3·31	2·01	1·73	6·63
		W/m²	186	258	553	696	795	787	798	726	518	273	147	136	798
	DISC	14	-1·0	-0·3	+0·3	+0·6	+1·1	+1·9	+2·0	+2·2*	+1·6	+0·8	+0·1	-0·8	+2·2*
		6	-4·0	-3·9	-3·5	-3·1	-2·6	-1·4	-1·0	-0·9	-1·3	-1·9	-2·9	-3·7	-4·0
RED SEA (3)	AIR TEMP	6	8·5	9·5	11·5	14·5	18·0	20·5	22·5	22·5	20·5	18·5	14·5	10·5	8·5
		14	20·5	21·5	24·5	28·0	32·5	35·0	36·5	36·5	33·5	31·0	26·5	22·0	36·5
	RH	6	70	68	64	61	58	62	67	70	70	71	73	72	73
		14	46	42	36	31	30	30	32	33	37	39	45	48	30
	WIND	$\overline{V}$	1·8	2·1	2·3	2·5	2·5	2·7	2·7	3·0	2·9	2·6	2·0	1·8	3·0
		D	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW	NW
	SR	°C	2·71	3·57	5·11	5·96	6·41	6·42	6·46	6·08	4·84	2·90	1·34	0·82	5·46
		W/m²	211	302	508	657	749	751	760	680	467	231	94	57	760
	DISC	14	-0·7	-0·2	+0·3	+0·8	+1·3	+1·8	+2·3*	+2·2*	+1·8	+0·9	+0·2	-0·8	+2·3*
		6	-4·0	-3·9	-3·4	-2·8	-2·0	-1·2	-0·8	-0·8	-1·3	[illegible]	-2·9	-3·7	-4·0
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

* Approximate DISC values due to conditions in the margins of DISC scale in the SET charts.

Table (3.10) continued.

Region	Parameter		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
UPPER EGYPT (4)	AIR TEMP	6	9·5	10·5	14·0	18·5	23·5	25·0	26·0	26·5	24·0	21·5	16·5	13·0	9·5
		14	24·0	26·5	30·5	35·5	40·5	42·0	42·0	42·0	40·0	37·5	31·5	26·5	42·0
	RH	6	52	45	36	30	26	28	29	32	37	41	49	53	53
		14	27	21	16	14	13	14	16	18	19	21	27	30	13
	WIND	$\overline{V}$	1·8	2·2	2·6	2·6	3·0	2·4	1·9	2·2	2·0	2·2	1·5	1·9	3·0
		D	N	N	N	N	N	N	N	N	N	N	N	N	N
	SR	°C	2·23	3·89	5·00	5·96	6·32	6·33	6·42	6·18	5·16	3·28	1·83	1·25	6·42
		W/m^2	167	339	539	658	730	733	752	701	516	270	133	87	752
	DISC	14	-0.2	+0·2	+0·6	+0·9	+1·8*	+2·4*	+2·5*	+2·4*	+2·0	+1·4	+0·5	0·0	+2·5
		6	-4·0	-3·7	-3·0	-2·0	-0·8	-0·4	-0·3	-0·1	-0·5	-1·2	-2·4	-3·2	-4·0
THE DESERT (5)	AIR TEMP	6	4·0	5·5	8·0	12·0	17·0	19·0	20·5	20·5	18·5	15·0	10·0	6·0	4·0
		14	19·5	22·0	28·0	30·0	34·5	37·0	39·0	38·0	35·0	32·5	26·5	24·5	38·0
	RH	6	73	69	64	60	55	58	66	68	68	66	69	73	73
		14	47	42	37	34	32	31	34	34	38	40	45	49	31
	WIND	$\overline{V}$	2·0	2·0	2·5	2·4	2·3	2·1	2·0	1·8	1·5	1·3	1·3	1·6	2·5
		D	W	W	W	NW	NE	N	NW	NW	NW	NW	W	W	NW
	SR	°C	5·36	6·82	7·67	7·78	8·04	8·47	8·52	8·08	7·11	6·15	5·24	4·95	8·52
		W/m^2	549	730	967	1043	1127	1143	1151	1064	918	701	529	483	1151
	DISC	14	-0·2	+0·2	+1·0	+1·2	+1·8	+2·2*	+2·5*	+2·6*	+2·2*	+1·8	+0·6	+0·4	+2·6
		6	-5·0	-4·7	-4·2	-3·4	-2·2	-1·8	-1·2	-1·1	-1·8	-2·7	-3·7	-4·6	-5·0
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

effect on human comfort calculated using the SET index. This is expressed in the DISC scale which states the deviation of the expected physiological response within the prevailing conditions from the optimum comfort conditions, Appendix 3. Therefore, these conditions will be taken as the limits for spring and autumn, that is, conditions with a score of more than +0•5 DISC will be considered as summer conditions, while those with a score below -0•5 DISC will indicate winter conditions.

The charts in figure (3.17) show the curves of the DISC throughout the year for each of the five regions. These are expressed for three main conditions: sunny, shade, and night time. For the cold periods the night conditions will be considered.

In Lower Egypt, fig.(3.17a), for the period from the beginning of December till the end of February the DISC value of the sunny periods falls under -0•5 DISC with January the coldest at -1•8 DISC. In the shade, and during cloudy conditions, this period may extend from the second half of November till the third week of April, with January again having the lowest value of -2•2 DISC. During night time for the whole year except August (-0•5 DISC), DISC values fall under -0•5, with February (-4•3) as the coldest month. The period from the second week of May till the second week of October, and on sunny days, has a DISC value of over +0•5, with August (+1•3 DISC) the highest. In shade and/or cloudy conditions there will be no period whin the DISC value exceeds +0•5, with August the hottest month at 0•5 DISC exactly. In Lower Egypt winter will be considered as starting from the beginning of December until the end of February; spring from the beginning of March to the middle of May; summer from the middle of May to the middle of October; and autumn from mid-October till the beginning of December. The coldest month will be taken as February, -4•3 DISC, while the hottest will be August at +1•3 DISC.

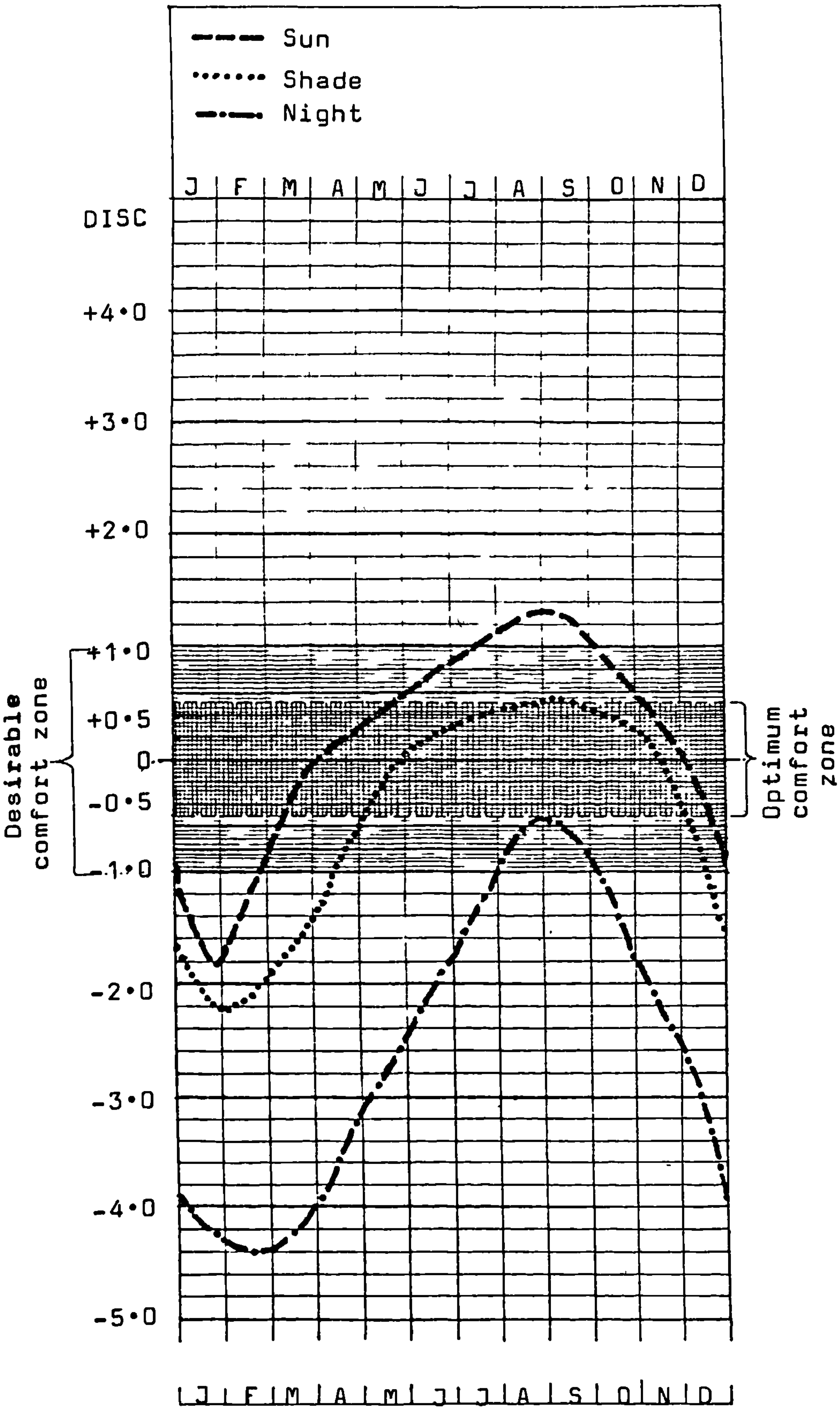

Figure (3.17a) The deviation of the prevailing climatic conditions (DISC) from the optimum comfort zone (0•9 Clo, 1•0 Met), Lower Egypt.

The cold conditions of Cairo zone prevail from the beginning of December to the first week of February, fig.(3.17b). When it is cloudy this period may be extended from the last week of November till the last week of March. During both of these periods the climatic conditions fall under -0·5 DISC. The coldest month is January when conditions range from -0·5 DISC at sunny times to -4·0 DISC at night. Throughout the year night conditions fall under -0·5 DISC. The period from the first week of February till the end of March has climatic effects of between ±0·5 DISC during the sunny periods. This falls within the optimum comfort zone. Hot conditions prevail from the beginning of April till the end of October when the climatic conditions are hotter than the optimum comfort zone, with August as the hottest month (+2·2 DISC). On the comfort chart this coincides with the upper limit of sweat rate for a healthy man, $500g/m^2h$ (0·5 W). Under these conditions the danger of heat stroke increases and any increase in air temperature, solar radiation or relative humidity will enhance the possibility, therefore air movement is of great importance during this period. Night conditions during October fall below -0·8 DISC which is outside the optimum comfort zone from the cold side. Therefore in Greater Cairo, winter will be considered to extend from December to February, and summer from April till October, with January as the coldest month (-4·0 DISC), and August as the hottest (+2·2).

In the Red Sea region the cold conditions start a week later than in Cairo, around the second week of December, and end by the first week of February. If it is cloudy, this cold period will extend from the last week of November to the end of March. At night the climatic conditions fall under -0·5 DISC, with August the highest, and January the coldest (-0·7 and -4·0 DISC respectively). The period from the end of March till the end of October is usually sunny and falls within the hot side, with July the hottest month (+2·3 DISC) when conditions exceed the maximum sweat

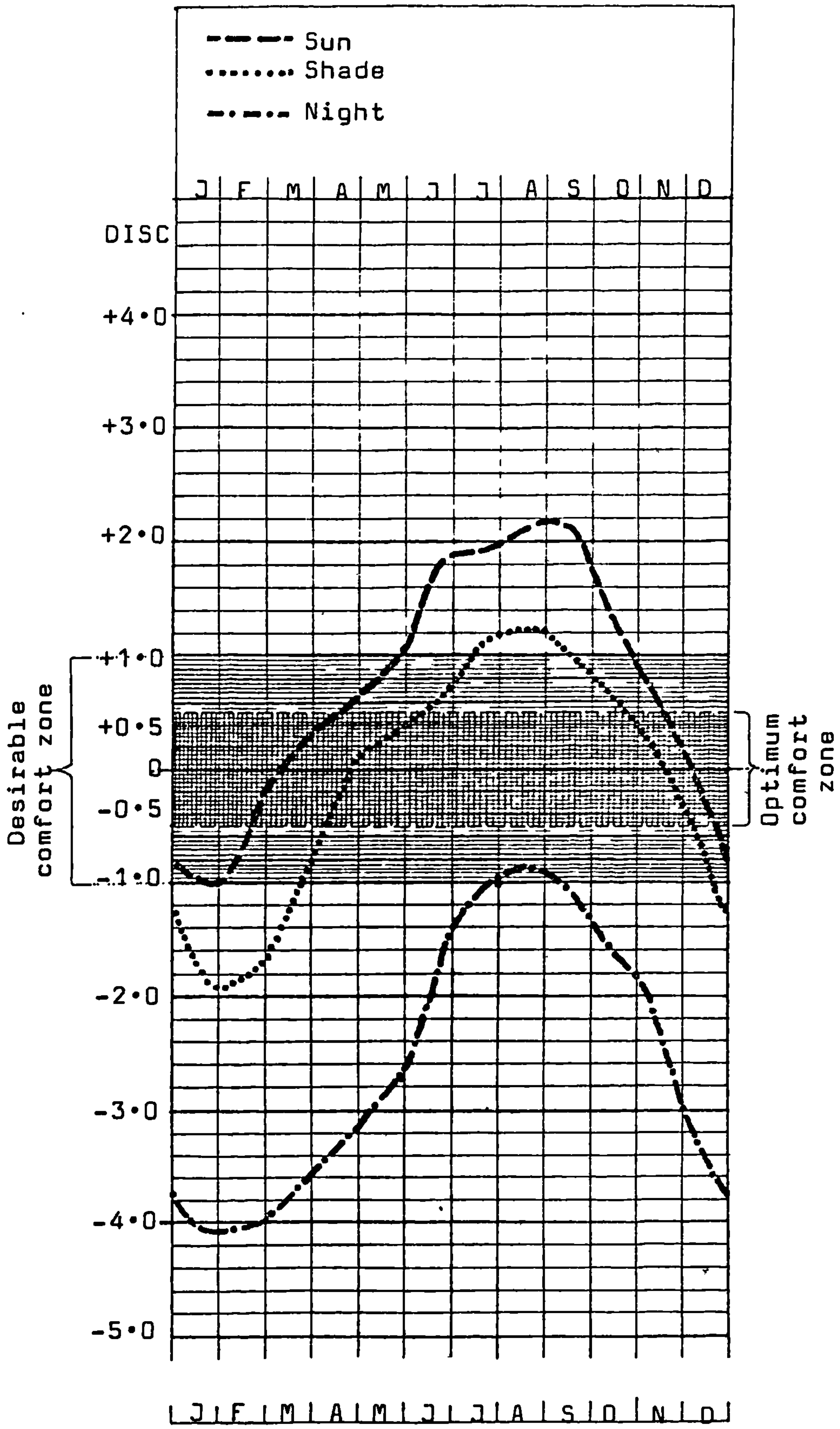

Figure (3.17b) The deviation of the prevailing climatic conditions (DISC) from the optimum comfort zone (0.9 Clo, 1•0 Met), Cairo.

expected for a healthy person wearing clothing of 0•9 clo (light suit) and engaged in sedentary activity. The heat stroke risk is very pronounced under these conditions. The period from the beginning of February till the end of March may be considered as spring, while autumn prevails during November and the first week of December, fig.(3.17c).

Upper Egypt enjoys clear skies with very intensive solar radiation throughout the year, which can be defined into two main seasons - a short spring and a very long summer. Spring starts around the third week of December and ends by the first week of March. The coldest month is January (-0•2 DISC) with a daily range of 3•8 DISC. Night conditions throughout the year are extremely cold due to the outgoing long wave radiation, the coldest month again being January (-4•0 DISC), however, the period from the beginning of June till mid-September falls within the optimum comfort zone. Summer conditions prevail from the last week of March till the first week of December. During the period from June till August man may experience very hot conditions with July (+2•5 DISC) the hottest month. The risk of heat stroke in sunny areas is very high but shading could bring conditions to much more tolerable levels, around +1•2 DISC in July and a maximum of +1•3 DISC in August. Generally, during this period shading and maximum air movement are of prime importance in Upper Egypt. During spring, however, due to the dusty Khamaseen winds, prevention of direct ventilation has the same importance as for night times, figure (3.17d).

In Egypt the hottest region of all may be considered the Desert region. This is a very severe area with the possibility of sun stroke during hot seasons, and frost during night in cold seasons. The main character of this region is aridity, with a diurnal range of up to 5•5 DISC and an annual range of 7•6 DISC. The hot season extends from the beginning of March till the last week of November with

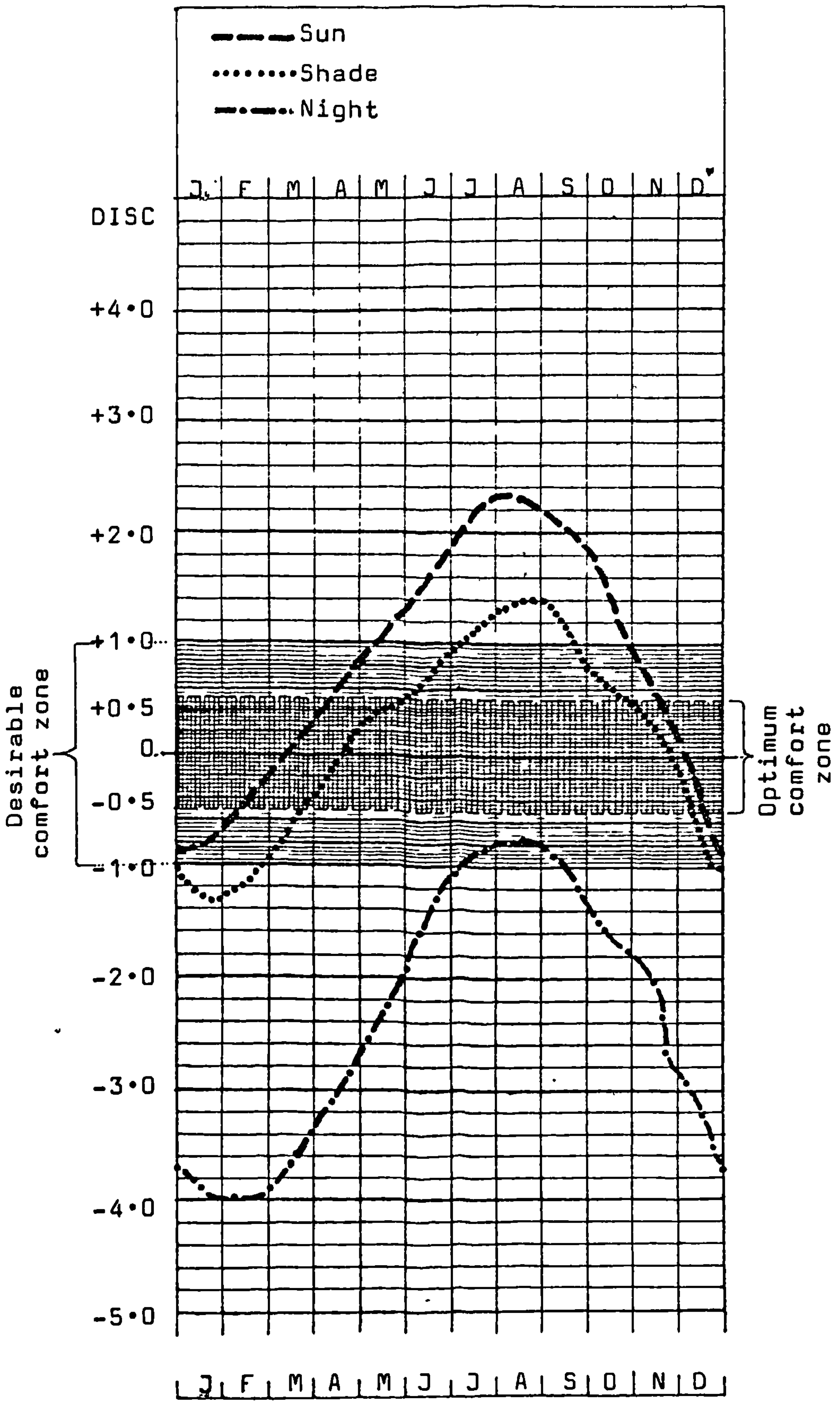

Figure (3.17c) The deviation of the prevailing climatic conditions (DISC) from the optimum comfort zone (0•9 Clo, 1•0 Met), Red Sea.

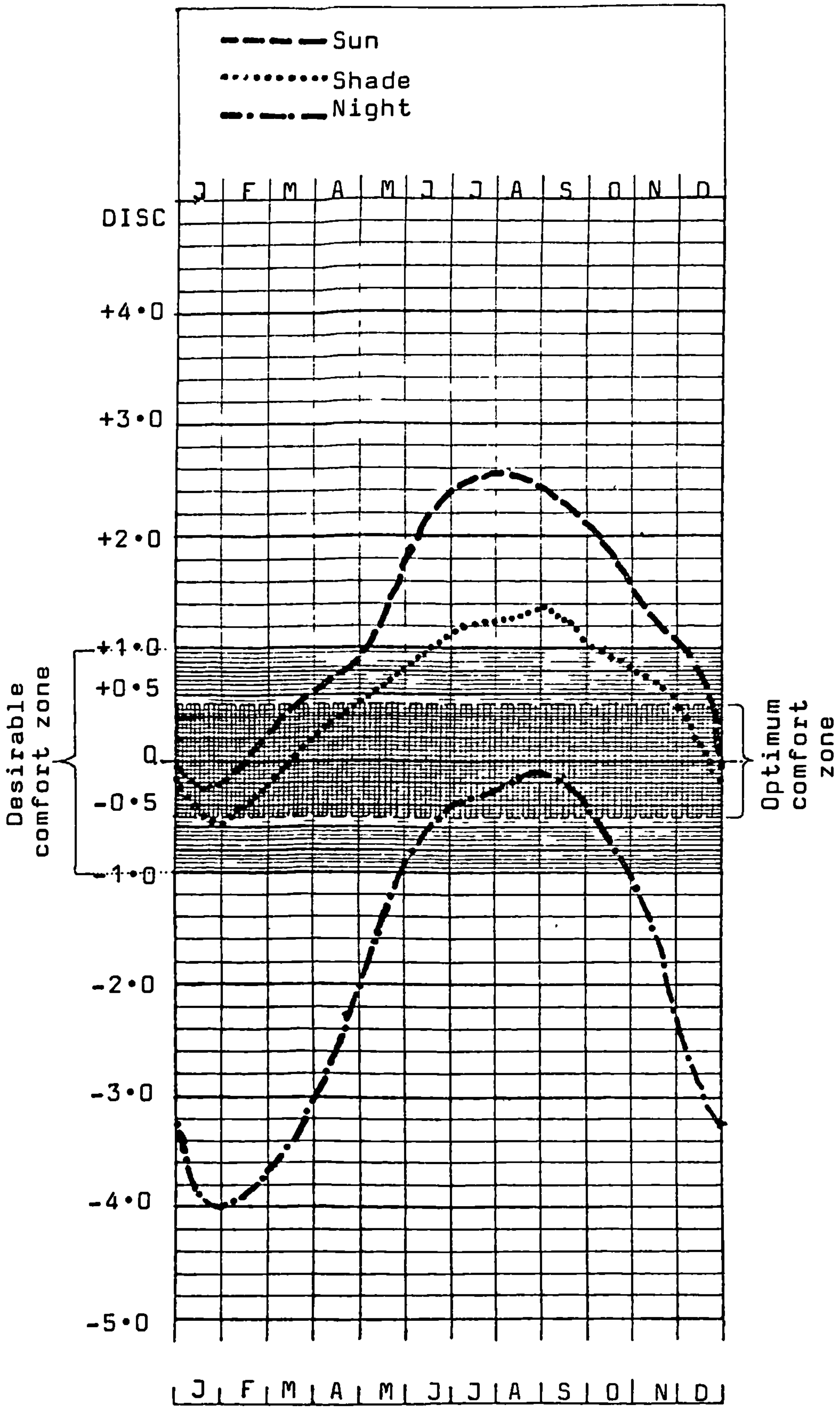

Figure (3.17d) The deviation of the prevailing climatic conditions (DISC) from the optimum comfort zone (0•9 Clo, 1•0 Met), Upper Egypt.

August as the hottest month. The neutral season, which can be termed as spring, starts from the last week of November and ends by the end of February, with January (-2·2 DISC) as the coolest month. The period from the second week of June till the second week of September is characterised by the high risk of heat stroke and the maximum sweat rate limit exceeded. At night the whole year around, the climatic conditions range from cool to very cold with the coldest month, January, scoring -5·0 DISC, which falls under the shivering line. It is interesting to note the possibility of converting this hostile climate into a friendly one by architectural means. The ingenious peoples of Siwa in Egypt, Ghadames in Libya and Matmata in Tunisia managed this by different means. The first by insulation and ventilation; the second by compact planning; and the third by building underground, fig. (3.17e).

3.1 Climatic Design Criteria in the Egyptian Regions

Identifying the hottest and coldest months in each of the Egyptian regions, from the human comfort point of view, and bearing in mind the Egyptian way of life, it is possible to establish the lower and upper design limits for each of them. The lowest design limit will be assumed as the lowest prevailing conditions for at least 90% of the time on a typical day of the coldest month. The activity level, metabolic rate and the clo value at the time will be considered. The upper design limit is assumed on a similar basis for a typical day of the hottest month.

Examining a typical day in January, the coldest month in Lower Egypt, the inhabitants experience air temperature higher than 10·8°C for at least 90% of the day, as shown in figs.(3.18) and(3.19a). The relative humidity, calculated on the same basis from fig.(3.21a) will be 79% at

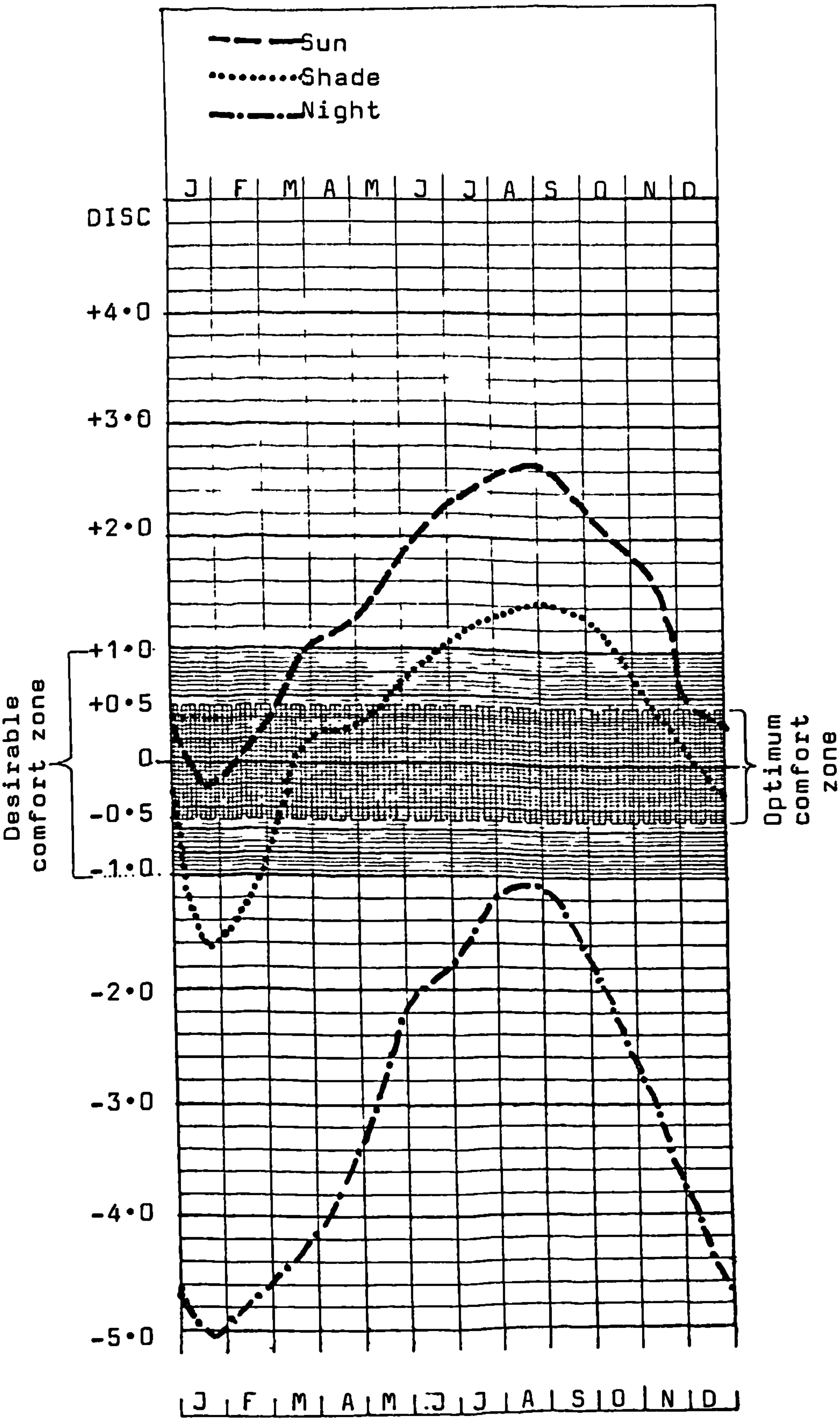

Figure (3.17e) The deviation of the prevailing climatic conditions (DISC) from the optimum comfort zone (0·9 Clo, 1·0 Met), Desert.

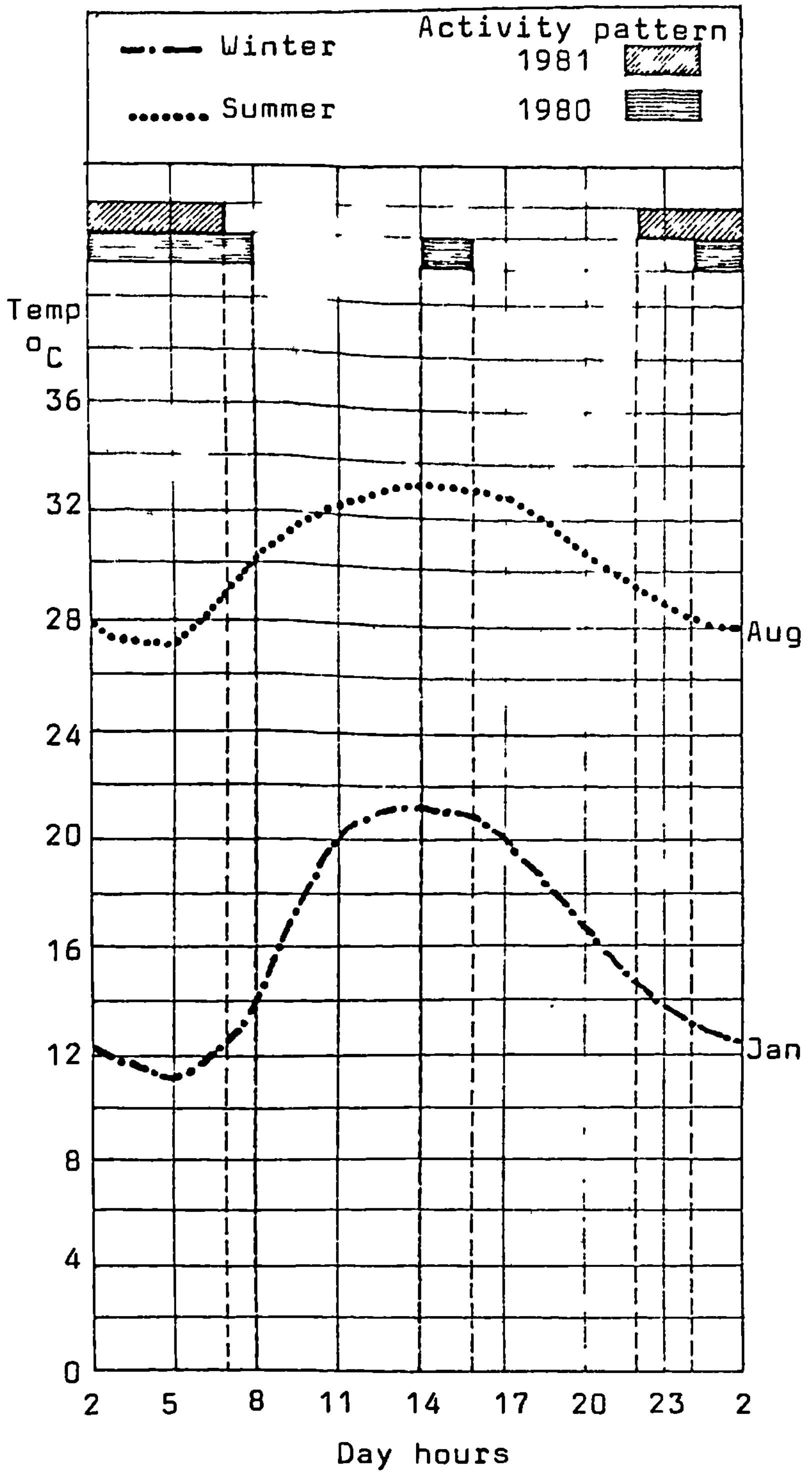

Figure (3.18) Mean monthly temperature measured hourly. Lower Egypt, 31°12'N, 29°57'E.

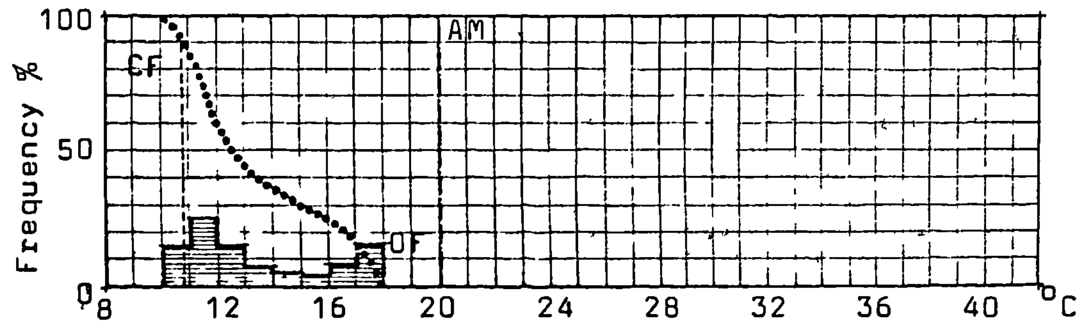

Figure (3.19a) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Lower Egypt, January.

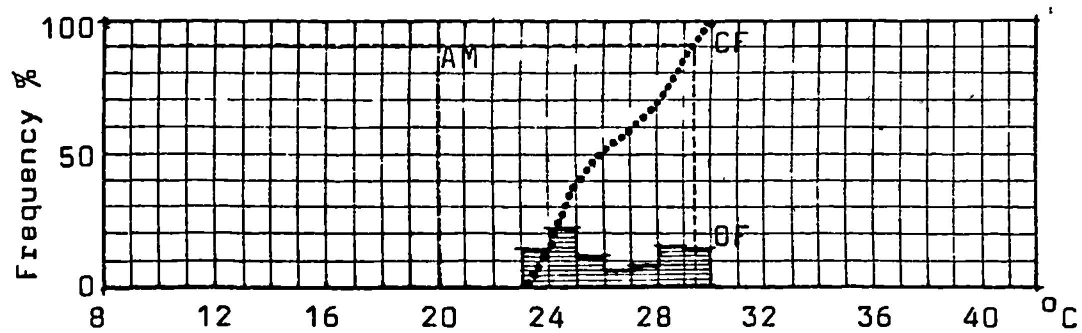

Figure (3.19b) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Lower Egypt, August.

02.00 and 07.00, fig.(3.20). The wind direction ranges from northwest to southwest, with the strongest winds, maximum intensity 4·4 m/s, blowing from the northwest. The percentage of sunshine hours, total actual to total possible, is 72%. Considering all these factors, the climatic conditions for January in Lower Egypt give a discomfort value of -4·0 DISC, which can be taken as the lower design limit for this region, table (3.11).

The hottest month in Lower Egypt is August, when for at least 90% of the day the upper limit of air temperature is 29·2°C, fig.(3.17). Relative humidity measured over the same period as the air temperature is 61%, which is the upper limit for only 10% of the day, and there may be other times during the day when the relative himidity exceeds this value and the combined effect of both air temperature and relative humidity can cause the inhabitants greater discomfort than these previous conditions. The relative humidity upper limit for at least 90% of the day is 82% and it occurs at 03.00 and 05.00, at which times the air temperature is 23·5°C. Comparing the physical effects of these two conditions on human comfort, the prevailing conditions from 13.00 till 16.00 fall outside the optimum comfort zone on the hot side of the DISC scale. Hence, this will be taken as the upper design limit in Lower Egypt.

In the Cairo zone, the coldest month is January when the climatic conditions on a typical day are as follows: the upper limit of air temperature for at least 90% of the day is 10·5°C, occurring at 03.30 and 06.30, fig.(3.22). At those times the relative humidity is 71%, which is the upper limit for at least 90% of the day, fig.(3.25). The wind speed is 3·40 m/s blowing from the northeast. These climatic conditions, giving a value of -3·8 DISC, will be taken as the lower design limit for the Cairo zone, table (3.12). Both July and August in the Cairo zone have the highest records on the discomfort scale, fig.(3.17). In

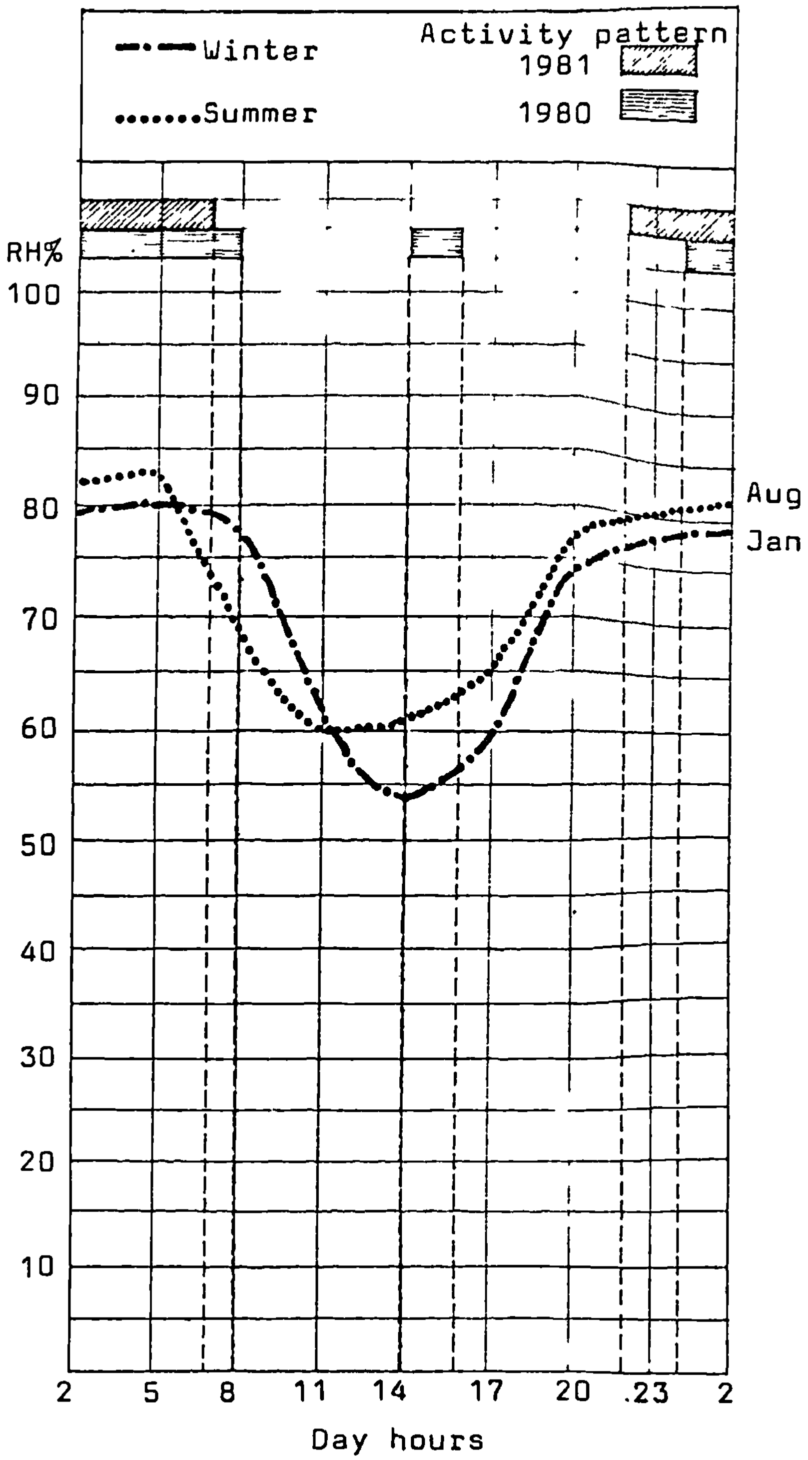

Figure (3.20) Mean monthly relative humidity measured hourly. Lower Egypt, 31°12'N, 29°57'E.

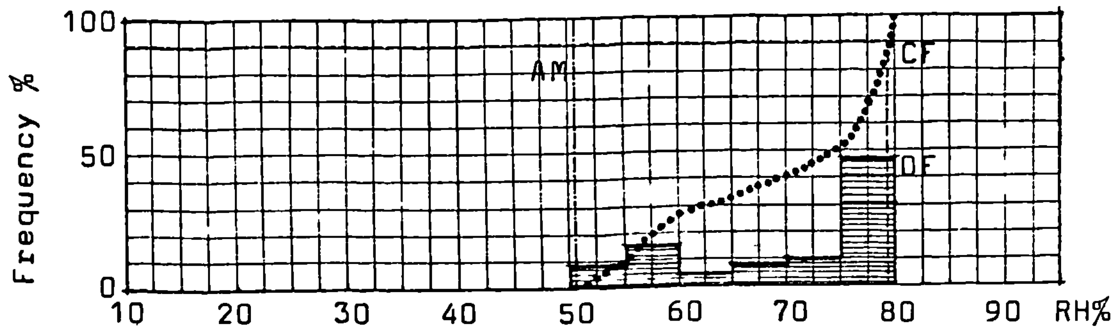

Figure (3.21a) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM),Lower Egypt, January.

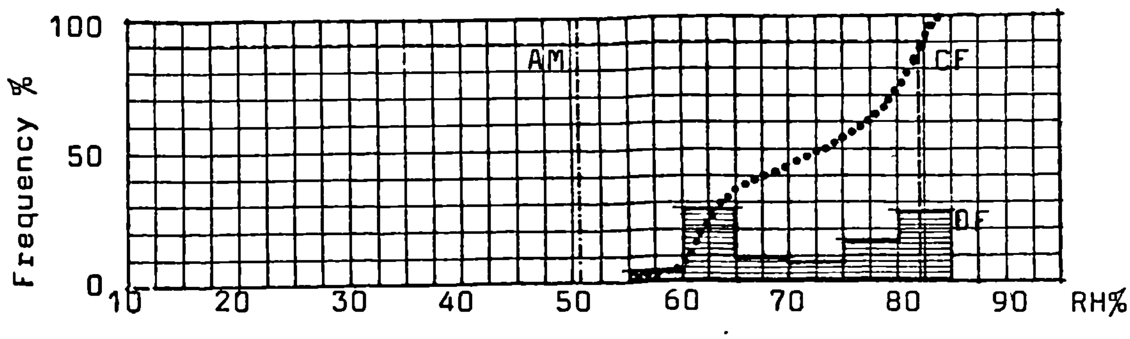

Figure (3.21b) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Lower Egypt, August.

Table (3.11) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in Lower Egypt during the coldest and hottest seasons.

Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	03.30 06.30	10·8	79	4·4		1·0	0·9	-4·0'
Summer Aug	13.00 16.00	29·2	61	4·0	734	1·0	0·9	+1·6"
	03.00 05.00	23·5	82	4·0		1·0	0·9	+1·0

' Lower Design Limit

" Upper Design Limit

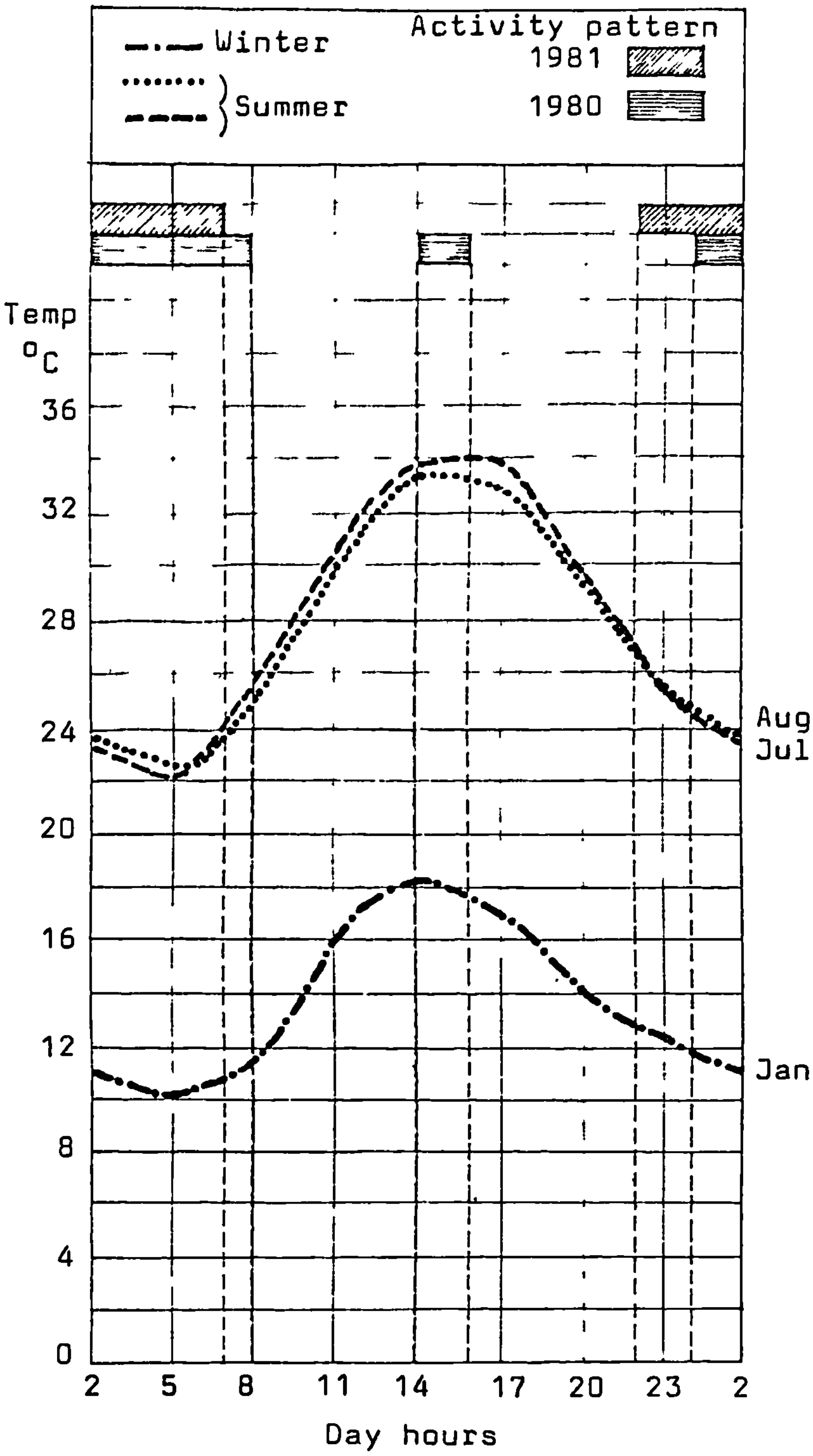

Figure (3.22) Mean monthly air temperature measured hourly. Cairo, 30°08'N, 31°34'E.

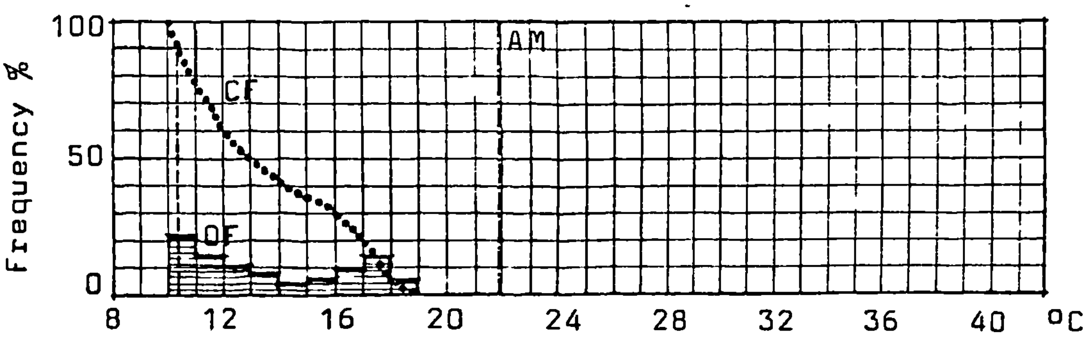

Figure (3.23a) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Cairo, January.

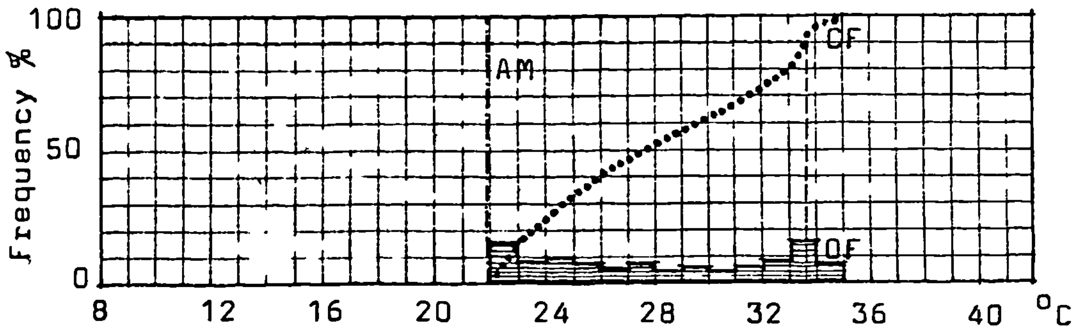

Figure (3.23b) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Cairo, July.

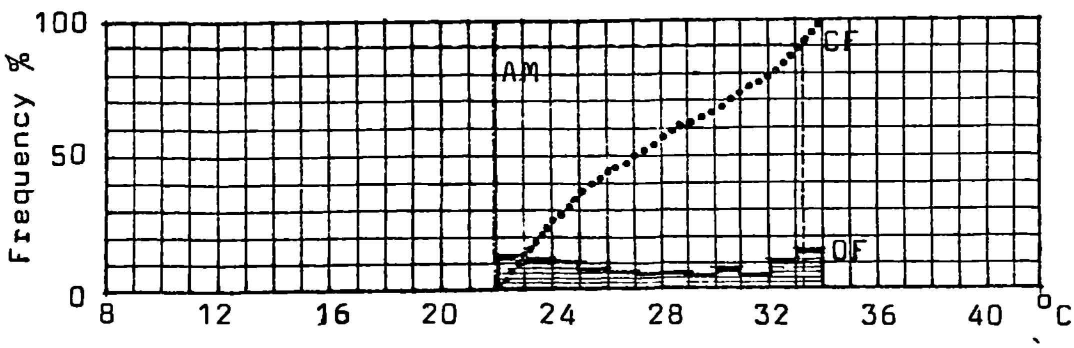

Figure (3.23c) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Cairo, August.

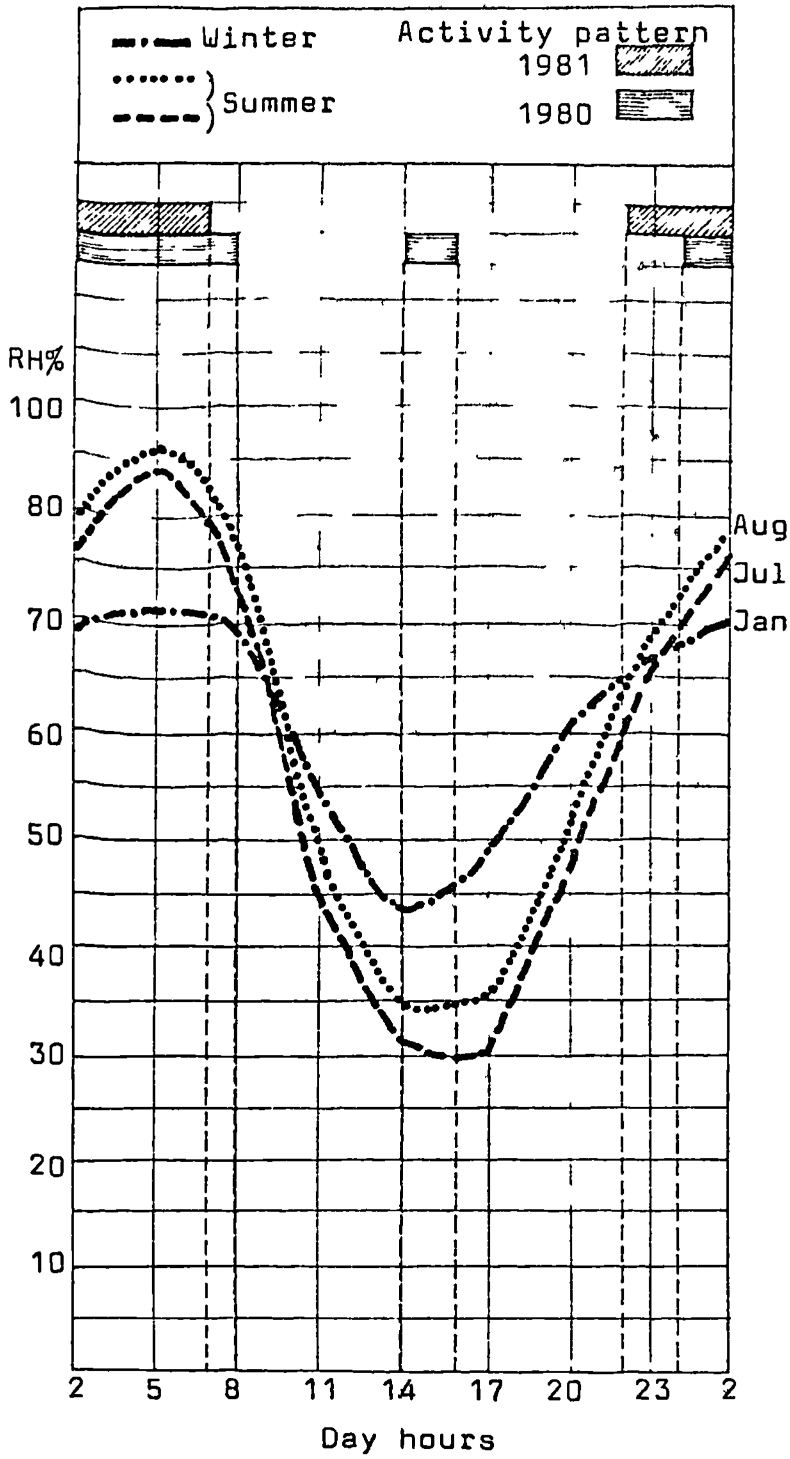

Figure (3.24) Mean monthly relative humidity measured hourly. Cairo, 30°08'N, 31°34'E.

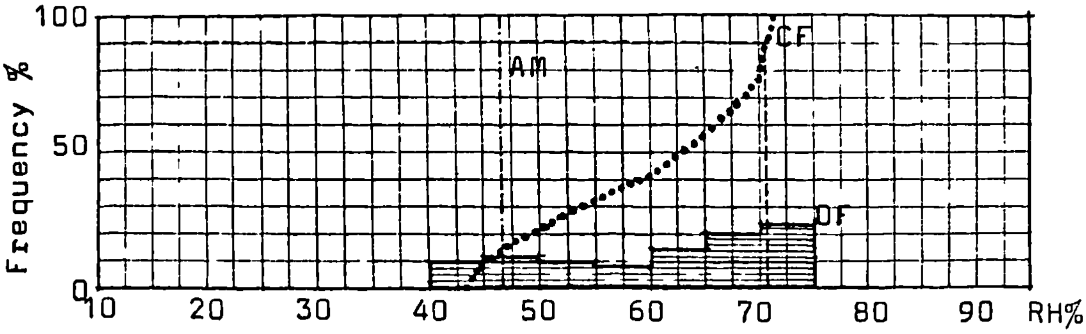

Figure (3.25a) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Cairo, January.

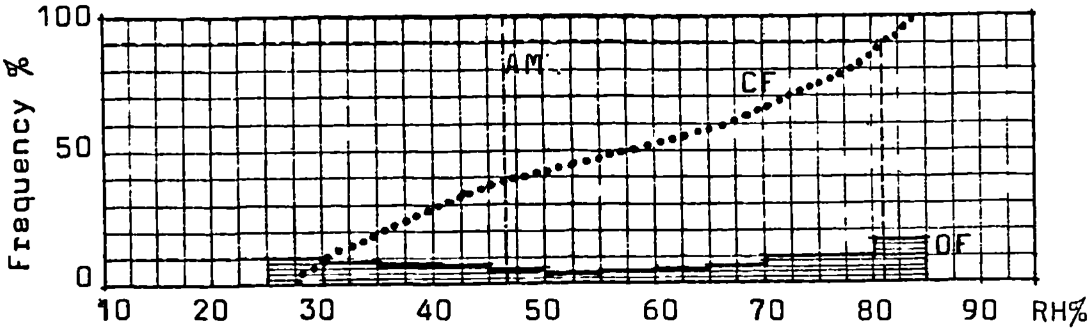

Figure (3.25b) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Cairo, July.

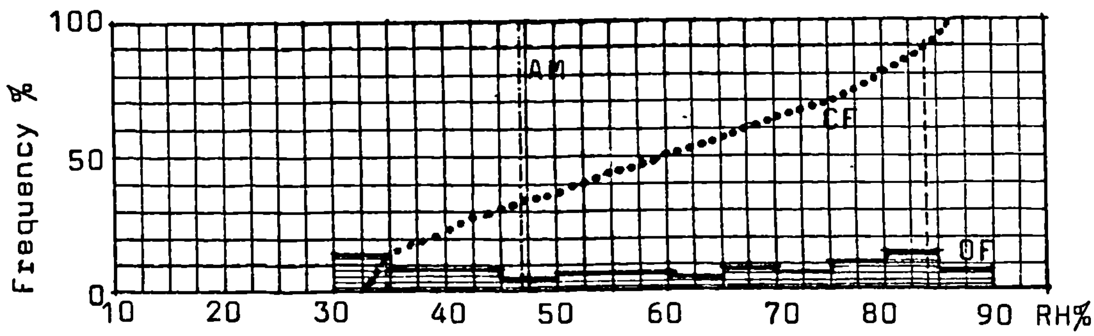

Figure (3.25c) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Cairo, August.

Table (3.12) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in Cairo zone during the coldest and hottest seasons.

Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	03.30 06.30	10•5	71	3•4		1•0	0•9	-3•8 '
Summer Jul	14.00 17.00	33•8	52	2•5	798	1•0	9•0	+1•2
	03.30 06.30	24•0	81	2•5		1•0	0•9	-0•4
Summer Aug	13.30 16.30	33•3	35	2•6	726	1•0	0•9	+1•5 "
	03.30 06.30	23•3	84	2•6		1•0	0•9	-0•1

' Lower Design Limit

" Upper Design Limit

July the air temperature upper limit for 90% of the day is 33·8°C at 14.00 and 17.00, yet the highest relative humidity for that period, 52%, is the upper limit for only 45% of the day. The climatic conditions when the upper limit of the relative humidity, 81%, covers at least 90% of the day occur at 03.30 and 06.30, table (3.12). The air temperature upper limit for 90% of a typical day in August is 33·3°C at 13.30 and 16.30. For these times the upper limit of the relative humidity is only 35% covering 15% of the day. Winds blow from the southeast and the east with a velocity of 2·6 m/s, and the total radiation is 726 W/m^2. The lower value of the relative humidity suggests that there may be other times when the combined effect of relative humidity and air temperature along with wind and solar radiation conditions, will cause the inhabitants greater discomfort than those described above. The magnitude of the upper limit of the relative humidity covering 90% of the day is 84% occurring at 03.30 and 06.30. At these times air temperature reaches 23·3°C, the upper limit for only 15% of the day. The climatic conditions in July give discomfort values of +1·2 DISC for the afternoon and -0·4 DISC for the early morning, while in August it is +1·5 in the afternoon and -0·1 in the early morning. Hence August conditions for the afternoon will be taken as the upper design limit in the Cairo zone. The micro-climates of the Cairo zone should also be considered, and will be dealt with in the next section (3.5).

The climatic conditions in the Red Sea, Upper Egupt and the Desert regions have been considered on a similar basis to those of Lower Egypt and the Cairo zone, and the results are illustrated in tables (3.13), (3.14) and (3.15).

In the Red Sea region the lower design limit is taken as the climatic conditions on a typical day of January at 03.30 and 06.30, giving -3·3 DISC. The upper design limit is that of the climatic conditions at 13.30 and 16.00, Table (3.13) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in the Red Sea during the coldest and hottest seasons.

Season	Time hours	Air temp oC	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	03.30 06.30	11·5	55	1·8		1·0	0·9	-3·3'
Summer Aug	13.30 16.00	33·2	43	3·0	680	1·0	0·9	+1·7"
	03.00 06.00	27·8	48	3·0		1·0	0·9	+0·2

' Lower Design Limit
" Upper Design Limit

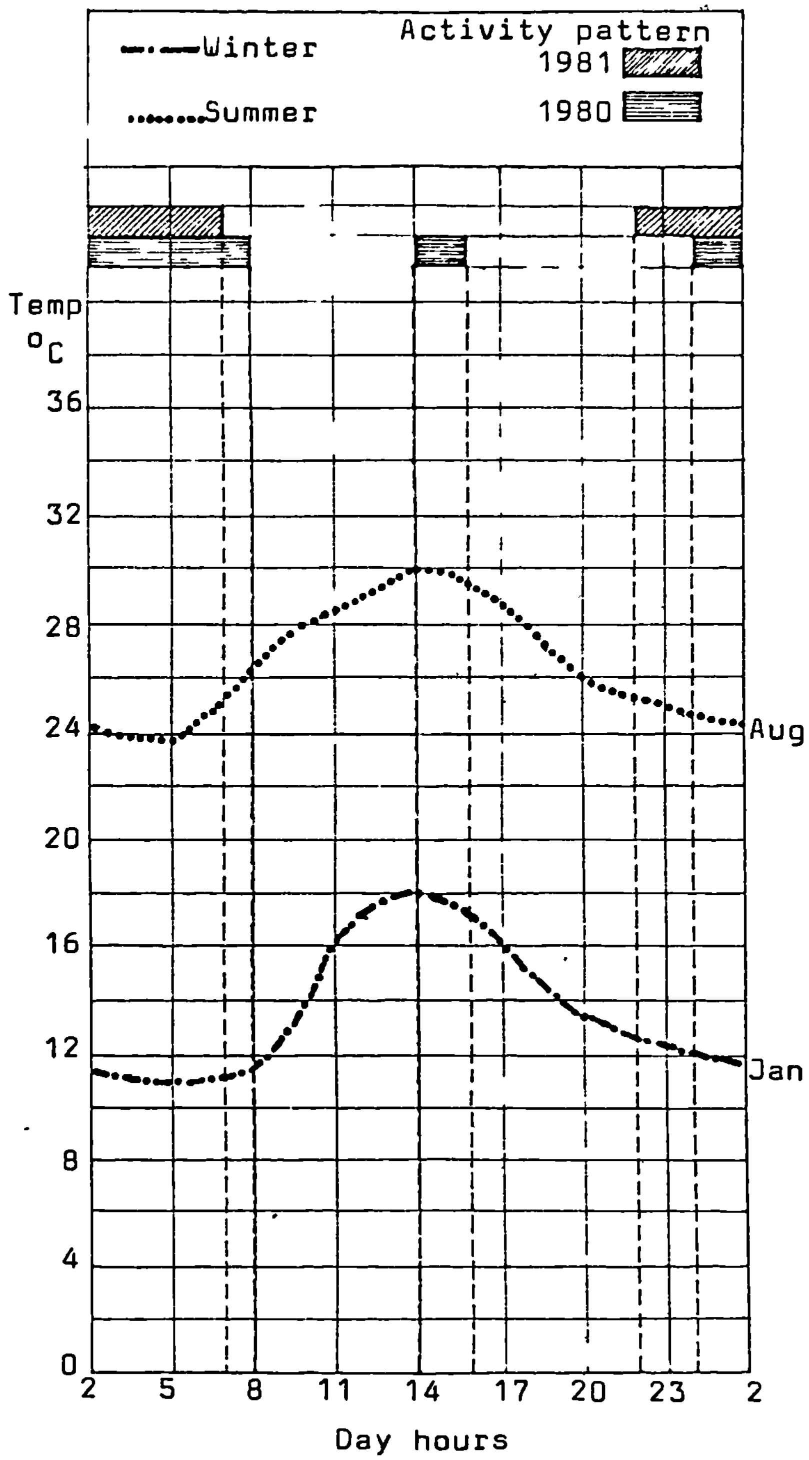

Figure (3.26) Mean monthly air temperature measured hourly. Red Sea, $27^{\circ}17'N$, $33^{\circ}48'E$.

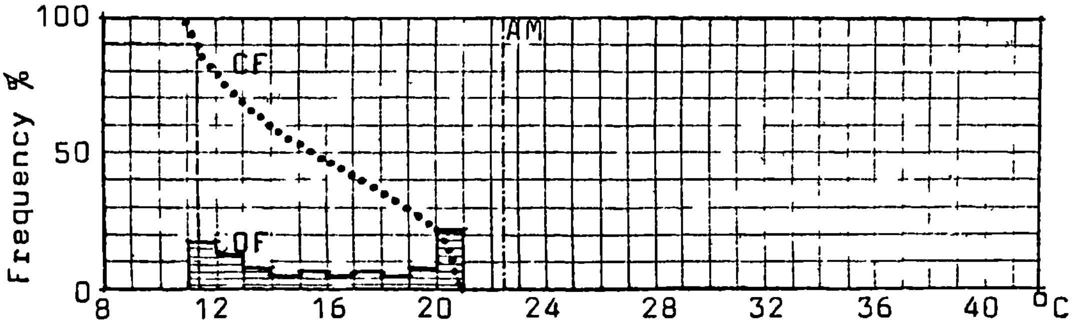

Figure (3.27a) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Red Sea, January.

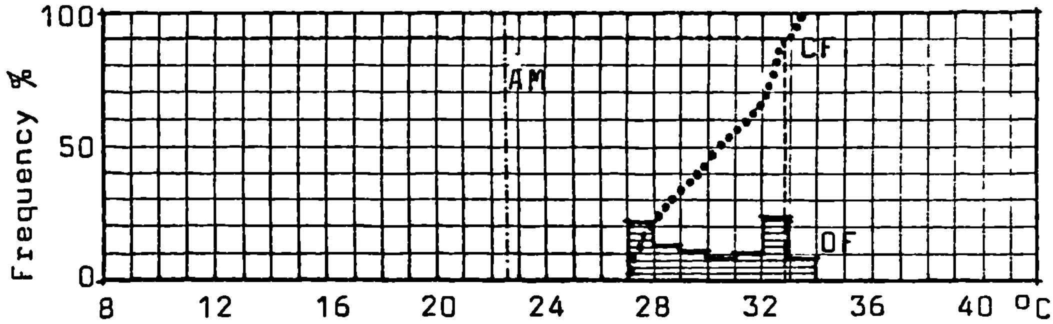

Figure (3.27b) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Red Sea, August.

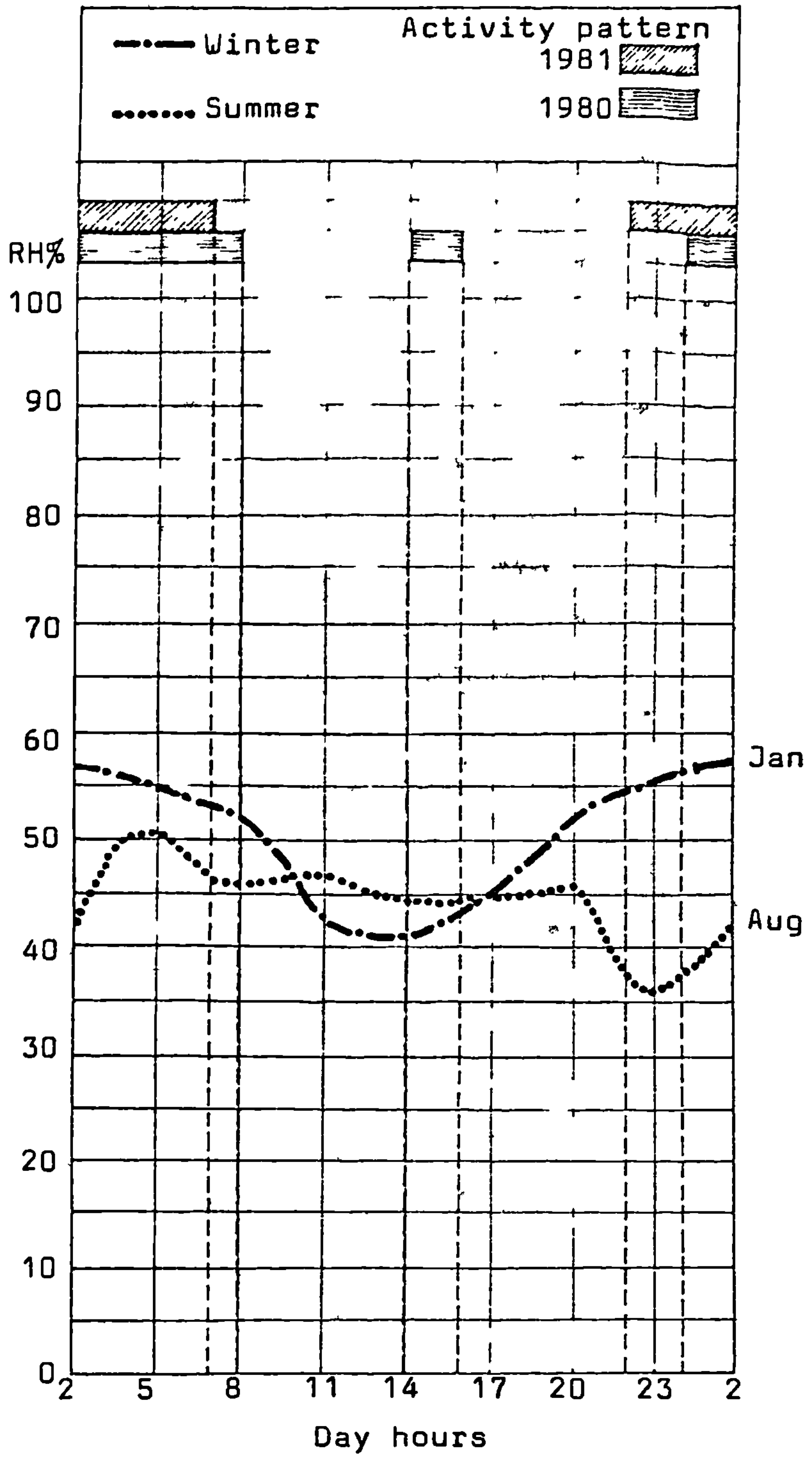

Figure (3.28) Mean monthly relative humidity measured hourly. Red Sea, 27°17'N, 33°48'E.

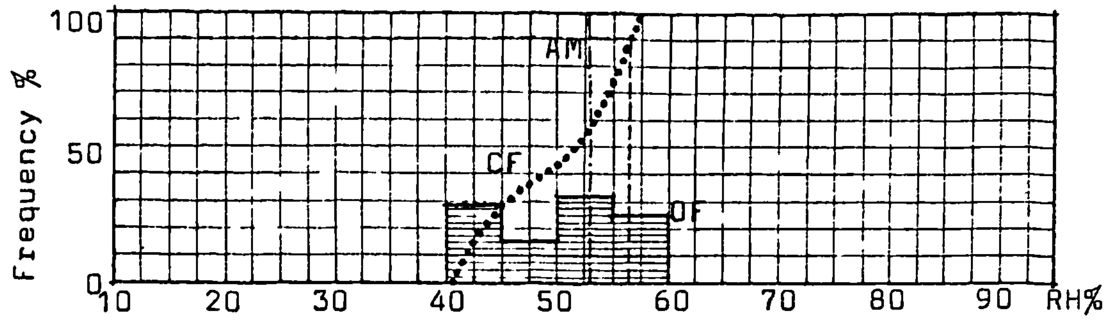

Figure (3.29a) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Red Sea, January.

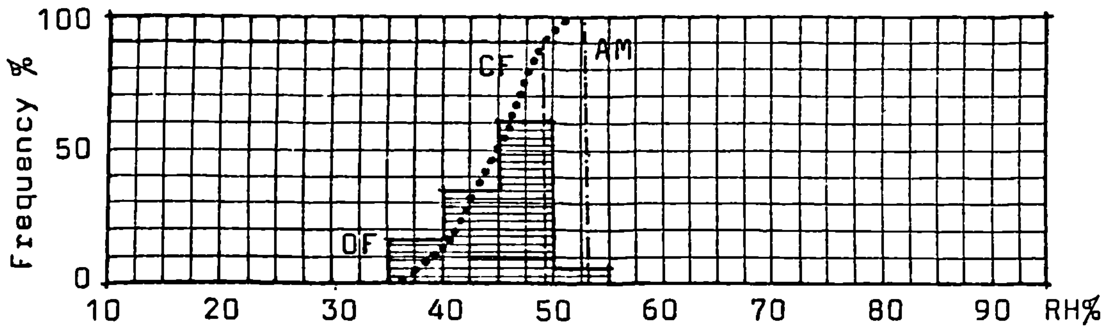

Figure (3.29b) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Red Sea, August..

Table (3.14) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in Upper Egypt during the coldest and hottest seasons.

Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m²	MET	clo	DISC
Winter Jan	04.00 07.00	10·4	50	1·8		1·0	0·9	-3·5 '
Summer Aug	14.30 17.00	40·2	11	2·2	701	1·0	0·9	+3·0 "
	04.00 06.30	28·2	28	2·7		1·0	0·9	-0·1

' Lower Design Limit

" Upper Design Limit - approximate value

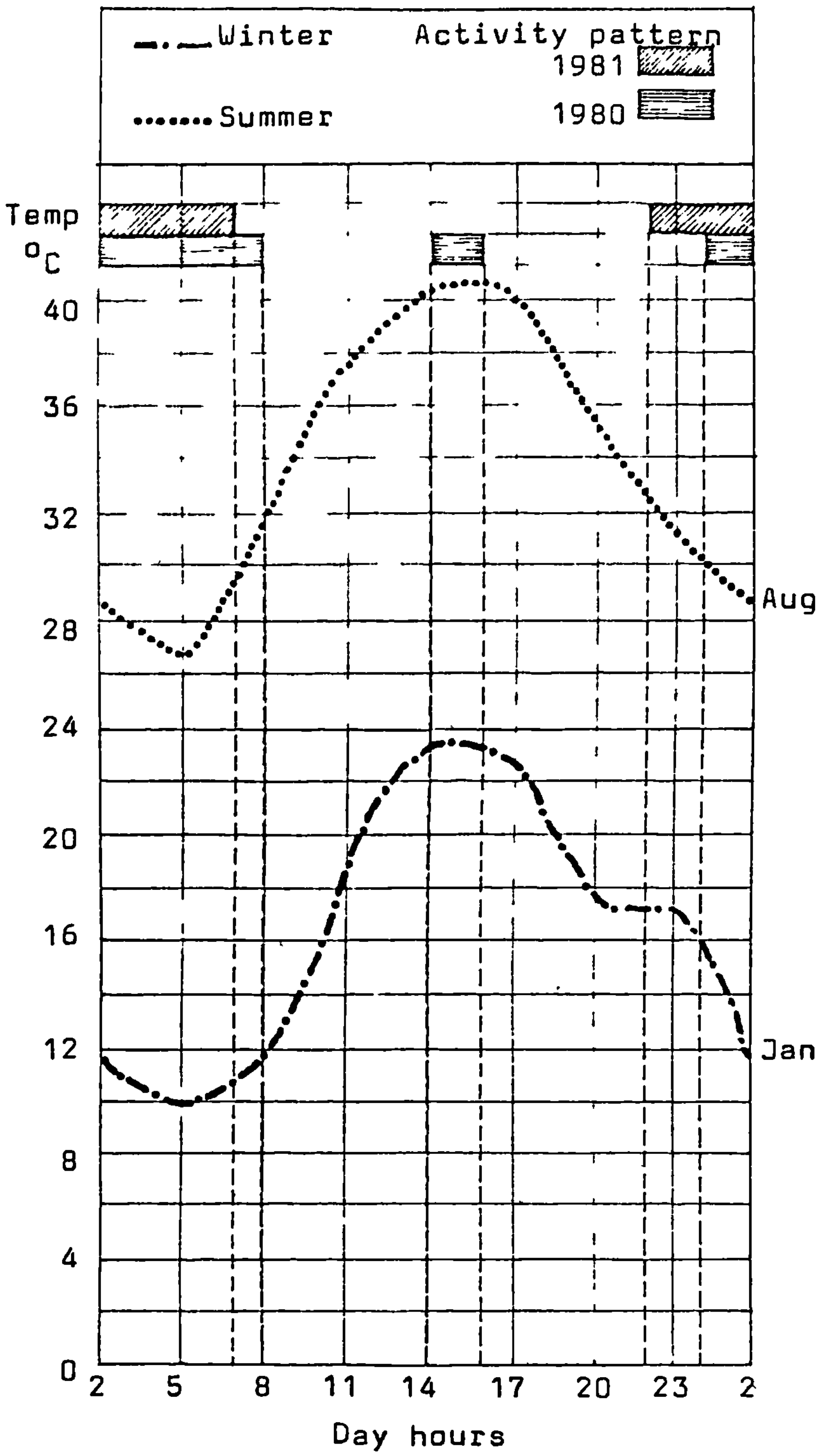

Figure (3.30) Mean monthly air temperature measured hourly. Upper Egypt, 24°02'N, 32°53'E.

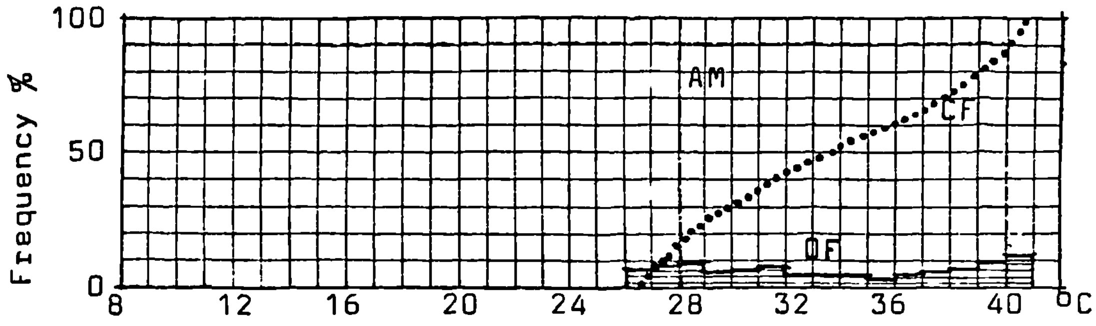

Figure (3.31b) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Upper Egypt, August.

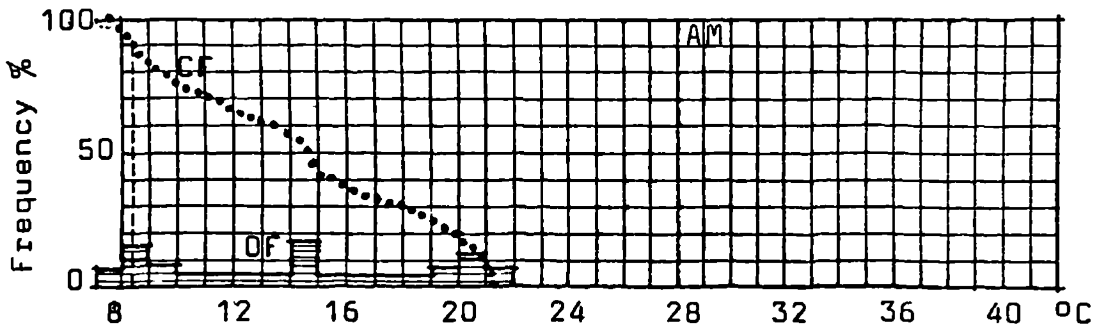

Figure (3.31a) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean (AM), Upper Egypt, January.

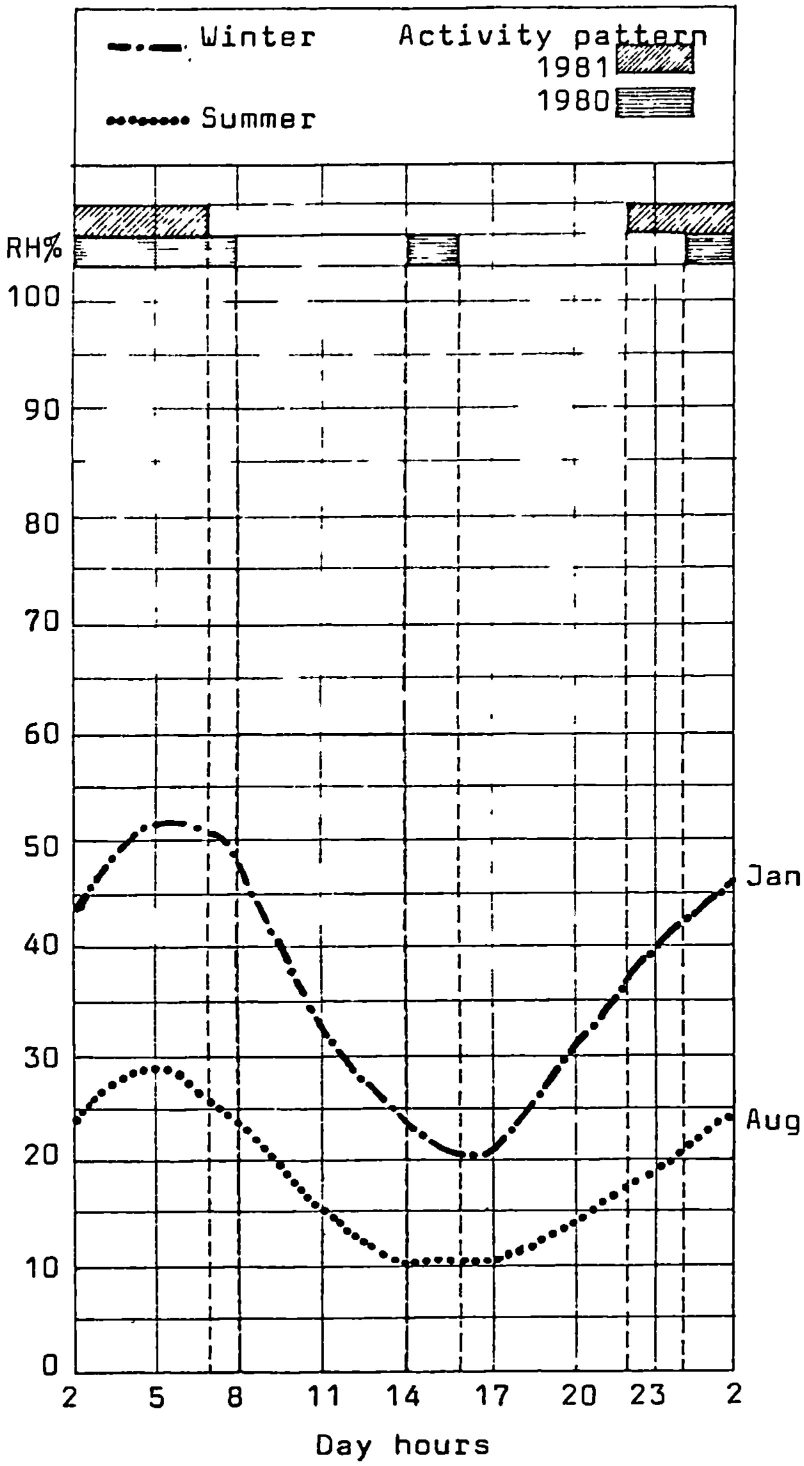

Figure (3.32) Mean monthly relative humidity measured hourly. Upper Egypt, 24°02'N, 32°53'E.

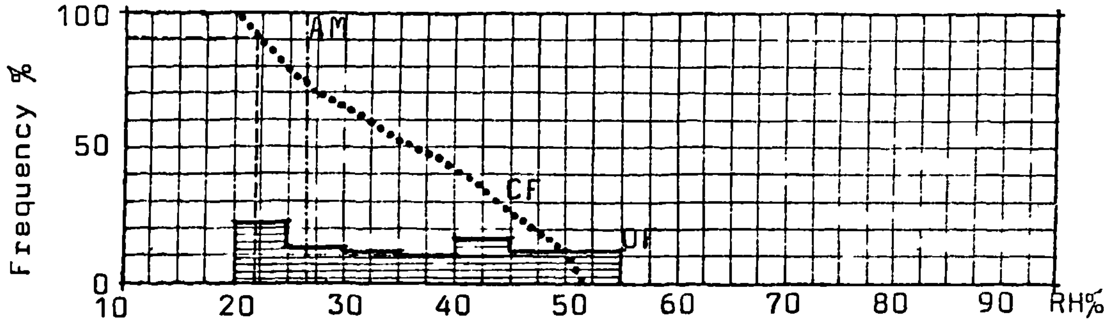

Figure (3.33a) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Upper Egypt, January.

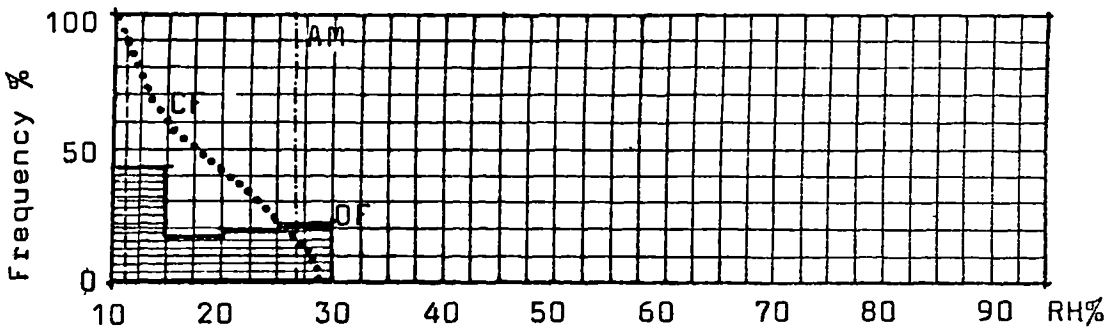

Figure (3.33b) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Upper Egypt, August.

Table (3.15) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in the Desert during the hottest and coldest seasons.

Season	Time hours	Air temp oC	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	04.00 07.00	6·3	70	2·0		1·0	0·9	-4·5 '
Summer Aug	14.30 17.00	35·5	20	1·8	1084	1·0	0·9	+3·0 "
	04.00 07.00	23·5	68	1·8		1·0	0·9	-0·5

' Lower Design Limit

" Upper Design Limit

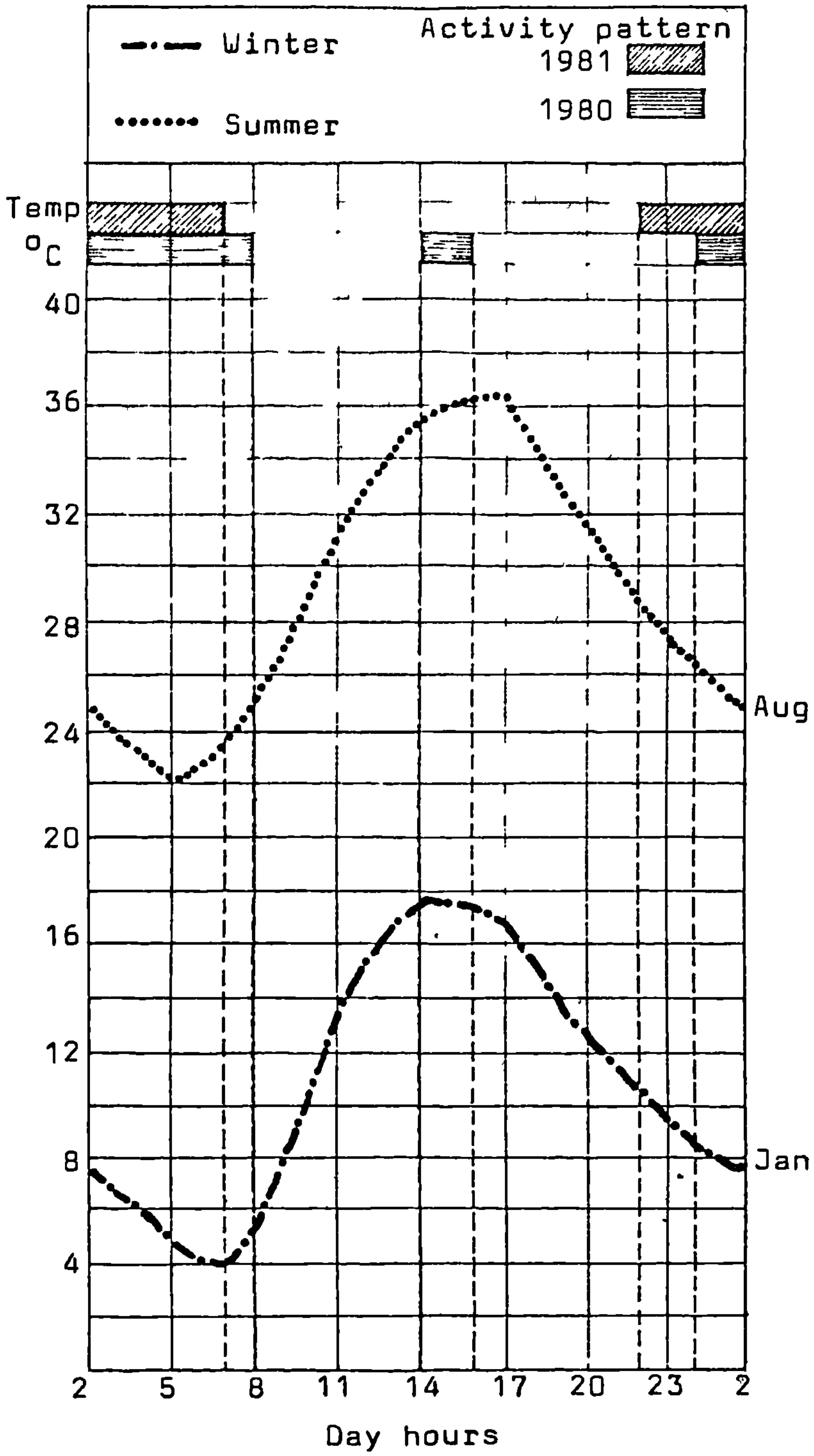

Figure (3.34) Mean monthly air temperature measured hourly. Desert, 29°12'N, 25°19'E.

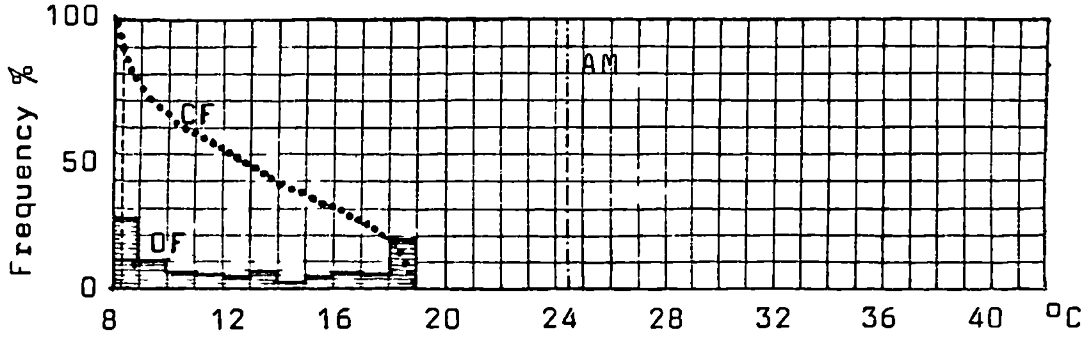

Figure (3.35a) Cumulative (CF) and occurrence (OF) frequencies for air temperature, related to annual mean(AM), Desert Region, January.

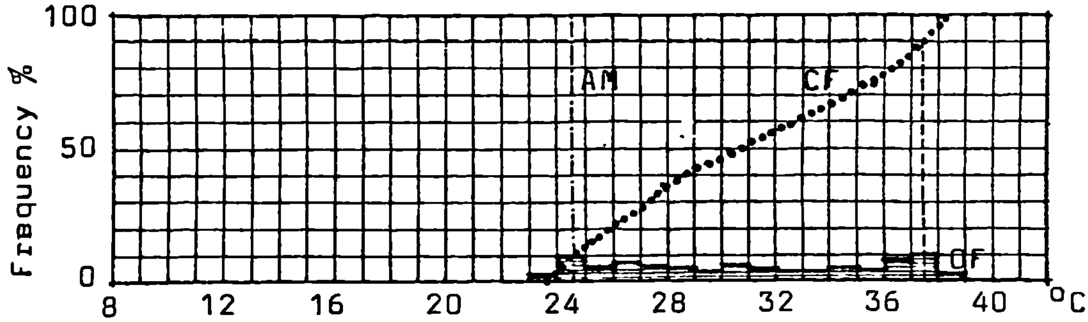

Figure (3.35b) Cumulative(CF) and occurrence (OF) frequencies for air temperature, related to annual mean(AM), Desert Region, August.

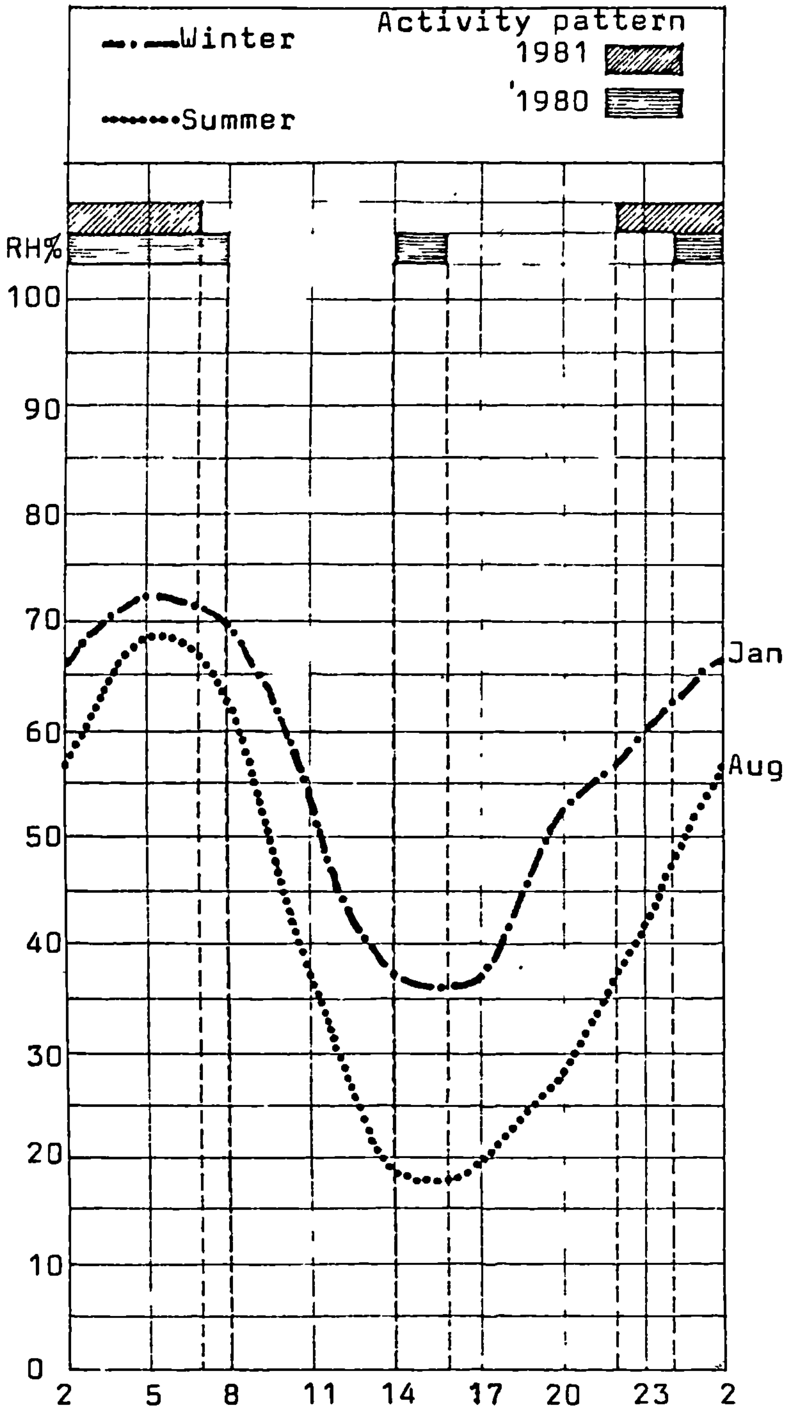

Figure (3.36) Mean monthly relative humidity measured hourly. Desert, 29°12'N, 25°19'E.

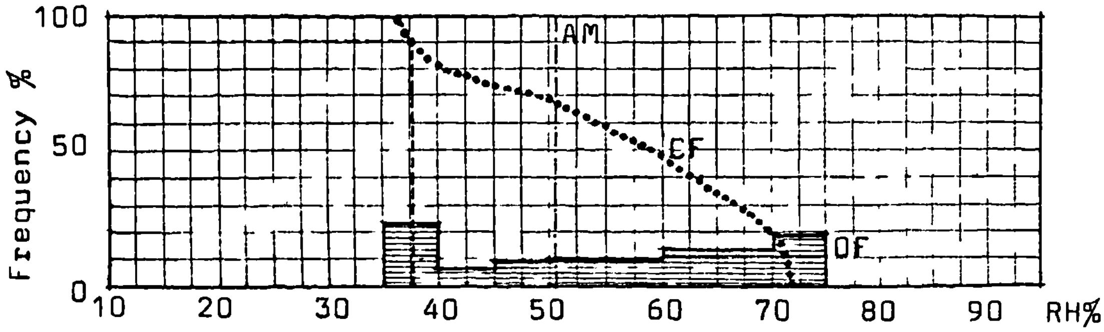

Figure (3.37a) Cumulative (CF) and occurrence (OF) frequencies for RH, related to annual mean (AM), Desert Region, January.

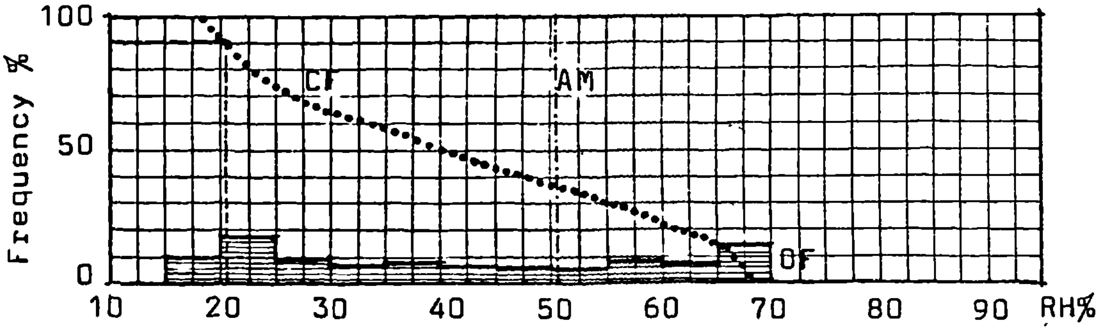

Figure (3.37b) Cumulative (CF) and occurrence (OF) frequenciec for RH, related to annual mean (AM), Desert Region, August.

which will give a discomfort level of +1:7 DISC. This upper design limit falls outside the optimum comfort zone.

In Upper Egypt the climatic conditions at 04.00 and 07.00 on a typical day of January gives the lower design limit with -3·5 DISC, while the upper limit is given by climatic conditions at 14.30 and 17.00 on a typical day in August, however this value falls outside the range of the SET index. The nearest conditions falling within the index range will give a value of +1·5 DISC.

For the Desert region the lower design limit has been taken as the environmental conditions at 04.00 and 07.00, which gives -4·5 DISC. The upper design limit has been taken as that of the climatic conditions at 14.00 and 17.00 which gives a discomfort level of +1:5 DISC.

3.4 Cairo Microclimates

The climatic conditions which affect human comfort in any of the Egyptian regions are subject to changes occurring within the region itself. This is due to the surrounding topography, exposure obstructions, including buildings, and the existing natural cover. As it is the aim of this research to establish a design approach for housing, the change in the climatic conditions and their effect on the living environment will need to be considered for the micro-climates, and Cairo micro-zones will be considered as an example.

Cairo is the capital, as well as the biggest city in Egypt with a population of about one quarter of the total Egyptian population. It has seven meteorological stations, fig.(3.38), these are: El-Khanka (30^{o} 13' N), Delta Barrage (30^{o} 11' N), Cairo (30^{o} 8' N), Almaza (30^{o} 6' N), Ezbeckieh (30^{o} 3' N), Giza (30^{o} 2' N) and Helwan (29^{o} 52' N), All

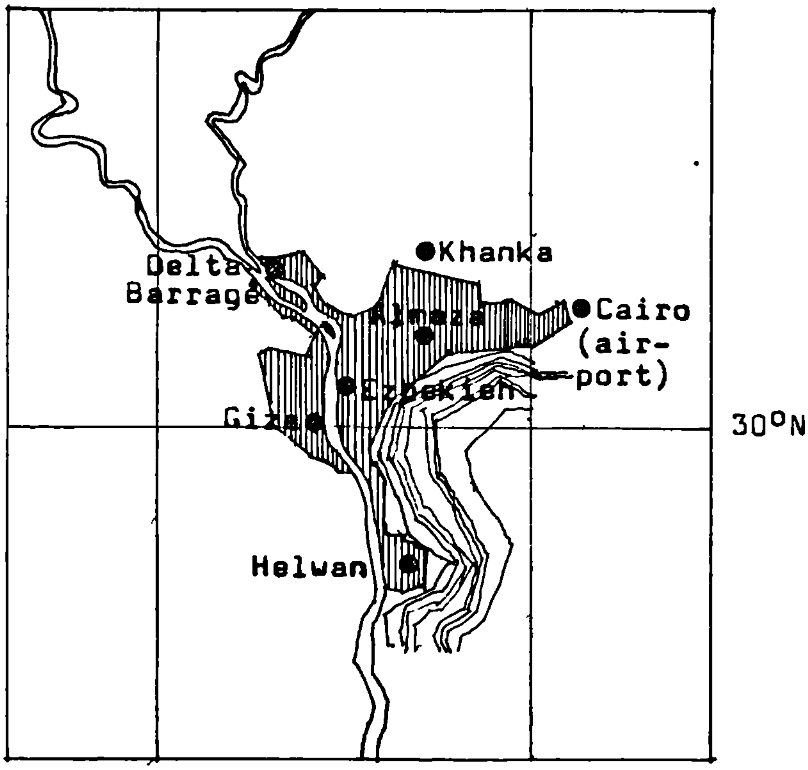

Figure (3.38) Meteorological stations within Greater Cairo.

of these stations have records for wind speed or direction. Each of these stations has different surroundings, and falls within a different zone of Greater Cairo. Thus, the Cairo region may be considered, for the purposes of this research, as seven micro-zones, each of which will be named after the meterological station located in it.

In the Greater Cairo region, air temperatures as high as 45°C have been recorded, the highest ever (48°C) was for Giza during May 1941. Temperatures higher than 40°C had been recorded in the months from April to October. The hottest day ever experienced in both El-Khanka and Cairo since records began was on 16 July 1947. In El-Khanka the air temperature was 45•1°C, while in Cairo it was 46•2°C. In the Delta Barrage, Ezbekieh and Helwan the hottest day ever experienced was 13 June 1933, in Delta Barrage the air temperature was 46•4°C, and in Helwan it was even higher at 47•5°C. In Almaza and Giza the hottest day was 9 May 1941 when the temperature was 47•3°C in Almaza.
As these record temperatures are extreme, and do not last for more than a few hours every 20 years or more, it would not be valid to consider them as bases for the design process. Instead the monthly mean minimum air temperature measured at 06.00, and the monthly mean maximum air temperature measured at 14.00 will be assumed as the lower and upper design limits. These are representative of approximately the lower and upper limits for 90% of a typical day of the month. The relative humidity has been recorded in a number of ways, the most important three of which are the maximum - measured at 06.00, the minimum - measured at 12.00, and the mean - measured at 18.00. The relative humidity at 06.00 on a typical day of the coldest month will be taken as the lower design limit, while that measured at 12.00 on a typical day of the hottest month will be assumed as the upper design limit. Solar radiation and wind will be considered on a similar basis.

El-Khanka meteorological station, located in the extreme northeast section of the Greater Cairo zone, may be considered as the hottest micro-zone from the temperature aspect. On the other hand, air temperatures of lower than 10°C have been recorded during the months from November to May. The lowest air temperature ever recorded in this area was -2·2°C on 7 February 1950. Such low temperatures are extremes and never continue for more than a few minutes occurring perhaps once in 20 years. The lowest monthly mean minimum air temperature is that of January, 6·2°C, while the highest monthly mean maximum in this micro-zone is for July and August, 36·1°C table (3.16). The monthly mean relative humidity in this area is about 61%, with the highest, 63%, occurring during August, September and December and the lowest, 56%, during April and May. Therefore the relative humidity lower design limit will be assumed as that of January (86%), while the upper limit will be either July (33%) or August (39%). Solar radiation as high as 800 W/m^2 at 12.00 occurs during the period from April till September with a maximum of 1059 W/m^2 for July. This will contribute at least 6·6°C to air temperature with a maximum of 7·8° in July, tables (3.9) and (3.16). The highest wind speed in this area is 1:3 m/s occurring in January, and the lowest is 0·5 m/s in July. These climatic conditions give discomfort values as low as -3·8 DISC in January, and as high as +2·6 DISC in August, table (3.17) and these will be assumed as the lower and upper design limits. Because of the arid nature of this region the and annual temperature range, as well as the daily variation in climatic conditions, can be very wide.

The Delta Barrage meteorological station is in the area where the delta of the Nile river starts. In this area air temperatures below freezing point were recorded during December 1936 and January and February 1950. Records for monthly mean minima as low as 6·3°C are common for January. The highest monthly mean maximum air temperature (35·6°C)

Table (3.16) The effect of the climatic elements on human comfort in Cairo Micro-zones.
Data from Taha (254). Solar radiation is estimated by a computer programme developed by the author.

Zone	Element		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
EL KHANKA (1)	AIR TEMP	6	6·2	7·0	9·2	11·8	15·6	17·8	19·4	19·9	18·0	16·2	12·2	8·1	6·2
		14	20·7	21·8	24·4	29·5	33·4	35·2	36·1	36·1	33·6	30·9	26·2	21·7	36·1
	RH	6	86	84	82	78	78	82	85	87	87	86	86	87	87
		12	38	38	36	34	34	36	33	39	39	38	38	39	33
	SR	°C	2·23	3·30	5·27	6·08	6·52	6·57	6·70	6·43	5·26	3·05	1·33	1·01	6·70
		W/m^2	167	329	534	681	774	784	814	754	532	246	97	71	814
	WIND	$\overline{V}$	1·3	0·9	1·5	1·5	1·1	0·8	0·5	0·7	0·7	0·6	0·9	1·1	1·5
		D	E	SW	NE	NE	NE	NE	NE	NE	NE	NE	E	E	NE
	DISC	6	-3·8	-3·6	-3·5	-3·4	-1·7	-1·1	-0·7	-0·5	-1·1	-1·7	-2·5	-3·4	-3·8
		14	-0·3	+0·1	+0·2	+0·7	+1·8	+2·1	+2·2	+2·6	+1·8	+1·0	+0·2	-0·4	+2·6
DELTA BARRAGE (2)	AIR TEMP	6	6·3	6·9	8·6	11·2	14·9	17·6	19·3	19·9	18·4	16·1	12·5	8·3	6·3
		14	19·9	21·3	23·9	28·4	32·4	34·5	35·6	34·6	32·0	30·3	25·9	21·5	35·6
	RH	6	78	75	69	66	62	66	72	73	76	76	79	76	79
		12	42	41	37	36	34	36	38	39	42	42	43	42	34
	SR	°C	2·42	3·96	5·28	6·17	6·56	6·65	6·78	6·53	5·38	3·26	1·55	1·12	6·78
		W/m^2	184	336	536	699	783	804	833	775	552	268	109	78	833
	WIND	$\overline{V}$	2·2	2·0	1·9	1·6	1·3	0·8	1·1	1·0	1·0	1·1	1·5	1·8	2·2
		D	SW	SW	NW	N	N	N	N	N	N	N	N	NW	SW
	DISC	6	-4·4	-4·3	-4·1	-3·5	-2·7	-1·3	-0·7	-0·6	-1·0	-1·7	-3·2	-4·1	-4·4
		14	-1·0	-0·4	+0·2	+0·7	+1·3	+1·8	+2·5	+2·1	+1·6	+1·0	+0·1	-0·9	+2·5
CAIRO (3)	AIR TEMP	6	8·6	9·1	11·3	13·9	17·4	19·9	21·5	21·6	19·[illegible]	17·9	13·9	10·4	8·6
		14	19·1	20·7	23·7	28·2	32·4	34·5	35·4	34·8	32·3	29·8	25·1	20·7	35·4
	RH	6	79	75	69	64	59	64	69	75	77	77	81	85	85
		12	39	37	35	32	28	32	35	37	39	39	41	43	28
	SR	°C	2·44	4·04	5·38	6·16	6·62	6·58	6·63	6·30	5·17	3·31	2·01	1·78	6·63
		W/m^2	186	258	553	696	795	787	798	726	518	273	147	136	798
	WIND	$\overline{V}$	3·4	3·6	3·8	4·0	3·9	3·5	2·5	2·6	2·9	2·9	3·1	3·0	4·0
		D	SE	NE	SW	NW	NW	NW	SW	SW	NW	NW	NW	NW	NW
	DISC	6	-4·3	-4·3	-3·9	-3·3	-2·5	-1·8	-0·8	-0·7	-1·3	-2·0	-2·8	-3·6	-4·3
		14	-1·2	-0·8	+0·1	+0·4	+0·7	+1·2	+1·6	+1·5	+1·1	+0·6	0·0	-0·9	+1·6
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

Station	Variable		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
ALMAZA (4)	AIR TEMP	6	8·6	9·3	11·3	14·0	17·7	20·2	21·8	22·0	20·1	17·8	14·2	10·4	8·6
		14	19·4	21·0	23·7	28·3	33·2	34·5	35·6	34·9	32·2	30·2	25·6	20·8	35·6
	RH	6	77	73	69	60	57	64	72	76	80	79	81	80	81
		14	39	37	35	30	29	32	36	38	40	39	41	40	29
	SR	°C	2·11	3·62	5·24	6·18	6·55	6·68	6·72	6·34	5·19	3·09	1·23	0·44	6·72
		W/m²	156	388	528	700	780	811	819	733	522	250	86	66	819
	WIND	$\overline{V}$	4·3	4·1	4·5	4·6	4·4	3·7	3·4	3·6	3·8	4·0	3·9	3·9	4·6
		D	SE	NW	NW	NW	NW	NW	W	W	NW	NW	NW	NW	NW
	DISC	6	-4·6	-4·3	-3·8	-3·3	-2·5	-1·8	-0·8	-1·1	-1·8	-2·4	-3·1	-4·0	-4·6
		14	-1·5	-0·8	+0·1	+0·4	+0·9	+1·1	+1·4	+1·3	+0·8	+0·4	-0·2	-1·6	+1·4
EZBEKIEH (5)	AIR TEMP	6	7·8	8·6	10·8	13·7	17·3	20·1	21·9	22·0	20·1	17·7	14·1	9·8	7·8
		14	19·8	21·6	24·5	28·6	32·8	35·2	35·9	35·1	32·7	30·6	26·4	21·4	35·9
	RH	6	75	70	67	62	57	63	70	73	75	75	77	77	77
		14	43	38	34	30	27	29	32	36	41	40	45	47	27
	SR	°C	2·61	4·08	5·48	6·19	6·61	6·58	6·63	6·33	5·21	3·82	2·01	1·87	6·63
		W/m²	202	364	569	703	793	788	799	732	525	331	148	135	799
	WIND	$\overline{V}$					NO WIND	DATA	RECORDS						
		D													
	DISC	6	-4·6	-4·1	-3·6	-3·0	-2·1	-1·4	-0·8	-0·8	-1·3	-2·0	-2·9	-3·8	-4·6
		14	-0·9	-0·3	+0·2	+0·5	+1·0	+1·3	+1·5	+1·4	+1·2	+0·7	+0·2	-0·7	+1·5
GIZA (6)	AIR TEMP	6	6·1	6·6	8·7	11·7	15·6	18·6	20·5	20·5	18·4	16·1	12·2	8·1	6·1
		14	20·2	21·7	24·4	28·7	32·7	34·8	35·8	35·0	32·4	30·6	26·2	21·6	35·8
	RH	6	80	78	72	70	66	67	67	66	69	73	76	80	80
		14	43	38	34	28	25	29	30	35	40	38	43	46	25
	SR	°C	2·61	4·08	5·48	6·19	6·61	6·58	6·63	6·33	5·21	3·82	2·01	1·87	6·63
		W/m²	202	364	569	703	793	788	799	732	525	331	148	135	799
	WIND	$\overline{V}$	1·8	2·0	2·3	2·5	2·6	2·4	2·3	2·1	2·0	1·9	1·8	1·5	2·6
		D	NW	NW	N	N	N	N	N	N	N	N	N	N	N
	DISC	6	-4·7	-4·5	-4·1	-3·4	-2·5	-1·8	-1·2	-1·4	-1·8	-2·4	-3·3	-4·2	-4·7
		14	-0·9	-0·2	+0·2	+0·6	+0·9	+1·3	+1·4	+1·5	+1·1	+0·6	+0·2	-0·5	+1·5
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

Ezbekieh DISC values are approximate due to the missing wind data; Giza is the nearest site to Ezbekieh, hence its wind data is applied instead.

Station	Element		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	
HELWAN (7)	AIR TEMP	6	8·6	9·4	11·4	14·4	18·1	19·5	21·5	21·8	20·3	18·6	14·9	10·6	8·6
		14	18·8	20·6	23·8	28·3	32·6	34·5	35·3	34·9	32·3	30·1	25·2	20·3	35·3
	RH	6	67	64	59	56	48	57	67	69	70	67	69	68	70
		14	40	34	27	22	22	21	24	27	32	32	36	42	21
	SR	°C	2·62	4·09	5·40	6·15	6·60	6·49	6·55	6·20	5·04	3·13	2·20	1·76	6·60
		W/m^2	203	365	556	694	792	768	780	704	498	254	165	126	792
	WIND	$\overline{V}$	3·5	4·0	4·6	5·1	5·6	5·4	4·9	4·8	5·0	4·9	4·2	3·4	5·6
		D	N	N	N	N	N	N	NW	N	N	N	N	N	N
	DISC	6	-4·5	-4·3	-3·8	-3·2	-2·3	-2·0	-1·4	-1·1	-1·7	-2·2	-3·0	-3·6	-4·5
		14	-1·4	-0·7	+0·1	+0·4	+0·7	+0·8	+1·0	+0·9	+0·7	+0·4	-0·1	-0·1	+1·0
			JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	

List of Terms:

Air Temperature in °Centigrade		°C
Relative Humidity (RH) as %		
Solar Radiation (SR)	Intensity at 14.00	W/m^2
	Contribution to air temperature	°C
Wind Mean Velocity ($\overline{V}$)		m/s
Direction (D)		

Table (3.17) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in El-Khanka during the coldest and hottest seasons.

Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	06.00	6·2	86	1·3		1·0	0·9	-3·8 '
Summer Jul	14.00	36·1	33	0·5	1059	1·0	0·9	+2·3
	14.00	36·1	39	0·7	990	1·0	0·9	+2·6 "

' Lower Design Limit

" Upper Design Limit

occurs during July. The annual mean relative humidity in the Delta Barrage is 56% with the second highest maximum of 78% in January, while the July record of 38% is the third lowest. The total actual to total possible hours of sunshine is over 80% in June, July and October, and over 70% for the period from March to November. The lowest figure, 66%, occurs during January. The highest wind speed in this area is 2·2 m/s in January, while the lowest of 0·8 m/s is in June, with July recorded as 1·1 m/s. The climatic conditions prevailing at 06.00 on a typical day of January, with a discomfort value of -4·4 DISC will be assumed as the lower design limit, while July climatic conditions of +2·5 DISC will be taken as the upper design limit, table (3.18).

The prevailing climatic conditions on a typical day of the coldest and hottest months in Cairo, Almaza, Ezbekieh, Giza and Helwan have been analysed on the same basis as those of El-Khanka and the Delta Barrage, and the lower and upper limits are illustrated in table (3.19).

In Cairo zone January climatic conditions at 06.00 give a discomfort value as low as -4·3 DISC, and these will be assumed as the lower design limit, while the conditions of July, with a discomfort value of +1·6 DISC, will be taken as the upper limit. The climatic conditions during January in Almaza, Giza and Helwan give discomfort values of -4·6 DISC, -4·7 DISC, and -4·0 DISC respectively, and these will be taken as the lower design limits for these zones, while their upper design limits are +1·4 DISC, +1·5 DISC and +1·0 DISC respectively.

Table (3.18) The lower and upper design limits for at least 90% of the day as induced by the climatic conditiond in Delta Barrage during the coldest and hottest seasons.

Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m^2	MET	clo	DISC
Winter Jan	06.00	6·3	78	2·2		1·0	0·9	-4·4'
Summer Jul	14.00	35·6	38	1·1	1076	1·0	0·9	+2·5"

' Lower Design Limit
" Upper Design Limit

Table (3.19) The lower and upper design limits for at least 90% of the day as induced by the climatic conditions in Cairo, Almaza, Ezbekieh, Giza and Helwan during the coldest and hottest seasons.

Region	Season	Time hours	Air temp °C	RH %	Wind m/s	Radiation W/m2	MET	clo	DISC
Cairo	Winter Jan	06.00	8·6	79	3·4		1·0	0·9	-4·3'
	Summer Jul	14.00	35·4	35	3·0	1050	1·0	0·9	+1·6"
Almaza	Winter Jan	06.00	8·6	77	4·3		1·0	0·9	-4·6'
	Summer Jul	14.00	35·6	36	3·4	1067	1·0	0·9	+1·4"
Ezbekieh	Winter Jan	06.00	7·8	75	1·8		1·0	0·9	-4·6'
	Summer Jul	14.00	35·9	32	2·3	799	1·0	0·9	+1·5"
Giza	Winter Jan	06.00	6·1	80	1·8		1·0	0·9	-4·7'
	Summer Aug	14.00	35·8	30	2·3	1047	1·0	0·9	+1·5"
Helwan	Winter Jan	06.00	8·6	67	3·5		1·0	0·9	-4·5'
	Summer Jul	14.00	35·3	24	4·9	1031	1·0	0·9	+1·0"

' Lower Design Limit " Upper Design Limit

3.5 Summary of Climatic Design Considerations for Egypt

Wind speeds are measured in the meteorological stations at free stream, hence they may be reduced in the vicinity of the built up area due to the change in the nature of the land cover. Further reduction will be due to the physical configuration of the buildings, the opening and space partitions, as well as the angle of incidence. These factors will be considered in detail in Chapter 4. The effect of the change in wind speed on the level of human comfort in the Egyptian regions is illustrated in table (3.20). The proposed climatic design limits in the Egyptian regions are summarized in the first column; the effect on human comfort of reducing air speed from 70% down to 0% (still air), as computed using the Standard Effective Temperature, are shown in the same table. These values illustrate the importance of controlled ventilation during winter and maximum ventilation during summer for improving the environmental qualities of the built space.

In the micro-zones of Greater Cairo wind speeds can differ from one area to another by as much as 4·5 m/s at any one time (254). This causes a difference of almost -1·0 DISC during winter, and +1·5 DISC in summer, figure (3.39). This shows how the local wind conditions can dramatically affect the performance of the prevailing climatic conditions.

Further modifications to the environment would be expected due to building materials, forms and orientation of buildings, and particularly groups of buildings. Grouping can radically affect the local climate in thier vicinity. This affects the uses to which tha spaces between buildings may be put. The design and location of playgrounds and distances from dwellings to services such as shops, libraries and public transport should take account of all these

region	season		100% wind		70% wind		50% wind		30% wind		0% wind	
			m/s	DISC	m/s	DISC	m/s	DISC	m/s	DISC	m/s	DISC
Lower Egypt	Winter	Jan	4·4	-4·0	3·1	-3·7	2·2	-3·3	1·3	-3·0	0·1	-2·1
	Summer	Aug	4·0	+1·6	2·8	+1·7	2·0	+1·8	1·2	+2·0	0·1	+3·2
Cairo Region	Winter	Jan	3·4	-3·8	2·4	-3·6	1·7	-3·4	1·0	-3·1	0·1	-2·1
	Summer	Aug	2·6	+1·5	1·8	+1·6	1·3	+1·7	0·8	+1·8	0·1	+2·8
Red Sea	Winter	Jan	1·8	-3·3	1·3	-3·1	0·9	-2·9	0·5	-2·6	0·1	-1·8
	Summer	Aug	3·0	+1·7	2·1	+1·8	1·5	+1·9	0·9	+2·0	0·1	+3·2
Upper Egypt	Winter	Jan	1·8	-3·5	1·3	+3·3	0·9	-3·1	0·5	-2·8	0·1	-2·3
	Summer	Aug	2·2	+1·5	1·5	+1·6	1·1	+1·6	0·7	+1·7'	0·1	+2·5"
The Desert	Winter	Jan	2·0	-4·5	1·4	-4·2	1·0	-3·9	0·6	-3·6	0·1	-2·8
	Summer	Aug	1·8	+1·5	1·3	+1·6	0·9	+1·7	0·5	+1·8	0·1	+2·7

' Approximate values for conditions outside the range of the SET

" Exceeds the maximum sweat rate expected for a healthy person, possible risk of heat stroke.

Table (3.20) Wind effect on the proposed climatic limits in Egypt.

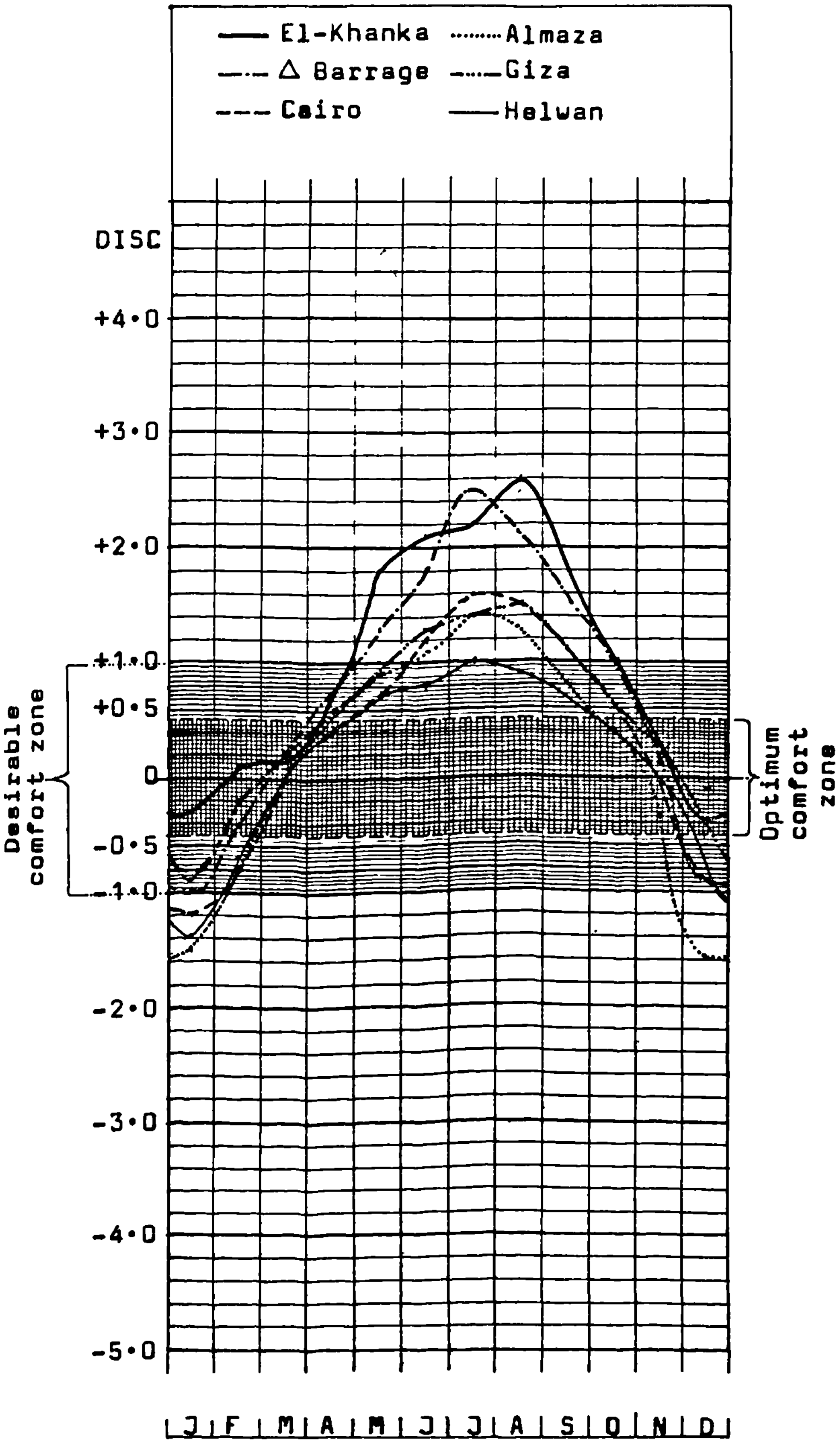

Figure (3.39) The deviation of the environmental conditions in Cairo micro-zones from the Optimum Comfort.

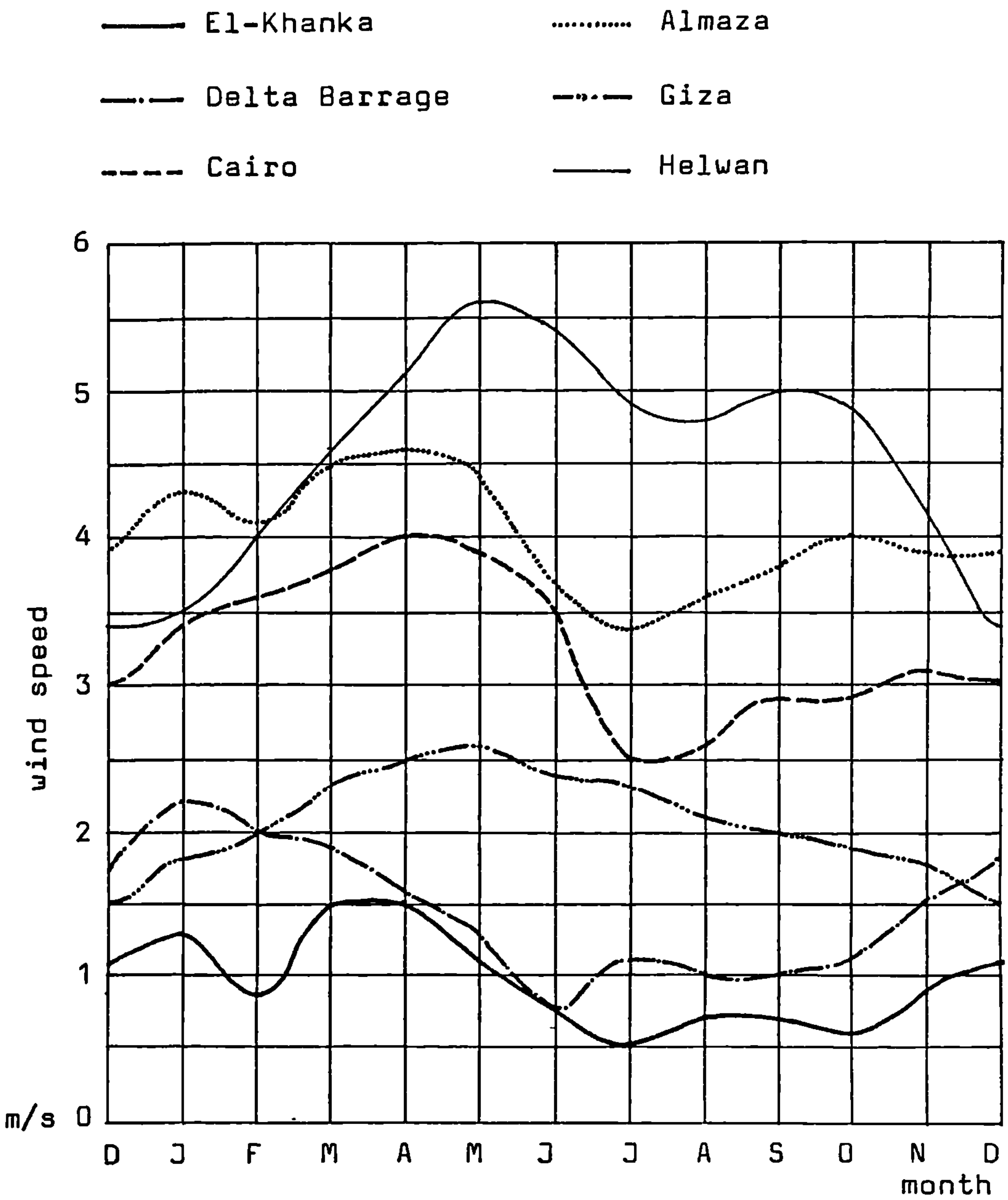

Figure (3.40) The variation in wind magnitude in Cairo micro-zones.

environmental factors. How often will it be possible to use these facilities without becoming uncomfortable? Which environmental factors will need reinforcement, and which will need to be eliminated? The quantitative answers to these questions may be achieved by a bio-climatic analysis based on the assessment of the integral effect of all the environmental factors, both climatic and human, as shown above.

Furthermore, the modifications needed to be made by means of building in order to create a built environment which satisfies the optimum human comfort can be assessed on the same basis. Form, orientation, fabric and building detail can be chosen and designed on the basis of this quantitative analysis. It is within the next Chapter that the analysis of the thermal stress impact on building forms and the part which ventilation plays in improving the built environment will be considered.

Chapter 4 : WIND FLOW PATTERNS :
Analysis of Wind Impact on Building Design

4.1 Wind Flow Patterns and Natural Ventilation

Wind, as one of the most important climatic elements affecting human beings, derives its energy from the sun. Large scale wind is caused by the Earth's pressure system which is the result of differential atmospheric heating. This temperature difference produces the basic north-south flow, while the rotation of the Earth generates east-west motion. However, though these forces govern the general atmospheric circulation, there are other important smaller mechanisms. The most significant of these is the diurnal temperature variation which is responsible for a large part of wind variation on comparatively still days, also for the sea-land breezes which can dominate the light wind climate of locations within a few kilometres of large bodies of water, due to the pressure reduction in air over land more than over sea on sunny days. This sort of pressure variation may also exist between large areas of vegetation and desert[1].

Wind might be of a destructive nature with dramatic effects as can be seen in the collapse of structures. Perhaps the most dramatic in this respect was the collapse of the Tay Railway Bridge in Scotland in 1879 which was due to wind loading (175), a subject that has gained recognition in structural consideration since then. In 1940 the Tacoma Narrows Bridge collapsed through aerodynamic instability which had not been considered in the structural analysis. More recently, wind damage in different parts of Britain

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1 This can be experienced in the cities of Upper Egypt, Luxor for example.

has been reported by Buller (57), Page (210) and Wilson (266). Page (210) reasoned the damage caused in Sheffield gales of 1962 to the gable roof loading, building forms and grouping[1].

The present state of knowledge on the subject of wind loading, after approximately a century of research, is that fairly comprehensive data are available on the static effects of wind and on the distribution of pressure over surfaces of buildings. The study of the dynamic effects of wind is still developing.

Less dramatic, though equally important, are the many environmental aspects of wind. Builders in the windswept places, as a general rule, take the least exposed sites[2], while in hot climates where natural ventilation has particular importance the reverse (ie greater exposure) is taken as a remedy against high temperatures and humidities. On the African shore of the Mediterranean cities like Alexandria show street patterns that channel the coolness of the sea breezes into their centres. In the old quarters of Cairo 'El-Kahira El-Fatimieh', builders of the last nine centuries, up to the beginning of the twentieth century, had used light latticework - 'Mashrabieh' - to let the slightest breezes into the house.

The environmental wind flow aspect is of special impottance to architects and urban designers. In cold climates the knowledge of wind flow around buildings will enable an estimation to be made of its qualitative (150) and quantitative effects on people near the ground in open spaces

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1 Page reported 101,000 private sector houses damaged due to wind in the Sheffield gales of 1962 and compared it with Glasgow wind damage that occurred on January 15th 1968 where chimney damage was very heavy.

2 In the Swiss Alps protection from cold winds is the motivation for the closeness (compact form) of the towns.

and around buildings. It will also provide a better means of controlling the performance of heating and ventilating systems, which are considerably affected by the local wind velocities near their inlets and outlets. Knowing the wind flow pattern around a building will enable a more accurate estimation of the effective U-value[1], and accordingly the neccessary protection from ths prevailing winter wind (247) or the desirable degree of exposure to summer wind. In addition, it will aid in the estimation of aerodynamic noise created by wind flow around buildings, and help in devising remedial action. It will also facilitate evaluating the possibilities for dispersal of airborne effluent in the vicinity of buildings.

Inside buildings, ventilation conditions have a direct effect on the human body through the physiological reactions to air motion, and an indirect effect through their influence on the temperature and humidity of the interior air, as well as the indoor surface temperature. The ventilation needs and their physiological effects will be considered in the following section.

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1 An increase in the effective U-value lowers the insulating properties by an amount (chill factor) dependent on the wind speed. Steadman (247) reports that a 9 m/s (20 mph) wind can double the heat load on a house normally exposed to 2·2 m/s (5 mph) wind speed.

4.2 Ventilation Requirements

Ventilation usually means the introduction of fresh air into an occupied space in order to remove any undesirable contaminants, or excess heat or moisture. However, satisfactory ventilation means much more than that. It should serve three distinct functions:

Firstly, to maintain the quality of air in the building above a certain minimum level by replacing indoor air, vitiated in the process of living and occupancy, by fresh outdoor air. This requirement may be termed Health Ventilation, and should be ensured under all climatic conditions.

Secondly, to provide thermal comfort by escalating heat loss from the body and preventing discomfort due to moist skin. Heat is lost from the body due to air motion by both convection and evaporation.

Thirdly, ventilation to cool the structural fabric of the building when the indoor temperature is above that of the outdoor air. This, along with removal of moisture from the air when the risk of condensation exists, can be termed Structural Ventilation (see Fig.(4.1)).

Each of the above functions has an important role to play in accordance with the climatic conditions prevailing for different seasons and regions. However, air movements involve air flows of varying magnitude and their satisfactory use sometimes calls for different design details. Unless the ventilation aspect is considered within the overall design concept to satisfy the occupants needs, unnecessary, and often expensive and less satisfactory, remedial solutions will have to be resorted to.

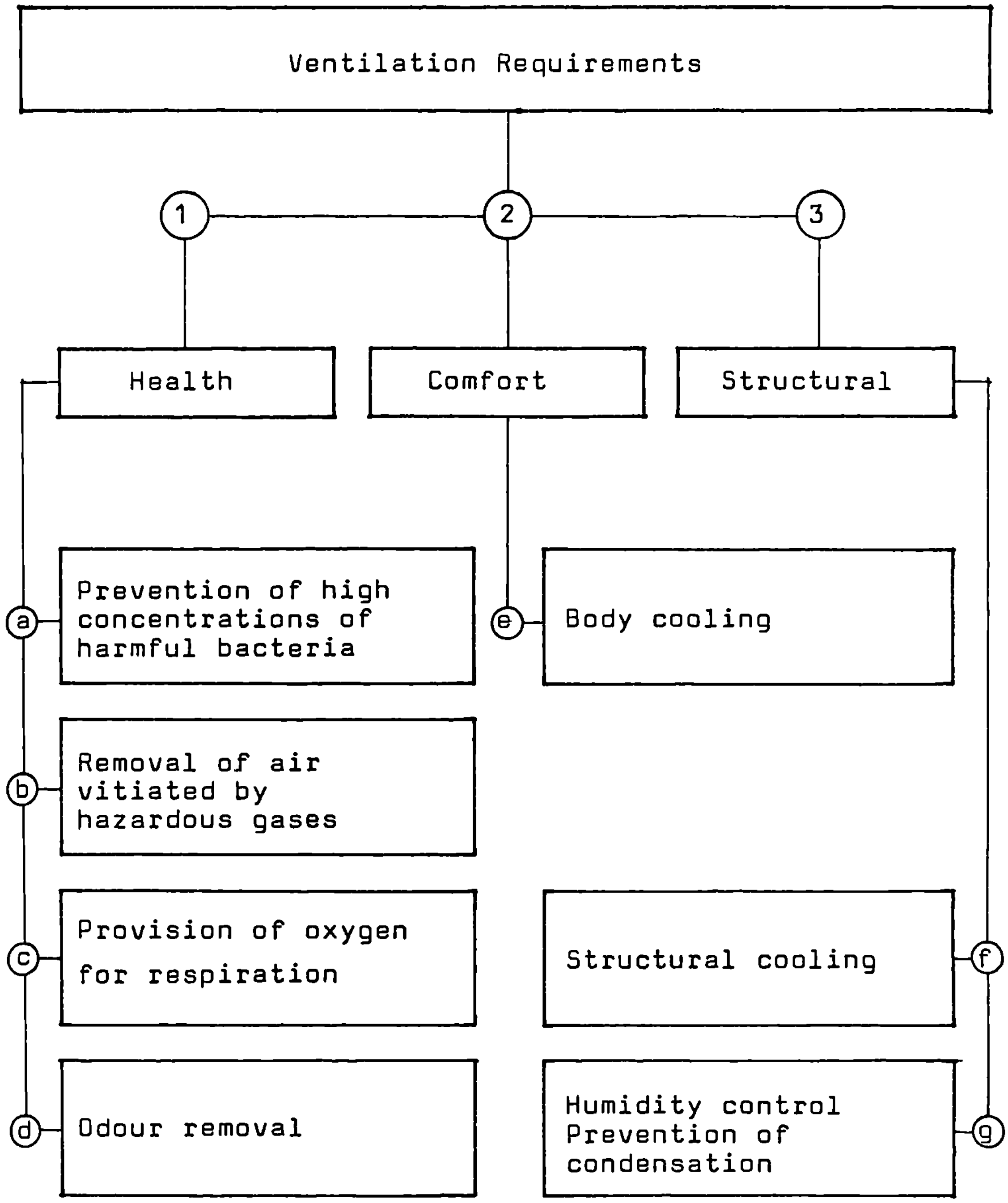

Figure (4.1) Ventilation requirements in the built environment.

4.2.1 Ventilation Requirements for a Healthy Environment

In all types of buildings ventilation is necessary if healthy conditions are to be maintained. This is termed health ventilation, and implies the prevention of high concentrations of harmful bacteria; the removal of air vitiated by hazardous gases and dust; the provision of the necessary oxygen for respiration; and the removal of disagreeable odours. Air outside buildings[1] is made up of a number of gases - on average dry air contains, by volume, 78·08% Nitrogen, 20·94% Oxygen, 0·03 to 0·04% Carbon Dioxide, 0·95% inert gases (mainly Argon), plus between 5 and 25 g/m^3 water vapour. However, both the composition and the quality of air inside buildings are affected by the living processes and activities. The air therefore contains many contaminants, and the function of ventilation involves their dilution and removal. The concentration of a contaminant in an occupied space depends on its rate of production, as well as the rate of ventilation. If these are known, then the concentration may be predicted as a function of time.

The concentration of a contaminant c at time t is given by the dilution equation[2]:

$$c = ((Qc_i + q)/(Q + q))\ (1 - \exp(-(Q + q)t/V)) + c_o\exp(-(Q + q)t/V \quad (4\text{-}1)$$

---

1 In urban industrial areas the outdoor air may itself contain unacceptable levels of pollutants which will alter its composition, McIntyre (180).

2 Equation (4-1) assumes constant air temperature and perfect air mixing, so that the concentration c is uniform over the space, and consequently equal to the concentration in the exhaust air, (180), (165).

where V = space volume — l

Q = ventilating air input — l/s

q = contaminant rate of production in the space — l/s

c_i = concentration of contaminant in incoming air — g/m^3

c_o = concentration of contaminant in the space at time t = 0 — g/m^3

Equilibrium concentration (c_e), which will be established after a long period, is given by the equilibrium equation:

$$c_e = (Qc_i + q)/(Q + q) \qquad (4\text{-}2)$$

If the source of a contaminant in the occupied space is localised, then it may be possible to extract the contaminated air locally and thus minimize its mixing with the rest of the air. However, the quality of the inside air and the nature of the contaminants in it will determine which of the four factors (a to d) in fig.(4.1) will govern the health ventilation process.

a) Harmful Bacteria Concentration - When a great number of people gather in a small space, the prevention of high concentrations of harmful bacteria becomes essential. This is to reduce the risk of infection by airborne micro-organisms. However, studies and results of work in this direction have been far from conclusive and do not yet offer any suitable basis for establishing minimum ventilation standards (245).

b) Air Vitiated by Hazardous Gases - In practice decisions must be made as to what constitutes an unacceptable level of contamination. This is of especial importance in industrial environmental control where standards for permitted concentrations are subject to revision as more information becomes available. The concept most widely used is that of the Threshold Limit Value

(TLV), the maximum airborne concentration of a substance to which it is believed that nearly all workers may be repeatedly exposed, day after day, without adverse effect. Three categories of TLV are defined:

1) Threshold Limit Value - Time Weighted Average (TLV-TWA) - the time-weighted average concentration for a normal 8-hour workday, or 40-hour workweek, to which nearly all workers may be repeatedly exposed day after day without effect.
2) Threshold Limit Value - Short Term Exposure Limit (TLV-STEL) - maximum concentration to which workers can be exposed for periods of up to 15 minutes.
3) Threshold Limit Value - Ceiling (TLV-C) - the concentration that should not be exceeded, even instantaneously.

While the above limits apply to work places, some people may be spending all day at home where they may be exposed to a contaminant for longer periods than that of the TLV-TWA. Thus, lower levels of TLV should be taken as the basis for health ventilation within the living space.

Carbon monoxide (CO), a colourless and odourless gas, is toxic[1] at low concentrations. In Britain more than 1000 people died in 1963 from accidental poisoning by carbon monoxide contained in town-gas. Since then town-gas has been phased out and replaced by natural gas which does not contain carbon monoxide. In dwellings with hot water and heating appliances equipped with proper air flues, contamination of air by such

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1 When carbon monoxide is breathed in it is absorbed in preferenceto oxygen by haemoglobin in the blood to form carboxyhaemoglobin (COHb). The haemoglobin is thus no longer available for oxygen transport and the victim will suffocate.

hazardous gases is not likely to be significant. However, in the houses of the lower income groups in many of the less developed countries, the risk is high. This is usually from the use of open fires and paraffin cookers in badly ventilated spaces. Straaten (249) reports experimental work in South Africa that showed the production of carbon monoxide from open braziers was far in excess of the safe limit for health[1]. He also observed that normal ventilation openings in houses are not a reliable means of controlling carbon monoxide concentrations, and suggested the provision of special hoods and flues for removing the fumes from braziers, or the installation of suitable heating appliances. Garages, long tunnels and workshops are places with similar problems since carbon monoxide, lead vapour and dust are among the products of internal combustion engines as well as other industrial processes.

The TLV-TWA of 50 parts per million for carbon monoxide is the limit for exposure during an industrial working week of 40 hours. The level of continuous exposure should be less than the TLV-TWA and the Environmental Protection Agency recommends a maximum concentration for the general population of 9 parts per million. McIntyre (180) reports a study of the emissions of carbon monoxide (CO) from gas cookers where the pilot light emission was 100 mg/h, and a fresh air input ventilation would be needed at a rate of about 2·5 l/s. The oven emission rate could be up to 4000 mg/h, but as it is not used continuously manual ventilation may be considered adequate.

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1 The safe carbon monoxide limit is generally accepted to be 50 parts per million of air for inhalation over extended periods (TLV-TWA).

Another contaminant which is an important constituent of the irritating atmosphere of some cities is ozone (O_3). This is a highly reactive form of oxygen, produced by a complex series of reactions involving nitrogen oxides and hydrocarbons from motor car exhausts, plus sunlight. It can be produced by high-voltage electric discharges or electric sparks in motors, but its highly reactive nature ensures that it decays rapidly[1]. Ozone is unlikely to be a problem indoors.

Carbon dioxide (CO_2), a pollutant produced through the respiration process, is not toxic except at high concentrations[2]; expired air contains approximately 4% CO_2. The ratio of carbon dioxide expired to volume of oxygen used in the lungs, which is known as the respiratory quotient, is not unity, as might be expected, but varies between 0·7 and 1·0, as the rate of carbon dioxide production is dependent on the metabolic rate. However, for the purpose of this study, carbon dioxide may be considered to be produced at a fairly standard rate. Carbon dioxide concentration gives a general indication of the adequacy of ventilation in an occupied space, fig.(4.2).

If the only source of production of carbon dioxide is respiration, the ventilation rate is proportional to the number of people and their activity, and it is believed that for normal indoor activity 1 litre/s per person is a convenient ventilation rate. The effect

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1 Decay occurs fastest on organic surfaces, so in a room with many furnishings it will not last for more than a few minutes.

2 The TLV-TWA recommended by the American Conference of Governmental Industrial Hygienists is 0·5%, and this is usually taken as the upper limit when designing the ventilation of occupied spaces.

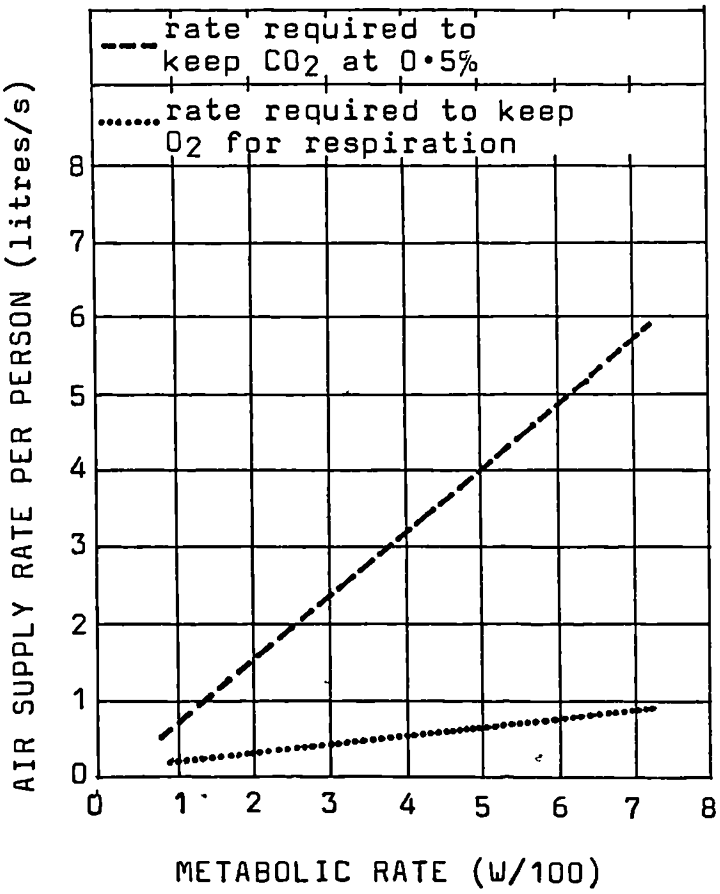

Figure (4.2) Air supply rate for respiration compared to air required for CO_2 of 0•5% concentration. After Harris-Bass (137).

of CO_2 on the respiration process will be discussed in the next section.

Tobacco smoke is the most common source of pollution indoors. The link between lung cancer and smoking is well established, however the health effect on the nonsmoker (passive smoker) has not yet been established but the irritation and odour produced by tobacco smoking indoors needs to be reduced by ventilation. In practice, the most sensitive factors governing ventilation rate are poor visibility, objectionable smell and eye irritation. The effect of smoke on visibility only occurs in a large space with long sightlines. Reaction to odour and eye irritation differ with length of exposure. The effect of smell reduces with time, while that of irritation grows stronger with increased exposure time and once eye irritation has started it is regarded as the most unpleasant effect of tobacco smoke. Dry climates as well as low humidity levels increase the amount of smoke emitted per cigarette and the sensitivity of people to odours. A dilution limit of 10 m^3/cigarette is suggested to dilute the carbon monoxide produced by tobacco, fig.(4.3). However, a figure of 20 m^3/cigarette is suggested[1] to guarantee acceptable odour level to sensitive passive smokers. Figure (4.3) gives a comparison of the effects of tobacco smoke at increasing dilutions. Translating this into ventilation rate, in Britain a rate of 7 litres/second per person is required[2]. In small spaces ventilation must be

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1 The American Nation Air Quality Standard (AQS) for ambient air is 75 $\mu g/m^3$ average over the year, and 250 $\mu g/m^3$ for the worst day of the year; 20 m^3/cigarette is a reasonable compromise suggested by McIntyre (180).

2 Yearly cigarette consumption is suggested to be 1·3 cigarettes/hour per person (day = 13 hours) in Britain, and double that in USA.

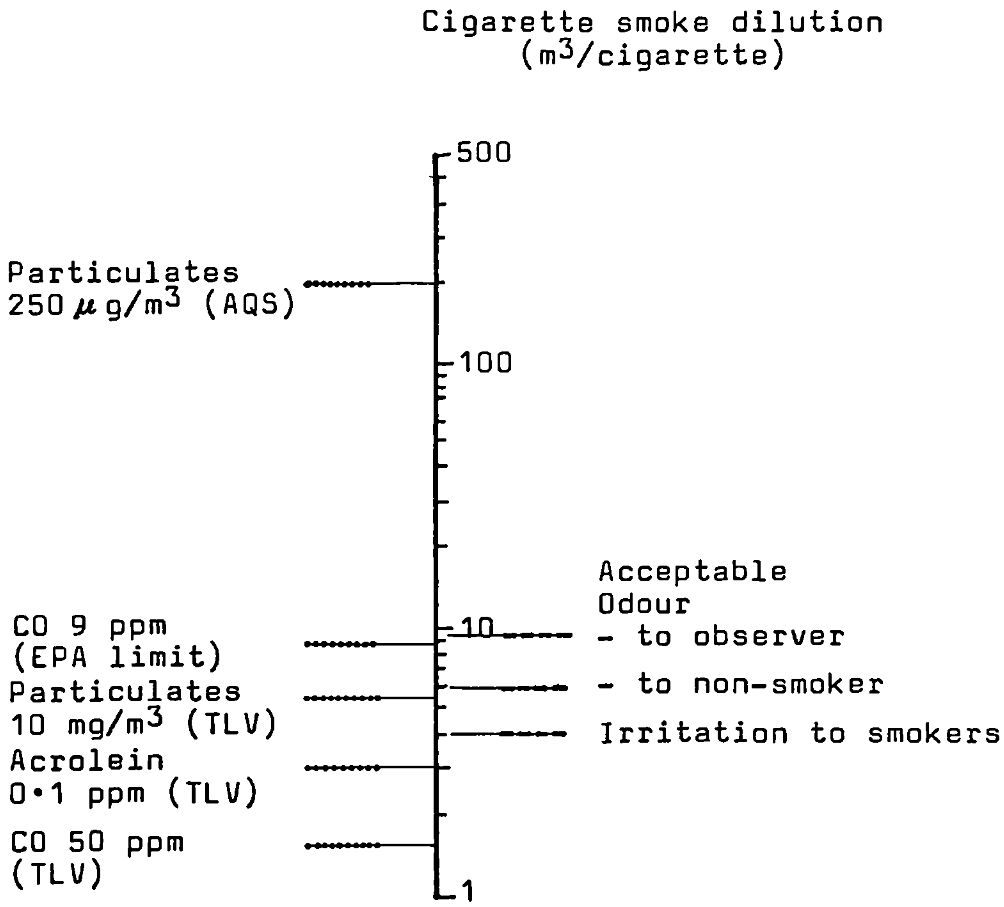

Figure (4.3) A comparison of the effects of tobacco smoke at increasing dilutions. (180).

calculated on this basis, but in large buildings/ spaces without smoking restrictions smoker ratio may be assumed as 50% of occupants and consequently the ventilation rate may be reduced.

On these grounds it follows tnat dilution and removal of air polluted by hazardous contaminants should be ensured by either mechanical or natural ventilation[1], or by both.

c) Oxygen For Respiration - The provision of oxygen [illegible] relates to metabolic rate of the occupants, 1 litre of oxygen inhaled provides on average 20·6 kJ (5·8 W/h, 5 kcal) of energy. Expired air contains about 16·3% oxygen, 4% carbon dioxide and 79·7% nitrogen and other gases discharged by the body, plus about 45 g/m^3 water vapour (saturated air at 37^oC). Thus, net oxygen intake is approximately 4·6%. McIntyre suggested that the metabolic rate ($M\ W/m^2$) per unit body surface area for someone with a normal mixed diet, corresponding to breathing at a ventilation rate of V litres/s can be estimated as:

$$M = 20{,}600 \cdot V(O_i - O_e)/S$$

where O_e = fraction of oxygen in expired air

O_i = fraction of oxygen in inspired air

S = body surface area, which can be taken as $2{\cdot}15\ m^2$

For the purpose of this section the variation between

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1 In workshops, with openings properly distributed to ensure cross ventilation, the recommended minimum ventilation rates, in naturally ventilated rooms, are 5 l/s (600 ft^3/h) in nonsmoking areas, and 12 l/s (1500 ft^3/h) in areas where smoking is allowed (158).

people of differing body size and the amount of oxygen in expired air can be considered negligible. So the ventilation rate[1] required to maintain the necessary oxygen concentration can be expressed as a function of the metabolic rate M as follows:

$$\dot{V} = 1{\cdot}06 \times 10^{-3} \times MS \quad l/s$$
$$= 3{\cdot}8 \times MS \quad l/h$$
$$= 8{\cdot}17 \times M \quad l/h \text{ per person}$$

Other living processes, such as cooking, also release carbon dioxide into the atmosphere. The combustion of one cubic metre of gas for cooking produces approximately 0•6 m^3 carbon dioxide.

Nevertheless, in buildings for normal occupancy, such as residential, commercial, educational and industrial establishments, fluctuations in oxygen and carbon dioxide content of the air are of little significance. In practice the concentration of carbon dioxide and the reduction of oxygen fluctuations in buildings are rarely above 1% (122). Therefore, the concentrations of carbon dioxide and oxygen are not suitable as direct criteria for the specification of ventilation requirements, but as air quality is a product of many factors, carbon dioxide concentration can be used to give an indirect indication of the levels of other factors governing the ventilation process which would be more difficult to assess quantitatively.

A level of 0•2% CO_2 is suggested by Givoni (122) as a basis for specifying a minimum ventilation rate in

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1 Givoni (122) suggested the amount of air needed (l/h man) to provide oxygen in a living space to be 4•25 times the metabolic rate M in kcal/h; ie 4•93 times the metabolic rate M in W/m^2.

residential, office and school buildings. In France the maximum permissible concentration of carbon dioxide is 0·1%, while in the USA it is 0·5%[1], which, for the purpose of this section, will be considered acceptable.

In general, the desirable rate of fresh air supply depends upon the purpose for which as internal space is utilized, the number of occupants and, to an extent, their individual activities. The British Standard code of practice (39) recommended some minimum rates of ventilation (fresh air supply) for occupied rooms in dwellings which may also be applicable in hot climates, such as Upper Egypt where fresh air may contain dust and the dwelling openings are shuttered during the day. Table (4.1) shows the minimum recommended ventilation rates in various spaces within dwellings.

The volume of fresh air required per person, q_v in m^3/h, to keep the indoor carbon dioxide concentration below 0·5% is given by the equation:

$$q_v = q \times 100/(0{\cdot}5 - 0{\cdot}05)$$
$$= q/0{\cdot}0045 \quad m^3/h \text{ per person} \qquad (4\text{-}3)$$

where q = volume of CO_2 (m^3/h) produced per person

Therefore, for sedentary activity, when carbon dioxide production is approximately 0·018 m^3/h, q_v will be 4 m^3/h per person. However air supplies according to these values are not enough to eliminate odours and industrial contaminants. To satisfy the minimum requirement of odour level for a healthy environment,

1 IHVE recommended this percentage as the maximum permissible concentration for Britain (148).

Table (4.1) Some minimum rates of fresh air supply for occupied spaces in dwellings (39).

Space	Minimum rate of air change
Bathrooms & WC	2 air changes/h
Halls & passages	2 air changes/h
Kitchens & catering for not more than 6 people	56 m^3/h
Living rooms & bedrooms offering:	
8•5 m^3 per person	20 m^3/h per person
11•5 m^3 per person	17 m^3/h per person
14•5 m^3 per person	12 m^3/h per person

Table (4.2) Numerical scale for odour level as established by Consolozio and Pecara (122).

Odour level	Scale No.
No odour	0
Odour barely perceptible	1
Definite odour, but not objectionable	2
Strong objectionable odour	3
Very strong, disagreeable & yet tolerable	4
Overpowering, unbearable	5

the ventilation process usually involves a greater air supply than would be indicated by oxygen and carbon dioxide fluctuation levels.

d) Ventilation For Odour Removal - Odour level is not a health factor in the strict sense, but does contribute to a feeling of comfort and sense of well-being. When people have control over ventilation in a building with openable windows the decision to ventilate is mainly taken because of objectionable odours, moisture content, or high temperature in summer. Odours are not easily quantified, however, the nose is extremely sensitive and can detect the presence of some substances at concentrations below the level at which they can be measured by the most sensitive equipment. In dealing with odours a distinction should be made between the quantitative aspects and the qualitative. Within a building odours may arise from sources such as occupants, cooking and smoking, and this depends on a number of factors, among which are number of occupants, their hygienic status and their living habits. It is usual to require a decrease in disagreeable odours to a level that would not be noticeable, however people vary greatly in sensitivity to odours. For instance, females are generally more sensitive to smells than males and this varies throughout the menstrual cycle (194). Odour sensitivity increases with the elevation of ambient air temperature and decreases with the fall in relative humidity. Intensity of perception of an odour can depend on much more than just the concentration of the odourant. Adaptation to odour occurs rapidly and a person staying in a space where there is a gradual elevation in the level of an odour is less sensitive to this change than others just entering that space. Adaptation can occur after a few minutes, and a much higher odour level can be tolerated.

In the case of internally located kitchens, bathrooms and lavatories, ventilation is of great importance. The concentration of gas emitted at a constant rate can be computed using equation (4-1), while the minimum recommended air extract rate from a WC or from a bathroom with no WC is 20 m^3/h; from a bathroom with a WC it is 40 m^3/h. The extracted air should discharge directly to the outside air and the system should be separated from any other ventilation circuit (49). Body odours have been found to be unstable, tending to disappear with time even without any air changes. In this respect they are less stable than odours from chemicals. Givoni reports a scale for odour levels, established by Consolozio and Pecara (table 4.2), on the basis of the effect of ventilation rate.

There is a good correlation between instantaneous and residual odour impressions. The score of instantaneous odour impression increased arithmetically with the logarithm of air supply. The strength of body odours in an unventilated room has been reported as falling from very objectionable to perceptible but not objectionable within 5 minutes, while chemical odours took 6 to 7 hours to undergo such a reduction. The intensity of cigarette smell increased during the first three hours and then started decreasing slowly, reaching the odour barely perceptible level of 1 (table 4.2) after 17 to 18 hours, depending on the number of cigarettes smoked (122).

In most cases, providing for the effects of odours and contaminants with the highest required ventilation will usually mean that other aspects of health ventilation are also satisfied, ie individual health ventilation requirements are not additive.

4.2.2 Ventilation Requirements for Thermal Comfort

Air moving over the human body can be felt either by its cooling effect or by its physical pressure. The relative importance of these effects depends upon air speed, and the difference between skin temperature and ambient air temperature. The effects of air movement inside a building are listed in table (4.3). Physical effects are hardly evident below 0•20 m/s, and air movement of 1•00 m/s can be taken as the upper limit for office work.

In warm climates the ambient air temperature is relatively high and in many cases is higher than that required for comfort. In such circumstances air movement should be employed to provide thermal comfort in the indoor environment. This involves the prevention of discomfort due to excess heat stress and skin wetness. Excess heat stress on any object inside the built environment can be removed by radiation, conduction,convection or evaporation. The importance of each of these depends on the nature of the object and its relation to the surroundings. For body cooling of healthy people evaporation can be considered as the most important, and heat removal will depend on the evaporation rate, which is a function of ambient air temperature, humidity and air movement. When both air temperature and humidity are high, air movement becomes of great importance.

e) Air Movement for Body Cooling - The prevention of discomfort caused by skin wetness is usually achieved by evaporation. The production and evaporation of sweat is the body's most powerful temperature control mechanism. The phenomenon of sweating consists of two distinct elements, the physiological regulatory system (discussed in Chapter 2 section (2.4)) which controls sweat production, and the physical process of evapor-

Table (4.3) Air movement effects on the human body indoors, (100, 180, 206).

Air speed m/s	Mechanical effect	Effect on man in domestic environment	Ambient air temperature °C, Dry skin 15	Dry skin 20	Dry skin 25	Dry skin 30	Moist 30
			Cooling effect °C				
0·10	Still air.	May feel stuffy, rarely met in occupied rooms.	0	0	0	0	0
0·25	Smoke from cigarette indicates movement.	Movement noticeable only at low air temp; speed of natural convective flow overhead.	2·0	1·3	0·8	0·5	0·7
0·50	Candle flame flickers, movement noticeable.	Feels fresh at comfort conditions, draughty at cool temps.	4·0	2·7	1·7	1·0	1·2
1·0	Constant awareness of air movement, loose papers may be moved.	Blows hair; pleasant when comfortable or warm; max limit for night comfort; equivalent to walking speed.	6·7	4·5	2·8	1·7	2·2
1·5	Draughty, loose papers blow.	Draughty at comfortable temps, max limit for desk work with loose papers.	8·5	5·7	3·5	2·0	3·3
2·0	Equivalent to a fast walking speed.	Acceptable only in very hot, humid conditions when no other relief is available.	10·0	6·7	4·0	2·3	4·2
Over 2·0	Annoying	Work and health affected; requires corrective measures.					

ation of sweat from the surface of the skin.

Liquid sweat is composed of large numbers of molecules in a continual state of vibration, bumping against one another in all directions. The energy of the molecules actually determines the violence with which they collide, and the higher the temperature the more violent will be the vibration. The molecules at the surface of the sweat have only the air above to collide with, and many of them escape into the surrounding air. If this air is stationary and its temperature is constant it will soon reach its saturation point after which it will not accept any more vapour. This may be described in terms of vapour pressure. Saturation point will be reached when the vapour pressure of the air/vapour mix is the same as that of the sweat. If the surrounding layer of moist air is continuously removed by air movement evaporation will be accelerated, bringing the surrounding environment nearer to the optimum comfort conditions. It is interesting to note that every gram of water evaporated consumes in the process about 0·58 kcal[1]. When the body loses water by evaporation heat is taken from both the body itself and the ambient air. The ratio of heat removed from the body by evaporation is defined as the physical efficiency of sweat evaporation (E/E_{max})[2]. When sweat forms a thick layer on the body it builds up higher resistance to heat flow from the body to the evaporation surface, and a certain amount of heat will be taken from the air,

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1 This is the latent heat for vaporization.
2 This is sometimes referred to as the cooling efficiency of sweating which can be expressed as a function of the ratio between the overall heat stress operating on the body (metabolic heat production ± heat exchanged with the surrounding environment), which is equal to the required evaporative cooling (E), and the potential evaporative cooling of the environment (E_{max}).

thus reducing the actual cooling received on the body. However, the effectiveness of air movement depends mainly on the degree of discomfort due to excess heat stress, and air movement is most effective in aiding body cooling by evaporation, particularly under humid conditions. The lower the air vapour pressure, and the higher the air velocity, the greater the evaporative cooling potential.

When high ventilation rates are involved, as may be necessary for thermal comfort in hot climates, the patterns of air velocity will not be homogeneous, and noticeable variations will occur within the ventilated space. Accordingly, ventilation should be specified in terms of air velocity rather than rates of air supply. A turbulent flow at low rate might yield higher average velocities in the occupied area of a room than a laminar flow at a higher rate of change, but directed just below the ceiling. This relation between flow rate and velocity depends also on the geometry of the space, its internal design and divisions, and the location of openings. It is possible to compute from the SET index (see Appendix 3) either the air velocity required for comfort under different conditions of temperature, solar radiation, humidity, clothing and metabolic rate, or the velocity for ensuring minimum heat stress for any defined prevailing conditions. The potential body cooling by evaporation expected in the Cairo zone during the summer season is illustrated in table (4.4). The air velocity required to attain comfort increases in relation to air temperature. This is due to the fact that the same cooling effect must be obtained through a smaller temperature difference between a body and its environment. This relationship holds until air temperature and skin temperature are equal, that is, until air

Table 4.4 The influence of air movement on body cooling by evaporation expected during summer (August) in Cairo, as expressed by the DISC value of the SET.

mean wind speed m/s.	DISC value DISC	percent of actual prevailing wind %
5·00	+0·8	200
2·50	+1·5	100
1·75	+1·6	70
1·25	+1·7	50
0·75	+1·8	30
0·10	+2·8	0

The prevailing - air temperature = 35·4°C

relative humidity = 35%

solar radiation = 798 W/m^2

air speed = 2:50 m/s

temperature is 35°C (95°F)[1]. Although these factors determine the magnitude of the required velocity, this is only true as long as the air velocity required for preventing moist skin is lower than that causing maximum accepted convective heating.

4.2.3 Structural Ventilation

Structural ventilation is the supply of air movement to satisfy two important functions, firstly structural cooling and secondly humidity control. The ventilation of building space will reduce indoor temperature when there is a favourable difference in temperature between the outside and the inside air, ie the temperature inside is higher than that outside. The temperature difference may be due to a high diurnal range, heat gains from the exterior, internally generated heat gains, or a combination of all these factors. Moisture and humidity control by ventilation will prevent condensation on the structure's inner surface and allow any condensation to evaporate before the growth of lichens, moulds and similar organisms, which would consequently cause damage to finishes and structure, is encouraged.

f) Air Movement for Structural Cooling - Inside structures the excess heat liberated within occupied spaces, along with that gained through the various structural elements contribute greatly to thermal discomfort during the over-heated periods. Therefore, all excess heat in

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1. The effects of heat exchange between a body and the surrounding environment, by both evaporation and convection, will proceed in the same direction (providing for cooling) until the air temperature equals that of the skin. When ambient air temperature is higher than skin temperature the resultant effect of both convection and evaporation is their algebraic sum, and air movement will soon start heating rather than cooling the body.

the built environment should be removed. In unventilated spaces, indoor air temperature will attain that of the surrounding surfaces and may even exceed it by a few degrees at times. This is due, on the one hand, to the heat produced by the living processes, and on the other, to the very low heat capacity of air. The difference between indoor and outdoor air temperature is a function of the structure characteristics, and it will fluctuate mainly with changes in the indoor air temperature. The amplitude of fluctuation depends on the heat capacity of the structure, its thermal resistance and the pattern of external surface temperature. When the space is ventilated, fresh air entering will mix with and replace indoor air and heat will be exchanged with the inner surfaces of the structure. Heat exchange between air and the structure is mainly a function of the difference in air temperature between internal and external air (Δt), ventilation rate (q_v), and the thermal heat capacity of the air. The approximate rate at which heat is removed from the structure can be calculated by the formula (100):

$$Q_v = c_v \times q_v \times \Delta t \times k \qquad (W)$$

where:

Q_v = rate of heat gain or loss (W)

c_v = volumetric specific heat of air[1] (J/m^3 ^oC)

Δt = difference in temperature between internal and external air (^oC)

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1 Below one atmosphere pressure (1013 mb) the volumetric specific heat of the air at 0^oC is about 1310 J/m^3 ^oC while at 20^oC it is 1220 J/m^3 ^oC and at 30^oC it is about 1180, and this varies according to atmospheric pressure and relative humidity. A value of 1300 has been recommended for cold climates, and a value of 1200 for calculating heat loss in hot climates.

k = correction factor depending on the rate of air change

q_v = ventilation rate (m^3/s)
or (Vol of room x air changes/h)/3600

In the above equation the ventilation rate, q_v, is a function of air speed and it is possible to express it as follows:

$$q_v = A_o V_o$$

where:

A_o = area of outlet (m^2)

V_o = air velocity at the outlet (m^2/s)

Hence:

$$Q_v = c_v \times (A_o \times V_o) \times \Delta t \times k \qquad (4\text{-}4)$$

Alternatively the above equations can be rewritten:

$$q_v = Q_v/(c_v \times \Delta t \times k)$$

$$V_o = Q_v/(c_v \times A_o \times \Delta t \times k) \qquad (4\text{-}5)$$

Equation (4-5) will determine the ventilation needed to keep indoor air temperature within a given limit, determined by the difference in temperature Δt. During the overheated periods however, high rates of ventilation are required. The heat exchange between the building surfaces and the air is proportionally less than it would be at low ventilation rates. The surface resistance has a greater effect in reducing the transfer of heat to air, and the mixing of warmer and cooler air is incomplete, although with turbulent flow[1] caused

1 The proportion of heat exchanged between turbulent air inside the building and the surrounding surfaces will be greater.

by high internal air velocities the internal surface resistance is reduced. A correction factor of 0·9 is recommended for the above formulae (4-4, 4-5) when the ventilation rate is 2 air changes per hour. This is modified to 0·65 and 0·55 at 10 and 20 air changes per hour respectively. At very high rates, such as 100 air changes per hour, this correction factor may be as low as 0·2.

In hot-dry climates the architect should aim at transferring heat from the inner to the outer environment. The highest heat transfer rate will occur when the difference in temperature between the inside surface of the structure and the outside air is greatest. Unventilated heavy structures will have a long time lag, heat gained during the daytime will reach the inside surface during night-time. During the day external temperature is usually higher than that required for comfort, but at night-time it falls. In the traditional buildings of the hot-dry climates natural ventilation is usually employed for structure cooling during night time. However, if the initial difference in temperature between the internal environment and the comfort temperature is small, night time ventilation should be rationalized. Another factor in structural cooling by ventilation is the structure surface itself. Walls made of materials having high thermal capacity will cool much slower than low thermal capacity walls. In massive structures this will be advantageous during the cold season when air temperature drops under the comfort limit, as it will counteract the chill of the dawn.

Natural ventilation for structural cooling in hot-dry climates has been examined by many researchers. Givoni (121) examined the effects of ventilation on air temperature and surfaces on the western side of the built environment. He used thermal models[1] made of different materials and painted either grey or white. He found that ventilation reduced the temperature of both the indoor air and the surface maxima and minima for the grey model. When the white model was examined, the maximum temperature seemed to be more a function of the wall colour, however, ventilation reduced the minimum in all cases. The maximum reduction obtained with continuous (day and night) ventilation was 7°C below the outdoor air maximum, while with night ventilation only a reduction of 0·8°C below the outdoor air maximum was observed for the same model[2]. Kuba (162) examined the effect of natural ventilation on the indoor air and surface temperatures of a heavy structural model[3], using two ventilation arrangements. The first was 24 hours continuous ventilation, and the second was ventilated only during the night (19.00 to 06.00). In the first case the indoor air temperature followed that of the outdoor air during the daytime, but remained high after the outdoor temperature had dropped. In the second case, where ventilation was restricted to night-time only, the maximum indoor air and surface temperatures were 10 and 11°C lower than the maximum outdoors; after allowing the air in at night the indoor temperature followed the outdoor, fig.(4.4). Another finding was that the indoor air temperature sympathized with that of the indoor surfaces during the restricted ventilation period. There is some

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1 Givoni's models, of external dimensions 1·35 x 1·47 x 1·35 m, have two sheets of asbestos cement 5 mm thick and whitewashed. In the northern walls they have 0·40 x 0·60 m openings, while the southern walls have 0·20 x 0·40 m openings.

2 Recorded for a model having 12 cm concrete walls of grey colour (122).

3 The test building consists of a single cell of heavy mud structure, with 42 cm thick wall, oriented to the true north, and with the inside surface whitewashed.

conflict between the results obtained by Kuba (81 , 162) and those of Givoni (121, 122). However, more recently in 1979 full size thermal models[1] have been examined by the Egyptian General Organization for Housing, Building and Planning Research (GOHBPR) in Cairo. The experimental programme[2] included two ventilation arrangements in which night-time ventilation and non-ventilation sets were examined. Figure (4.5) illustrates the results obtained during two ventilation arrangements in one of the models. Inspecting these curves, the advantage of night-time ventilation over the closed state is clear. Harris-Bass (136) reported on the results of these experiments and suggested that every 1 m/s change in wind speed gives, on average, a change of 0·5°C in internal temperature[3]. The difference between the two curves amounts to 5°C at dawn and reduces to approximately 2°C at maximum indoor temperature. At the same time, the difference between outdoor and night-ventilated-space air temperature amounts to approximately 8°C. These findings regarding the importance of night-time ventilation for structure cooling agree with those of Kuba. The similarity in the indoor temperature curves for the nightly ventilated models, figs.(4.4 and 4.5), is very clear. Another observation which can be made from Kuba's results, and is reinforced by Harris-Bass, is the sharp rise in air temperature of the nightly ventilated model[4] in comparison with either the continuously ventilated or the closed model. This seems to be due to the high

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1 The thermal model considered in this section was built of 225 mm solid sandlime brick with heavily insulated concrete roof.

2 This is a collaborative research project between the British BRE and the Egyptian GOHBPR.

3 Aynsley <u>et al</u> (18) recommend 0·55°C increase for each 0·15 m/s up to 1·0 m/s for dry bulb temperatures below 37°C with comfort zone between 21 and 28°C.

4 The early morning air temperature in the night ventilated space exceeds that of both the continuous and the unventilated spaces.

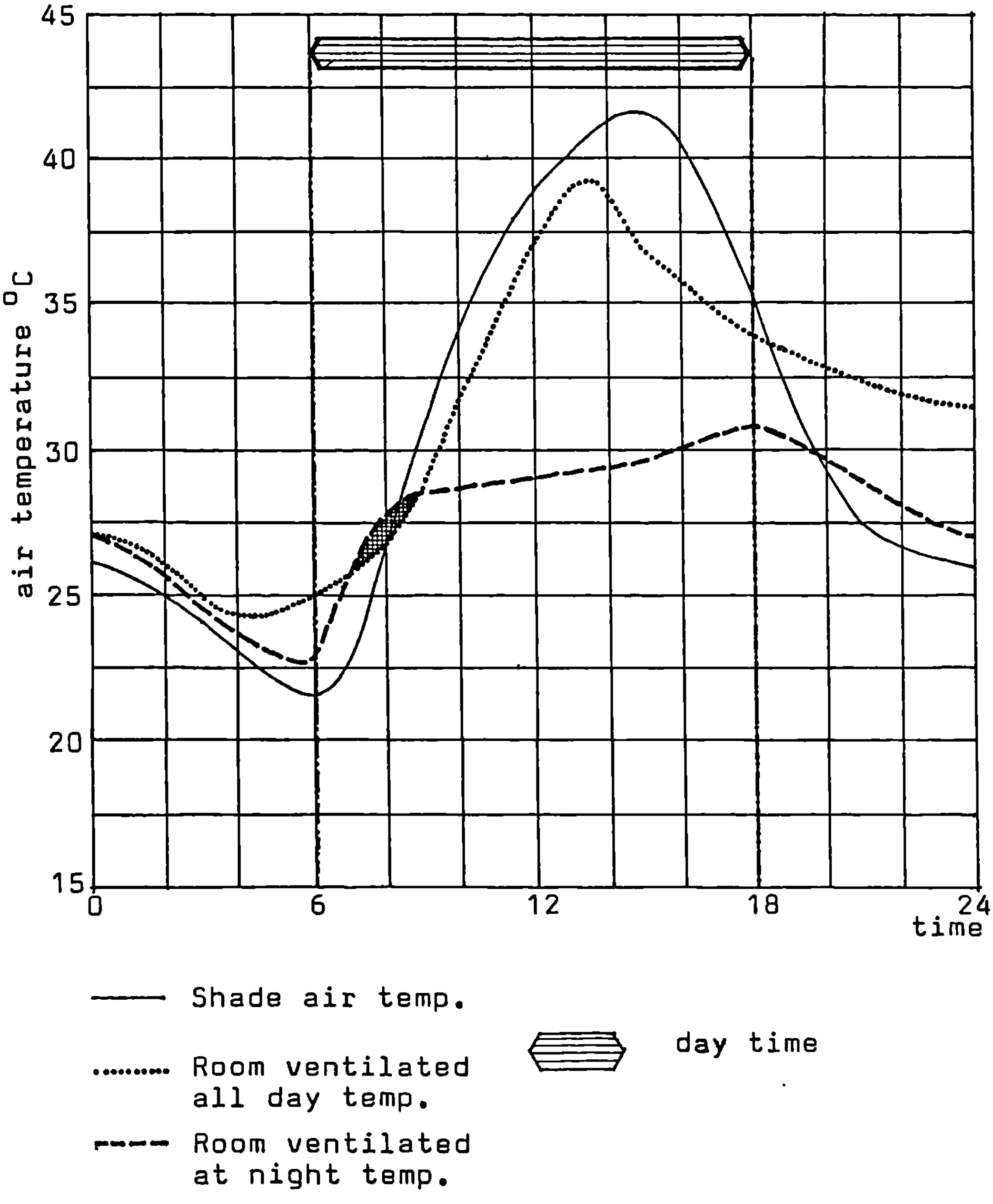

Figure (4.4) Comparison of indoor air temperature of a test room as ventilated throughout the day and night time. Model of a single cell of heavyweight mud built in hot-dry climate. (Data from Kuba (162)).

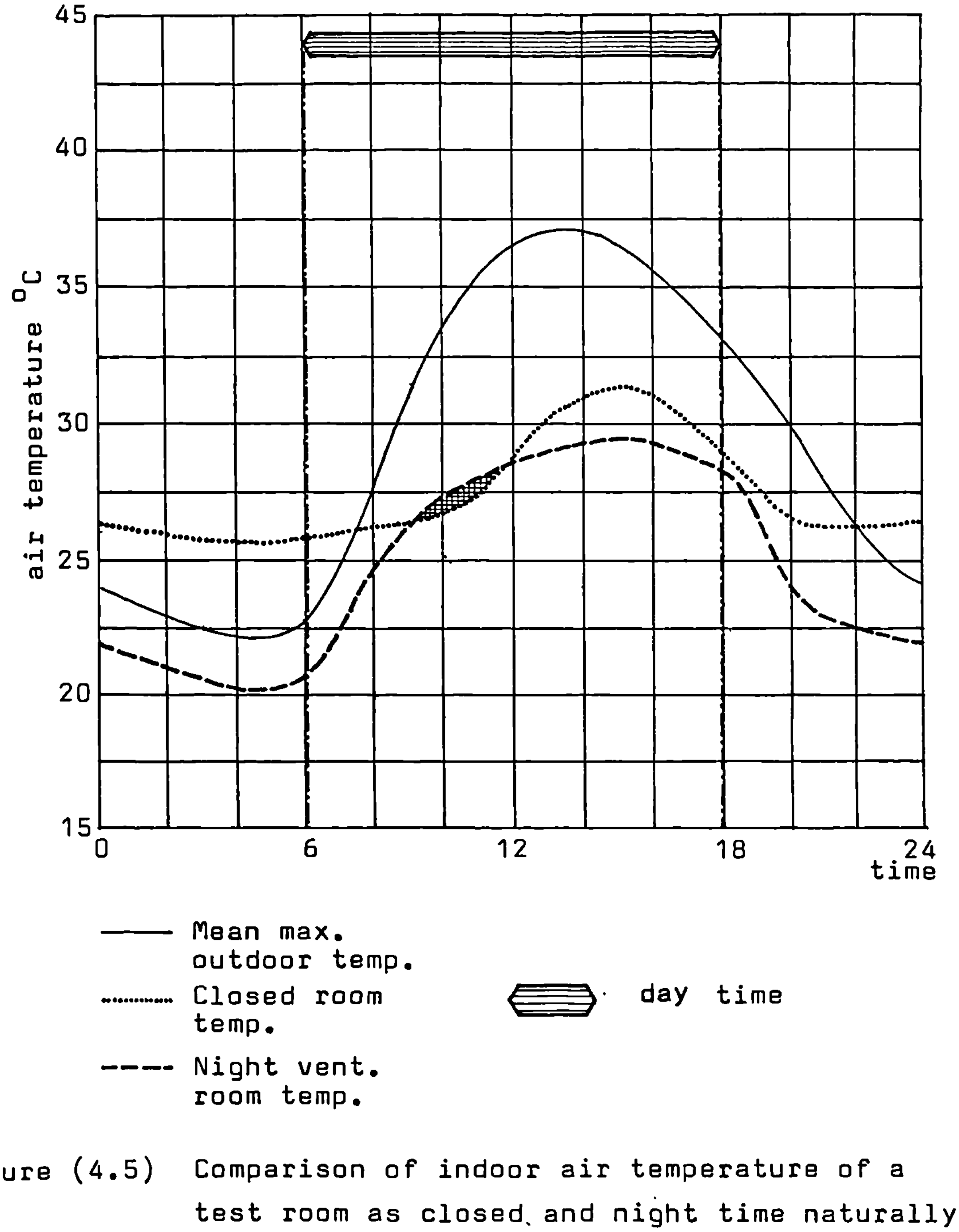

Figure (4.5) Comparison of indoor air temperature of a test room as closed and night time naturally ventilated (air temp is the mean for the period 16 Jun to 5 Jul).
Data from Harris-Bass (136).

thermal capacities of both structural shells. For night ventilation the structural shell having low thermal capacity and high thermal resistance will be more efficient in damping the sharp rise observed. The core of the building, ie the inner structure, should have high thermal capacity so that it can absorb heat gained through the daytime due to the living processes and heat transferred through the outer structural shell, and re-emit it during night-time to counteract the effect of cool air entering from outside. Bearing in mind that a single cell would be exposed to the maximum external heat stress on the structure's outer shell, one might consider night-time ventilation of great importance for hot climate environmental cooling.

g) Ventilation for Humidity Control and Condensation Risk - Humidity inside an occupied space is likely to be higher than that outside, and ventilation is necessary to prevent the humidity building up to unsatisfactory levels. The inhabitants of a building are themselves a source of moisture[1], but their living processes can be localized to minimise the rate at which humidity rises. Moisture is released by cooking, by washing and drying clothes and by combustion of oil or gas (table 4.5). The removal of moisture-laden air at a point near the source will help greatly in controlling humidity level inside the building. The relation between air temperature, moisture content and relative humidity is charted in the Standard Psychrometric Chart. The factors governing relative humidity indoors are moisture content, its rate of production, and the

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1 A person doing sedentary activity breathes out more than one litre of water as vapour in 24 hours; physical exertion may raise this to four times the rate.

Table (4.5) Moisture emission in a five-person house. After McIntyre (180).

Regular emission source	Moisture emission kg/day
Five persons asleep for 8 hours	1•5
Two persons active for 16 hours	1•7
Cooking	3•0
Bathing, dish washing	1•0
Total	7•2
Additional sources:	
Washing clothes	0•5
Drying clothes	5•0
Combustion (per kW):	kg/hr
Natural gas	0•15
Kerosene	0•10

ventilation rate. The ventilation rate required to maintain a given indoor moisture content is proportional to the rate of moisture production, and can be computed by the equation:

$$q_{vm} = w/(g - g_o) \qquad (5\text{-}6)$$

where q_{vm} = the mass flow of ventilation air — kg/s

w = the rate of moisture vapour production in the space — kg/s

g & g_o = the moisture content of the air in the space and in the ventilating air respectively — kg/kg

As the outdoor moisture content (g_o) rises towards the indoor (g), the required ventilation rate rises rapidly. In hot humid zones ventilation rates as high as 50 air changes per hour may be required to maintain the necessary relative humidity for comfort.

High values of relative humidity may damage the building fabric by increasing the risk of condensation. In order to avoid this it is necessary to understand its mechanism and the conditions favouring its occurrence. When the amount of water vapour in the air reaches the limit which can be held in that air, the air is said to be saturated and has a relative humidity of 100%. Saturation point varies with temperature[1], the higher the air temperature the greater the amount of water vapour it can hold. Air can not hold any extra water vapour after reaching saturation point,

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1 Saturation point may vary with pressure as well as temperature. In the types of building dealt with in this section a significant change in pressure is not likely to occur. Therefore, only temperature changes will be considered.

instead it will deposit it as condensation on cooler surfaces. A change in air temperature from 30°C, with 50% RH, to approximately 22°C will bring the relative humidity to 100%, therefore condensation will occur on any surface having a temperature below 22°C. The surface temperature is said to be equal to the dew point of the air. Water vapour will however tend to flow outwards through the structural fabric to restore the balance with the outside conditions. The progress of the water vapour is determined by the construction through which it must pass, the total difference in water vapour pressure across the structure and the resistance to flow that must be overcome. At the same time, heat will flow through the structure from the hot side to the cold. If in any part across the structural fabric the temperature falls below the dew point of the surrounding water vapour, interstitial condensation will occur (27 , 47). Tables (4.6 & 4.7) give a selection of typical values of thermal and vapour resistance. A ventilated cavity will help in diminishing the risk of interstitial condensation.

Condensation damage can occur in buildings even when air temperatures are within the comfort level or warmer, however, this is surface condensation rather than interstitial condensation. In warm and humid climates the dewpoint at midday may be a few degrees lower than ambient air temperature, while during night it is usually above the ambient air temperature. The surface temperature of a massive structure may reach the dewpoint of the ambient air during the early hours of the morning, and a small amount of moisture may be deposited in the building's surface. In cupboards, cabinets and wardrobes without ventilation condensation may be more severe, and mould growth is likely to develop. Ventilation is therefore essential for such spaces. On the other hand, in air conditioned buildings

Table (4.6) Typical values of heat and vapour resistance for building subjects (47).

Subject	Thermal resistance $m^2\ ^oC/W$	Vapour resistance MN s/g
Surfaces:		
Wall - inside	0·12	
- outside	0·05	
Roof (or ceiling) - inside	0·11	
- outside	0·04	
Internal air space	0·18	
Membranes:		
Average gloss paint film		7·5-40
Polythene sheet (0·06 mm)		110-120
Aluminium foil		4000

Table (4.7) Typical values for heat and vapour resistance for building materials (77).

Material	Thermal resistivity $m^2\ {}^oC/W$	Vapour resistivity' MN s/g m
Brickwork	0•7-1•4	25-100
Concrete	0•7	30-100
Rendering	0•8	100
Plaster	2	60
Timber	7	45-75
Plywood	7	1500-6000
Fibre building board	15-19	15-60
Hardboard	7	450-750
Plasterboard	6	45-60
Compressed strawboard	10-12	45-75
Wood-wool slab	9	15-40
Expanded polystyrene	30	100-600
Foamed urea-formaldehyde	26	20-30
Foamed polyurethane (open or closed cell)	40-50	30-1000
Expanded ebonite	34	11000-60000

' Resistivity is the reciprocal of diffusivity.

with poorly insulated structural shells condensation will develop on outside surfaces resulting in dark algal growths.

Mould growth on internal surfaces is evidence of dampness which should be cured before any surface treatment is attempted. Fungi (moulds, mildew and yeasts) need organic material to feed on, but light is not necessary for growth. Moulds appear as spots of patches which may spread to form a furry layer on the surface, often grey-green, black or brown in colour. Moulds may also grow within a paint film causing staining, usually pink or purple, though the mould itself may not be visible. Some moulds may grow entirely within the plaster layer, destroying all of it before fruit bodies with leathery appearance come to the outer surface, fig.(4.6).

In cold climates the call for energy conservation has led to reduced levels of ventilation and permanent vents are no longer legally demanded in houses. As a result of focusing attention upon this aspect only, without considering all the consequences, the risk of condensation was greatly increased. Many housing estates have been reported as suffering severe condensation problems, and people are refusing to live in them.

Bearing in mind that ventilation[1] is the most practical way of moving water vapour from buildings, careful consideration and full-scale testing should have been

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1 calculations show that it is necessary to provide a certain minimum amount of ventilation which is much the same as is required for hygienic purposes, ie 0·5 to 1·0 air changes/h for the average house (171). However this has been recommended as 0·7 on empirical basis (262).

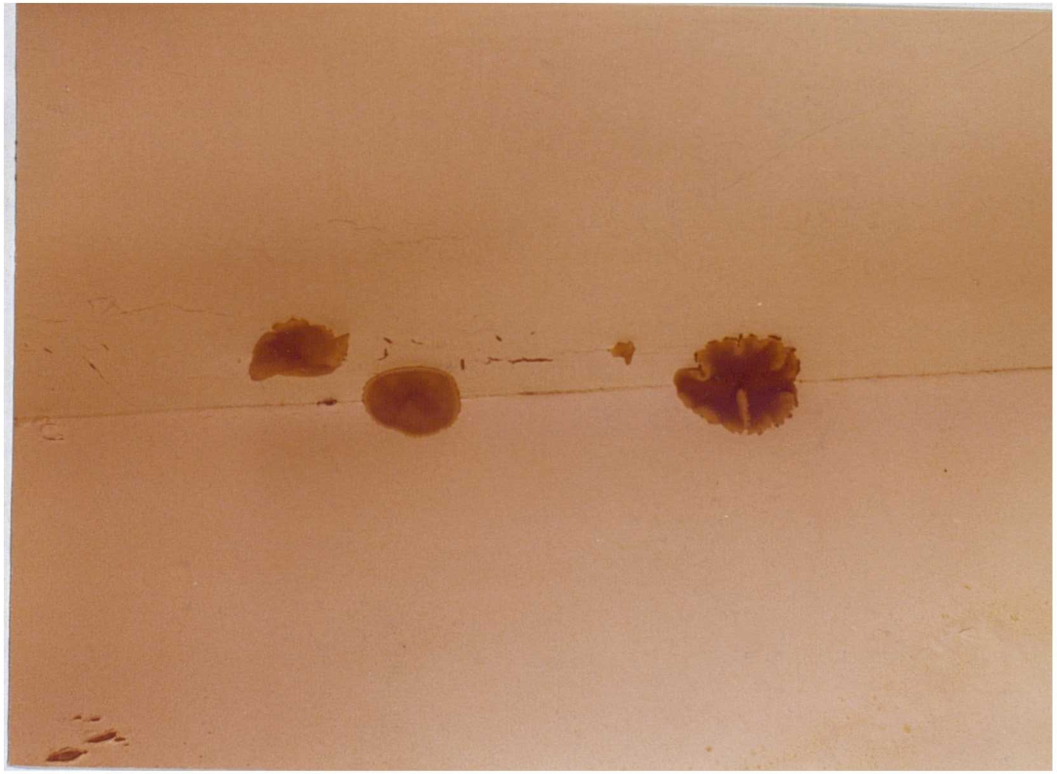

Figure (4.6) Plaster mould damage to the whole plaster layer, showing brown fruit bodies (leathery).

Conditions in the bathroom of a centrally heated building, shown above, can be summarized as - unsatisfactory ventilation, high water vapour production with continuous saturation, surface temperature below dew point, and organic materials in the plaster.

carried out before any attempt was made to reduce substantially the ventulation rates. The Institution of Heating and Ventilating Engineers (IHVE) Guide B2 states:

> The most direct, and indeed the essential way of checking this (condensation) is by adequate ventilation. The problem is dealt with by diluting the moisture content of the room air to a lower level, the incoming ventilating outdoor air being at lower moisture content than the air in the room.

In conclusion, ventilation should satisfy three main requirements. Firstly, health ventilation, which should be satisfied under all climatic and environmental conditions. The most exigent requirement under this category is ventilation for odour remeval, and it may lead the occupants to sacrifice other comfort aspects by allowing in air at an undesirable temperature to remove odours. Secondly, ventilation for comfort, which should assure body cooling in hot climates, and is essential during hot humid conditions when the outside air is the same or cooler than that inside. The air will need humidification[1] in hot-dry climates, though this would be undesirable in cold climates. Thirdly, ventilation for structural cooling, essential in hot-dry climates when the outside air is cooler than that inside by more than 2°C (100). Structures should be ventilated at night times during the high heat waves. High internal heat capacity with insulated light structural shells is advantageous in these conditions.

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1 In hot-dry climates the latent heat needed for the humidification process is usually taken from ambient air, or surrounding structures, depending on the techniques used.

4.2.4 Critical Factors in Ventilation Performance

Natural ventilation is the process of replacing, mixing and recirculating air within the built environment by natural forces. There is a continuing need to improve the effective use of this natural process for the control of the environmental comfort of the occupants, and cooling of the structure. The criterion for evaluating ventilation conditions depends on the type of occupancy and the prevailing climatic conditions. These will determine a range of air speeds within which comfort needs should be satisfied, and the essential design should aim at securing good air movements at living level during most of the hot season. An assessment of air movement effects on the human body indoors is given in table (4.4) and fig.(4.7). However, employing the Standard Effective Temperature (SET) index would enable a more accurate estimation of the required air speed. In Chapter 3 both occupancy and climatic conditions have been examined, and the possible and desirable air speeds have been assessed using the SET index.

The desirable air flow patterns and velocity distributions within a space vary according to its function. In hot climates equal velocity magnitude in all the expected seating areas, at sitting level[1], is the most desirable distribution to be achieved in a living room. In a bedroom air flow of high velocity should be oriented, at sleeping level, towards the part of the room where the bed is likely to be located. In office buildings high air velocities at desk level may disturb working conditions, therefore the main air stream should be directed at and above head level of a sitting person, ie, on average between 1·2 and 1·5 m above

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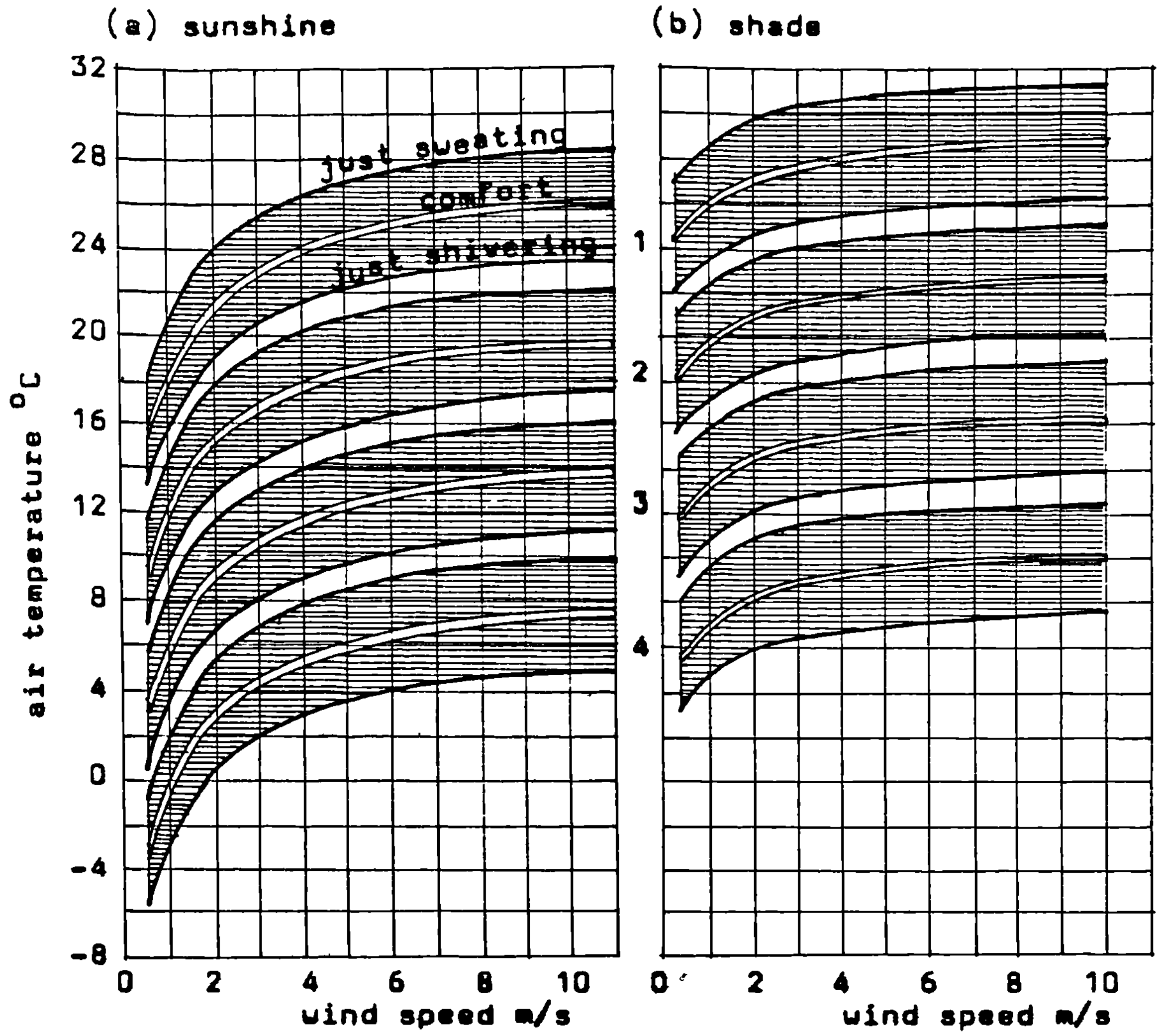
1 This will be approximately 1·0 m above the floor for modern chair styles, reducing to 0·6 m for the Arabic style chairs, and even lower when seated on the floor.



1 nude
2 light summer clothes
3 business suit
4 winter clothes with coat

Figure (4.7) Examples of comfort conditions for strolling (after Penwarden (216)).

the floor for normal office activity. Adjustable louvers, screens and vegetation are commonly used to control the direction of air flow and, if necessary, reduce air speeds at living levels. In this way the cooling effect of ventilation can be maintained while minimizing its disturbance to the function of the space.

The speed and quantity of air moving within a naturally ventilated space is a function of the total pressure difference between the inside and outside of the building. In a single cell space, this would be a product of either the stack effect due to the difference in thermal properties between the inside and outside environments, or the inertia forces of the wind. If the inlet is located on the windward side, and the outlet on the leeward, the pressure difference due to inertia forces will equal the difference in pressure between these sides of the building. In a multi-cell space, the common case in buildings, the problem is much more complicated as the differences in pressure between the cells affect the flow pattern considerably.

Ventilation performance can be estimated using different methods, those that are based on air changes and those considering air speeds. For cold climates where the aim of the designer is to supply the minimum ventilation required for health[1] while conserving all the heat energy within the built environment, the air change methods may be acceptable. In hot climates ventilation requirements are for body cooling and structure cooling as well as for health. Ventilation rates as high as 50 air changes/hour may be required during hot-humid conditions where body

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1 In cold climates ventilation rates as low as 0•5 air changes/h will satisfy health requirements and, to a certain extent, humidity control, hence this may be an acceptable level. Window opening however is a function of family habits (38).

cooling will be the dominant factor. Air change rate is no longer the only factor governing ventilation, as the speed of air moving past the body can have a greater effect on body cooling. Thus, methods for estimating ventilation should be based on air speeds rather than air changes. Methods of calculating ventilation will be examined in Section 4.3.4.

Ventilation patterns can be traced from measurements taken in buildings under natural conditions, or from model studies in a wind tunnel. Measurements in full scale should be repeated over a period of time[1] in order to obtain a reliable assessment of the prevailing conditions. Full scale tests are usually too expensive, time consuming and lack flexibility, but are very important for validating results obtained from smaller models in wind tunnels. In dealing with problems of indoor ventilation it should be remembered that velocities vary at different points within the space. Measurements taken at representative points may not reflect the conditions in other parts of the space which may be of greater subjective importance. Therefore, careful arrangement of measuring points should precede any experiment. After examination of the forces affecting the ventilation mechanism (Section 4.3), the use of models in wind tunnels and air flow patterns will be discussed in Section 4.4.

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1 This is due to the ever-changing nature of wind conditions, both in magnitude and direction.

4.3 The Physical Mechanism of Natural Ventilation

For ventilation purposes buildings can be regarded as a series of distinct cells, interconnected within themselves and also with the external environment by means of air flow paths. Usually these cells are ascribed different functions, and may be joined by more than one air flow path. The nature of the path can vary from small cracks in a component to large openings such as doors and windows. Air flow through them ranges from unintentional infiltration to invited ventilation. A phenomenon common to all of them is that the difference in pressure on either side of an opening induces the flow of air across it. Generally, pressure differences build up due to two[1] forces:

1 Thermal Forces - the result of temperature gradients between the cells, or between internal and external spaces.
2 Inertia Forces - the result of interaction between natural wind forces and the external environment.

The pressure differences due to both thermal and inertia (wind) forces act simultaneously, and the final air flow is the resultant. It has been suggested that the effective pressure due to both forces is their algebraic sum (18). The nature of the relationship between these two forces will be further examined in Section 4.4

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1 Molecular diffusion may induce a very small air flow between the inside and outside in comparison with these two mechanisms. However, thermal and inertia forces only will be considered.

4.3.1 Thermal Forces Inducing Natural Ventilation

Ventilation by thermal forces, also termed 'stack effect', occurs when air density differences are the dominant cause of air movement. Air density varies approximately as the inverse of the absolute temperature (56). Two vertical, separated air columns having different temperatures will differ in mass, and a pressure difference will apply across the intervening surface. The velocity of the air flowing between the two columns will depend on the magnitude of this pressure difference.

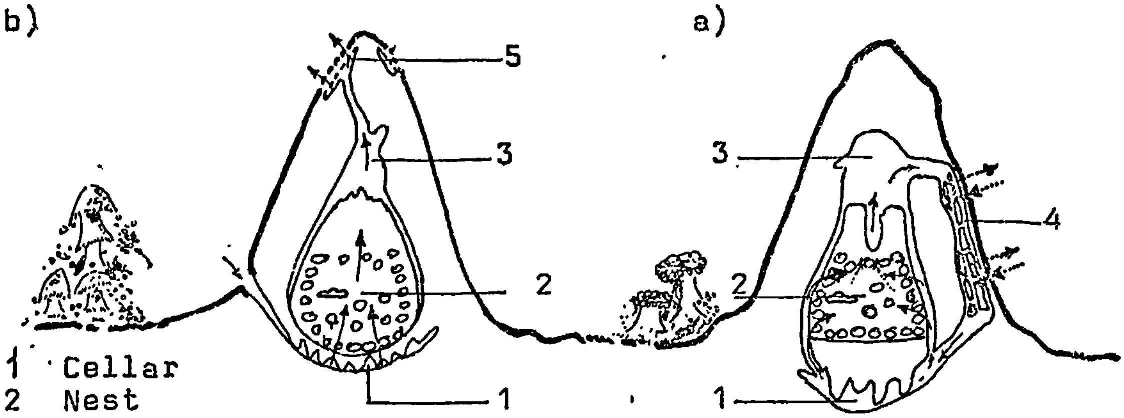
The forces of nature in the hot Ivory Coast of Africa have induced the termites[1] there to establish a strange and ingenious ventilation system for their termitaries (110). A cross-section made vertically through the centre of an Ivory Coast mound is compared with that of termites of Uganda in fig.(4.8).

When the internal and external air temperatures of a building are not the same, there will be a difference in air densities, and the vertical pressure gradient differs correspondingly. If the indoor air is warmer and therefore less dense, the indoor vertical pressure gradient will be smaller than that existing outdoors. This means that within an indoor space having only one opening, there is an excess pressure at any level above the opening and a depression below it. These differences tend to increase with vertical distance from the aperture. When two openings are provided at different heights and the indoor air temperature is higher than that outdoors, the pressure

---

1 Termites are the insects mistakenly called 'white ants'; the two groups are entirely different morphologically and phylogenetically, and are different genera. There are more than 2000 species of termite living in the tropical and subtropical regions of the world.

Figure (4.8) Thermal forces induce natural ventilation in termites. (110).



1 Cellar
2 Nest
3 Air spaces
4 Ducts in ridges
5 Flat chamber

Diagram of the circulation of air in termites' mounds.
b) Termitary from Uganda. a) Termitary from Ivory Coast.

Comparative Analysis

A termite mound has a height of three to four metres; it contains more than two million termites. They live, they work and they breathe.

a) In the Ivory Coast the ventilation system of the termitary is completely automatic. The air in the fungus chamber is heated by the fermentation process and termite activities. The hot air rises and is forced by the pressure of the continuous stream of hot air into the duct system of the ridges (lungs of the termitary) where gas exchange occurs. The air is cooled during its passage through the ridges. This cooler regenerated air now flows into the cellar by way of the lower system of wide ducts. From there it returns to the nest via the surrounding air space, replacing the rising warm air.

b) In Uganda the same termite species is found, but their mounds lack the conspicuous ridges with their air ducts. Instead, the warm air rising in the nest is led by ducts from the upper air space into flat chambers under the dome whose walls are so porous that air can escape to the outside. The cellars of their mounds are open to the outer air by means of wide channels, but they are closed at the nest and inaccessible to the inhabitants. However, the floor of the nest is so porous that it allows fresh air from the cellar to penetrate.

difference is formed so that excess indoor pressure builds up at the upper opening where air flows outwards, while a depression develops at the lower level inducing an inward flow. Heating of buildings for winter comfort creates significant indoor-outdoor temperature differences[1], which can be utilized to provide minimum ventilation rates by infiltration. In hot climates a similar temperature difference between indoors and outdoors is not common, and the stack effect may be insignificant. However, in spaces where high temperature processes are performed, such as industrial buildings, stack effect may induce air flow but is not likely to offset the high temperature stress on workers. Multi-storey buildings increase the height difference between wall openings for ventilation, and reduce the area of external wall and roof surfaces exposed to the weather. In such buildings stack effect can be utilized by providing ridges and high ventilators to promote air circulation on calm hot days. From the thermal comfort point of view. staircases of multi-storey buildings in a hot country like Egypt are usually cooler than the residential units as a result of the stack effect. This cooling effect is amplified when staircases are opened to the 'manwar'[2] or lighting well.

If the inlet and outlet areas are equal, then the quantity of air flow can be expressed as:

---

1 The British winter external temperature (design) is -1°C, while winter heating environmental temperature of 21°C has been recommended by the Institution of Heating and Ventilating Engineers for residential buildings (living rooms). This represents a temperature difference of 22°C.

2 'Manwar' is a common feature of the multi-storey residential blocks in most Egyptian cities. It is a very deep courtyard usually provided for lighting and ventilating the service areas and sirculation elements. With an area ranging between 10 and 12·5 m², it can be more than 20 m in depth.

$$Q_{vt} = CA(H \times \Delta T)^{\frac{1}{2}}$$

where:

Q_{vt} = air flow due to thermal forces

A = cross-sectional area normal to the flow

C = constant embodying the coefficients of resistance for the system, the ambient temp. and gravitational acceleration.

H = average height between inlet and outlet

ΔT = temperature difference between inside and outside the ventilated space.

Air flow efficiency of an opening is accommodated in the coefficient C, and for most types of openings a value[1] of 0·12 is recommended (18 , 122). Hence, the above equation can be written:

$$Q_{vt} = 0{\cdot}12 \times A(H \times \Delta T)^{\frac{1}{2}}$$

This equation assumes that inlet and outlet are of equal area, but where this is not the case a discharge correction factor, C_d, should be used and its value is obtainable from fig.(4.10). Therefore, the equation can be rewritten as:

$$Q_{vt} = 0{\cdot}12 \times AC_d(H \times \Delta T)^{\frac{1}{2}} \qquad (4\text{-}7)$$

When a space within a building is well-sealed with respect to the rest of the building, eg cellular offices or classrooms, it may have one or more openings in one wall only. Thermal forces will be the most important driving force for natural ventilation. The turbulant diffusion, interaction of an opening vane with the local air flow, and the mean pressure difference acting across openings will be

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1 For use in the British system a value of 9·4 has been recommended for C (122, 245).

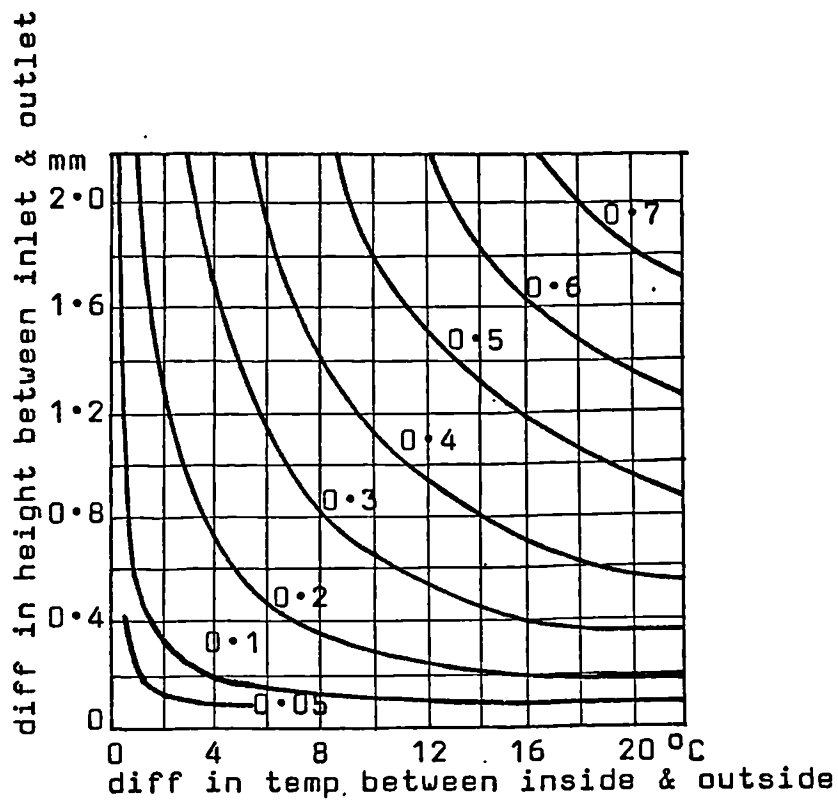

Figure (4.9) Wind speed in inlets due to thermal forces in m/s (where inlet and outlet are equal). The curved scale also indicates the ventilation rate in cubic metres per second per square metre of inlet area; after Evans (100).

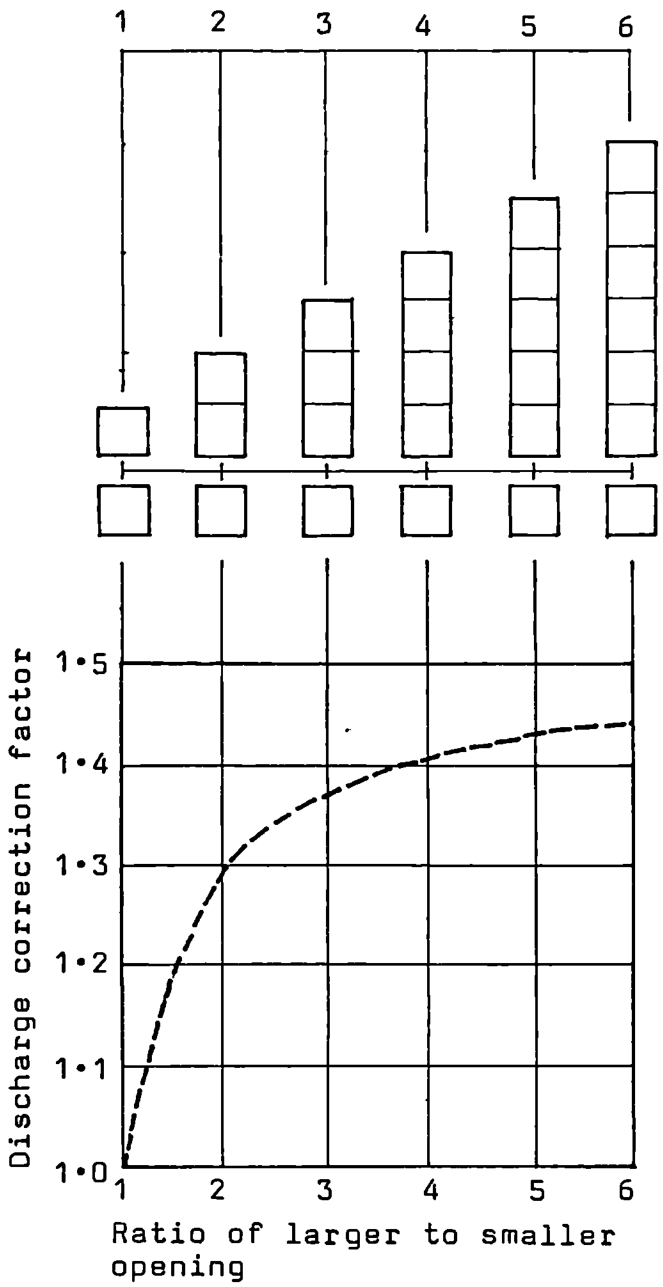

Figure (4.10) Correction factors for relative areas of inlets and outlets. After Aynsley (18).

the other main possible forces affecting the ventilation process. Inertia forces are the principal generators of these three forces.

4.3.2 Inertia Forces Inducing Natural Ventilation

Ventilation due to inertia forces, also termed wind ventilation, occurs when a difference in pressure builds up between the inside and outside spaces, and has its widest application in residential, educational and industrial buildings during summer and in hot climates. To achieve maximum air flow through a building its form, orientation and exposure must be such that the pressure differences between the inlet and outlet locations are maximised with respect to the local wind characteristics.

In a free stream state the total energy of a small unit of moving air is a function of the sum of its static and dynamic pressures, and is considered constant in wind loading and ventilation calculations. The total pressure p_o is given by:

$$p_o = p_a + \frac{1}{2}\rho\bar{V}^2$$

where:

p_a = atmospheric pressure
ρ = air density = $1{\cdot}266\ kg/m^3$ in UK
$\bar{V}$ = velocity of the smallest unit of air

When the flow of air is obstructed by a body, the velocity will change to V_1 and correspondingly a change[1] in the

---

1 An expression of the Bernoulli equation type when applied to homogeneous horizontal streamlines, or for a negligible change in height (18). Bernoulli's equation is valid only for free stream, is not valid in either the shear or wake regions in a fluid flow, fig.(4.25).

dynamic pressure P_1, which will act on the body surface, will be as follows:

$$P_1 = \rho \tfrac{1}{2} \left(\overline{V}^2 - \overline{V}_1^2\right)$$

The atmospheric pressure may change considerably over a period of time and can greatly exceed the variation of dynamic pressure, though this usually occurs relatively slowly[1]. The atmospheric pressure may be considered equal on all surfaces to which the atmosphere has access. It is therefore regarded as constant, and taken as a datum.

As wind approaches a building or any other object obstructing its flow at a right angle, a unit of the air will be brought to rest at the front of the object with its velocity reduced to zero at a defined point on its surface, usually referred to as the stagnation point, and all the kinetic energy of this small unit will be transformed into pressure (q):

$$q = \tfrac{1}{2}\rho V^2 \qquad (4\text{-}8)$$

at the same time, air around this unit will tend to deflect outwards towards the edges of the plate, the further they are from the stagnation point, the less they will be hindered by the object, and consequently the less the transformation from kinetic energy to pressure, and the lower the pressure acting on the object. The pressure at any point on the surface is usually expressed as a fraction of the dynamic pressure, q, and is termed the pressure coefficient 'C_p'.

---

1 The atmospheric pressure may change considerably over a very short time with the passage of tornadoes, hurricanes and tropical cyclones. Eaton (91 , 92) analyses and gives guidelines for designers, builders and occupants in areas likely to encounter such changes.

C_p = pressure at any point on surface/dynamic pressure
= (p/q)

where compression is indicated by a positive value of C_p and suction by a negative value. Incorporating C_p in equation (4-8), the pressure of wind on any point in the building face can then be calculated as follows:

$$P = \pm \tfrac{1}{2} \rho \, C_p \, V^2$$

$$= \pm \, C_p \, q \qquad (4\text{-}9)$$

Once the distribution of C_p at the surface has been determined for a single wind speed and a particular wind direction[1], the pressure can then be computed for any other wind speed. V is conventionally taken as the wind speed measured in the free wind at a height equal to that of the building. The pressure difference between any two points on the building envelope determines the potential driving force for ventilation when openings are provided at these points, figure (4.11).

Givoni (122) reported on experiments conducted by Irminger and Nokkentved using models in a medium speed wind tunnel[2]. They concluded that when the incident wind was normal to the building, the windward wall was subject to an elevated positive pressure, averaging +70%, ie C_p = +0·7. The velocity pressure of +95%, C_p = +0·95, near the stagnation point decreased to +85%, C_p = +0·85, at the roof, and to +60%, C_p = +0·6, at the sides. The side walls were subjected to a suction averaging -62%, C_p = -0·62, which was

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1 These are well established studies and data are available from many sources (18, 46, 64, 90, 122, 166, 201).
2 A medium speed wind tunnel is one which can produce air flow at a speed of 20 m/s.

highest, -70%, C_p = -0·7, at the upwind part of the walls and decreased to -30%, C_p = -0·3, at the farther corners[1]. Suction on the leeward wall was almost evenly distributed, averaging -28·5%, C_p = -0·285. The average suction over the roof was -65%, C_p = -0·65, decreasing from -70%, C_p = -0·7, upwind to -50%, C_p = -0·5, downwind fig.(4.11). As the wind changed direction and became oblique to the building the pressure on the windward wall decreased and the distribution altered. Higher pressure was recorded at the upwind corner, decreasing steeply downwind, with a marked pressure gradient established along the windward walls. The suction on the leeward walls was more pronounced and uniform as the angle between the wall and the wind increased. Pressures averaged over the surface of simple buildings are given in table (4.8). When the windows are provided at points experiencing differences in pressure, air tends to flow, so ventilating the space. The ventilation process reaches its equilibrium when air mass flow in and out of the building is equal. In buildings with openings in only one wall, with all other walls impermeable, fig.(4.12), the air pressure in and out of the space will be in equilibrium, with the windward opened space having +ve value and the leeward opened having -ve value. Most buildings, however, have some degree of permeability on each face through ventilation louvers, leakage or gaps around openings. Permeability is measured by the total cross section area of all openings which can be considered as air flow paths. The quantity of air flowing through any opening is proportional to the area 'A' of the opening, and the square root of the pressure difference $(P_e - P_i)$:

$$Q \propto A \; (P_e - P_i)^{\frac{1}{2}}$$

---

1 IHVE give the windward C_p range from 0·5 to 0·8, and the leeward range from -0·4 to -0·3 as the generally recommended coefficients.

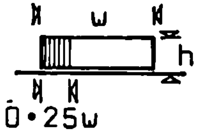
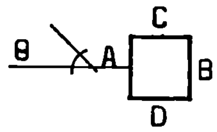
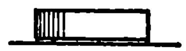
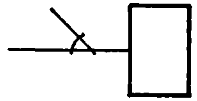
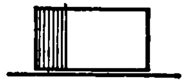
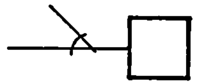
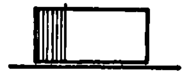
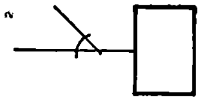
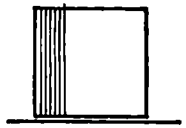
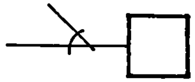
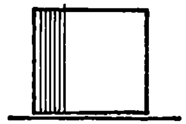
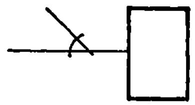
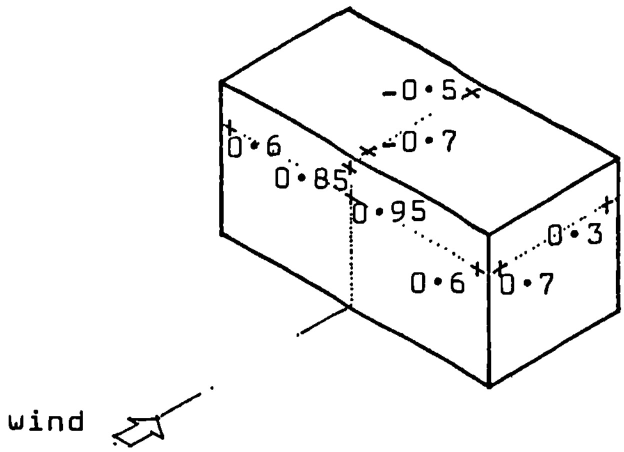
Building height ratio	Building plan ratio	Side elevation	Plan	Wind angle 'a'	Cpe for surface A	B	C	D	Local Cpe
$\frac{h}{w}<\frac{1}{2}$	$1<\frac{l}{w}<\frac{3}{2}$			0° 90°	+0·7 -0·5	-0·2 -0·5	-0·5 +0·7	-0·5 -0·2	-0·8
	$\frac{3}{2}<\frac{l}{w}<4$			0° 90°	+0·7 -0·5	-0·25 -0·5	-0·6 +0·7	-0·6 -0·1	-1·0
$\frac{1}{2}<\frac{h}{w}<\frac{3}{2}$	$1<\frac{l}{w}<\frac{3}{2}$			0° 90°	+0·7 -0·6	-0·25 -0·6	-0·6 +0·7	-0·6 -0·25	-1·1
	$\frac{3}{2}<\frac{l}{w}<4$			0° 90°	+0·7 -0·5	-0·3 -0·5	-0·7 +0·7	-0·7 -0·1	-1·1
$\frac{3}{2}<\frac{h}{w}<6$	$1<\frac{l}{w}<\frac{3}{2}$			0° 90°	+0·8 -0·8	-0·25 -0·8	-0·8 +0·8	-0·8 -0·25	-1·2
	$\frac{3}{2}<\frac{l}{w}<4$			0° 90°	+0·7 -0·5	-0·4 -0·5	-0·7 +0·8	-0·7 -0·1	-1·2

Table (4.8) Pressure coefficients C_p for vertical walls of rectangular clad buildings, (46).

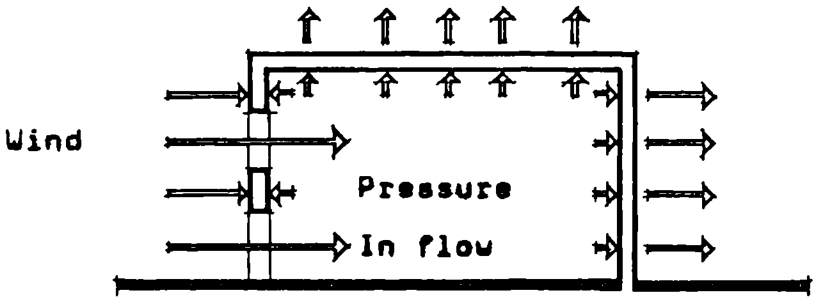


a) A simple bluff body subject to wind pressure normal to it.

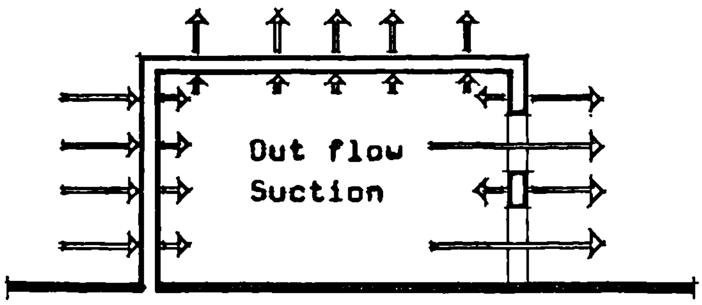
Pressure Coefficient	C_p			
	Windward	Side	Leeward	Roof
Max	+0•95	-0•70		-0•70
Min	+0•60	-0•70		-0•50
Average	+0•70	-0•62	-0•285	-0•65

b) The pressure coefficients (C_p) as applied to the simple bluff body.

Figure (4.10) Wind pressure coefficients of a simple bluff body (201, 122).



(a) Opening in windward wall



(b) Opening in leeward wall

Figure (4.12) Internal pressure in building with openings in one wall only and other impermeable walls (201).

Providing that the volume of air entering a building must be equal to the volume of air expelled, the summation of Q should equal zero, hence:

$$\sum (A (P_e - P_i)^{\frac{1}{2}}) = 0 \qquad (4\text{-}10)$$

In a building with identical openings in two opposite walls and two impermeable walls, fig.(4.13a), the average external pressure coefficients for wind directions 0^o and 90^o are as in fig.(4.13b), and the internal pressure can be calculated using the above equation (4-10). Knowing the internal pressure it is possible to calculate the air flow through any of the openings.

When an opening is inclined to the wind direction, significant pressure variation occurs across it, allowing the air to enter and exhaust through the same opening. If the space has openings on one side only, pressure fluctuation may occur giving rise to air flow[1] in and out of the ventilated space.

Air flow through buildings due to inertia forces can be estimated using two different approaches, each of which requires a separate evaluation for every prevailing wind direction on the site. The first approach is based on the wind pressure differences across the building, and allows for the geometry, dimensions and air flow discharge characteristics of openings in a discharge equation in order to estimate volumetric flow rate. The second approach involves wind tunnel testing of models to determine the ratios of wind speeds at points of interest inside the building to an external reference wind speed at a height for which

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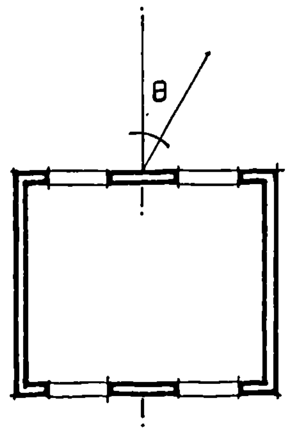
1 Warren (261) studied the mechanisms that give rise to the natural ventilation of rooms with openings on one side only, among which are difference in air temperature and mean pressure difference acting across openings.



a) Plan of single cell with identical openings in opposite faces.

Wind angle θ	C_{pe}			
	AD	BC	AB	CD
0^o	+0·7	-0·3	-0·7	-0·7
90^o	-0·5	-0·5	+0·7	-0·1

b) The pressure coefficients (C_{pe}) as applied on a single cell with identical openings in opposite faces.

Figure (4.13) Wind pressure in a single cell with identical openings in opposite faces. After Newberry *et al* (201).

wind records are available. Wind speeds are usually recorded at 10 m above ground in the free countryside (or sea) or, in urban areas, an average of 10 m higher than any obstruction near the measuring point (254).

a) Pressure Difference Method - The pressure difference between the windward and leeward sides due to wind interaction with a building will provide the driving energy for the ventilation process. The volumetric air flow can be calculated from the following equation:

$$Q_w = C_d A_w (V_z^2 (C_{p1} - C_{p2}))^{\frac{1}{2}} \qquad (4\text{-}11)$$

where: Q_w = air flow due to wind pressure
C_d = discharge coefficient depending on the dynamic loss coefficient which is a function of the window type[1]
A_w = the overall effective area of openings[2]
V_z = a reference known wind speed
C_{p1} = windward pressure coefficient
C_{p2} = leeward pressure coefficient

Considering airflow through a building consisting of two or more cells, fig.(4.14), air will tend to flow through openings in series to restore the difference in pressure between the cells and the outside. If the openings have areas A_1, A_2 and A_3, and are connected together with air paths having discharge coefficients C_{d1}, C_{d2} and C_{d3} with pressure differences $(P_1 - P_2)$, $(P_2 - P_3)$ and $(P_3 - P_4)$, the total air flow through any opening can be calculated using equation (4-11),

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1 It has become conventional to give C_d a value equal to that for sharp-edged opening which, at high Reynolds number, is 0·61 (148).

2 $1/A_w^2 = 1/(\Sigma A_i)^2 + 1/(\Sigma A_o)^2$
A_i = inlet areas, A_o = outlet areas

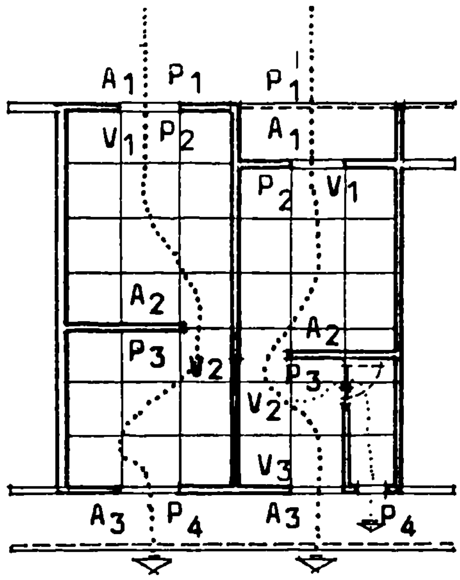
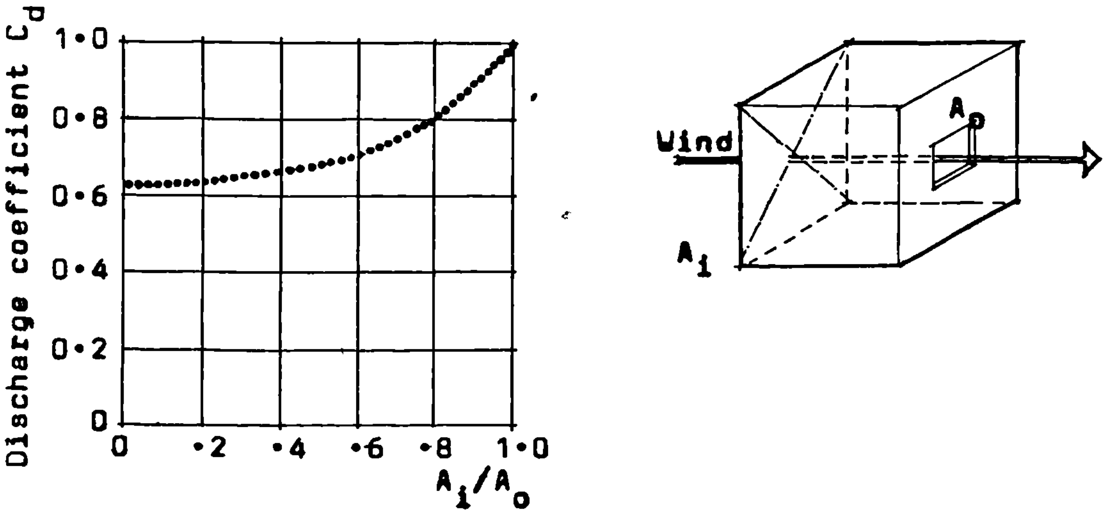


Figure (4.14) Typical air flow paths through building openings in series.



A_i/A_o:	0•0	0•2	0•4	0•6	0•8	1•0
C_d:	0•63	0•64	0•67	0•72	0•81	1•00

Figure (4.15) Discharge coefficients for outlet openings. (18).

while the total air flow through the building can be calculated using the following equation:

$$Q_w = \left[\frac{(C_{p1} - C_{p4})\ V_z^2}{(1/C_{d1}^2A_1^2 + 1/C_{d2}^2A_2^2 + 1/C_{d3}^2A_3^2)}\right]^{\frac{1}{2}}$$

For air flow through more than three openings:

$$Q_w = \left[\frac{(C_{pi} - C_{pn})\ V_z^2}{(1/C_{d1}^2A_1^2 + 1/C_{d2}^2A_2^2 + \ldots +1/C_{dn}^2A_n^2)}\right]^{\frac{1}{2}} \quad (4\text{-}12)$$

Aynsley (18) observed air flow rates through openings in series. Using coefficients from fig.(4.15) and table (4.9) he estimated that these were within 15% of the measured values obtained from wind tunnel studies on a variety of opening geometries and sequences. The areas of openings did not exceed 10% of the wall area.

Estimating ventilation using equation(4-12) would allow the growing source of wind pressure distribution data associated with wind loading to be used, without resorting to wind tunnel studies, provided that suitable pressure distribution and discharge coefficients are known. This may encourage the use of this method in the design office when dealing with openings of approximately 10% of the wall area. However, when openings through a building are in excess of 20% of the wall area, as is common in buildings in hot countries, the discharge coefficients may be questioned and the effective pressure difference may become increasingly difficult to determine. Moreover, the opening geometry may influence the discharge coefficients for rectangular openings in series. The arrangement of large inlet and small outlet increases the kinetic energy

Table (4 .9) Typical discharge coefficients for single openings in buildings (18).

Description of openings	Typical range for normal incidence	Jet Characteristics
Small openings in thin walls, less than 10% of wall area near the centre of the wall.	0•50-0•65	Small inertía due to small mass of air in jet.
Openings 10-20% near the centre of wall, with aspect ratio similar to the cross-section of the downwind space.	0•65-0•70	Significant inertia due to increased mass of air in jet.
Opening 10-20% of wall with one edge common with the downwind space, such as a doorway.	0•70-0•80	Wall effect reduces energy losses on one side of jet.
Opening similar in size to the cross-section of the downwind space.	0•80-0•90	Wall effect around the perimeter of the jet significantly reduces turbulent energy losses.

loss in the flow stream, while a similar or larger downstream opening reduces the energy loss. The alignment of openings with jets ensures minimum energy loss due to forced change in the flow direction. Surfaces close to and parallel to jets reduce the energy loss due to turbulent mixing by up to 40%. Windows inclined to the direction of the wind will reduce the effective area by approximately the cosine of the angle, and reduce the kinetic energy of the wind due to forced change in direction. The estimation of mean internal air speeds are only possible in locations near the inlets. Bearing in mind the main purpose of natural ventilation in hot climates, where body cooling is of prime importance, the restrictions of the pressure difference method are very clear. For body cooling, it is necessary for designers to be able to estimate air speeds at points of interest away from openings and outside the main air flow jet. Air speeds in these locations cannot be estimated by this method. Ensuring the occupants' thermal comfort may restrict the furniture arrangement to the air jet close to the openings.

b) Velocity Coefficient Method - This method involves the use of velocity coefficient C_{vn} which is the ratio of the mean air speed at a point of interest, $\overline{V}_n$, to the mean wind speed, $\overline{V}_z$, at a specified reference height upstream from the building in the undisturbed flow.

$$C_{vn} = \overline{V}_n/\overline{V}_z$$

Air speeds in different models can be directly compared when they are referred to a common reference wind speed. Evans (100) suggested that in rooms with plans near to a square, and wind blowing normal to the openings, the internal air speed does not increase significantly when window size exceeds 40% of the wall, fig.(4.16). Givoni (119) studied the coefficient velocity in many

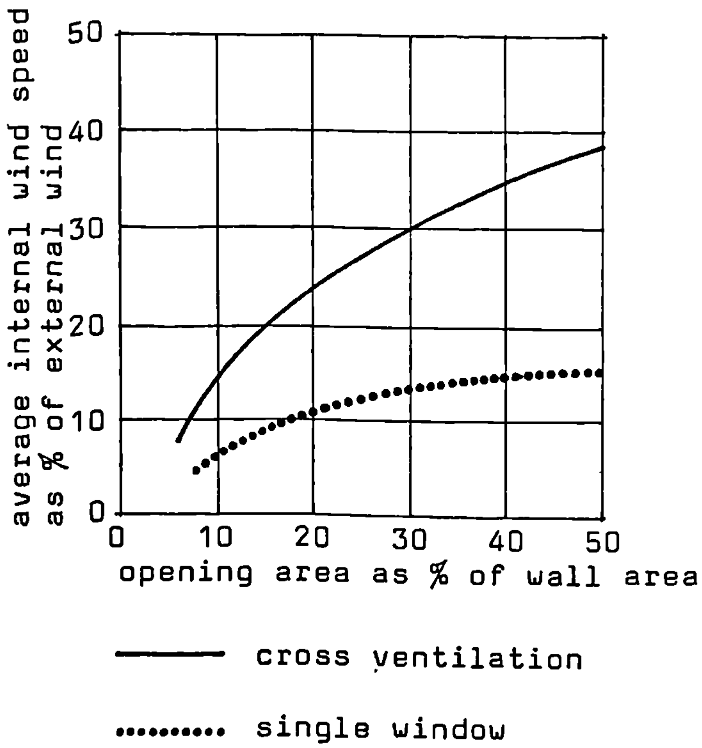


Figure (4.16) Graph assumes rooms which are close to square on plan and wind blowing directly onto the face of the building. Internal wind speed does not increase significantly when window size is increased beyond 40% of the wall area. After Evans (100).

models[1] consisting of a single cell and a single cell incorporating an internal partition, in which he referred his measurements to the air speed at 1·2 metres. Fig.(4.17) gives an account of his observations on the effect of the window size on the average internal air speed. When using low reference heights, it is important to ensure that the inlet is clear of local interference by any obstructions. A more useful reference would be the local meteorological wind records height, which is 10 m above the ground on open sites or 10 m above the buildings in urban areas (245). Knowing the 10 m wind speed for a particular month and time of day, eg the design limit for the overheating season, the air speed $\overline{V}_n$ in the area of interest within the full scale building can be estimated, provided the appropriate velocity coefficient is known from wind tunnel studies:

$$\text{Full scale } \overline{V}_n = C_{vn} \overline{V}_{10} \qquad (4\text{-}13)$$

Velocity coefficients for models with openings of 100% of the windward and leeward walls and for adjacent single cells have been determined by Aynsley (18). Fig.(4.18a) gives the C_{vn} for the air flow through single cells with 7·3 m depth, 4·9 m width and 0·9 m overhang, while in fig.(4.18b) the effect of extending both the end walls and the overhang is postulated. When the wind direction is inclined to the windward face, the

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1 Givoni used models 65 x 65 x 50 cm which occupied 27% of the working cross section, 80 x 150 cm. Model blockage is recommended to be about 5% as in (115), while some researchers recommend even 3%. This casts some doubt on the validity of the pressure distribution around the model in general, and that on the leeward side in particular. The use of air speed at window sill height as a reference will have caused unrepresentative turbulence near the opening, producing a higher speed than that of the actual flow.

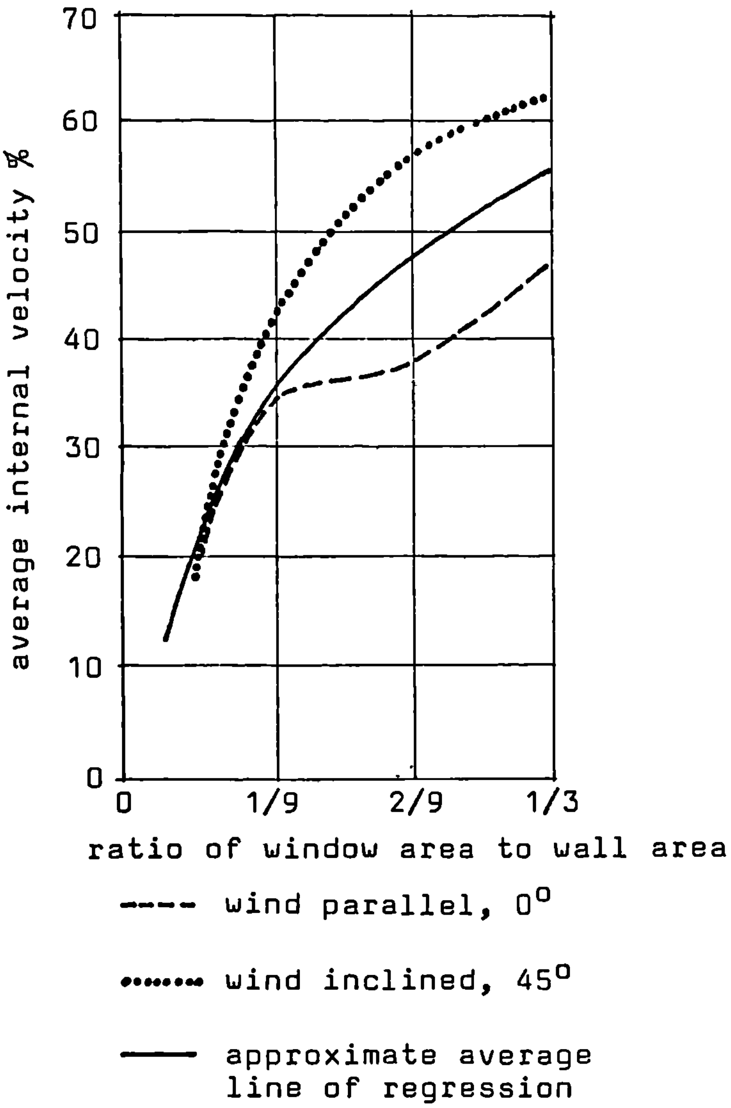


Figure (4.17) Effect of opening area when inlet and outlet change identically, (119).

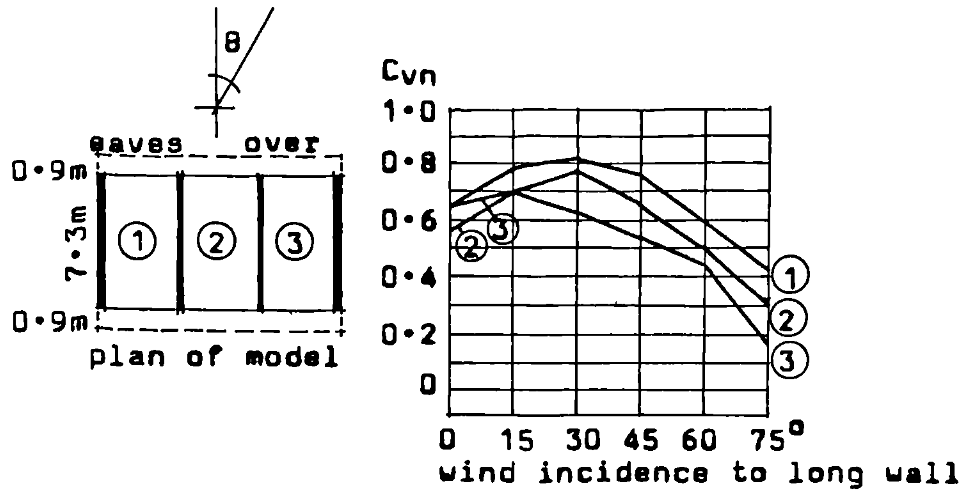


Figure (4.18a) Mean wind speed coefficients at varying incidence through a low set house with small eaves and two internal partitions.

NOTE: reference wind speed for wind speed coefficients was the mean wind speed at a height of 10m in a mean wind speed profile with a gradient height of 400m and an exponent of ∝ = 0;28.

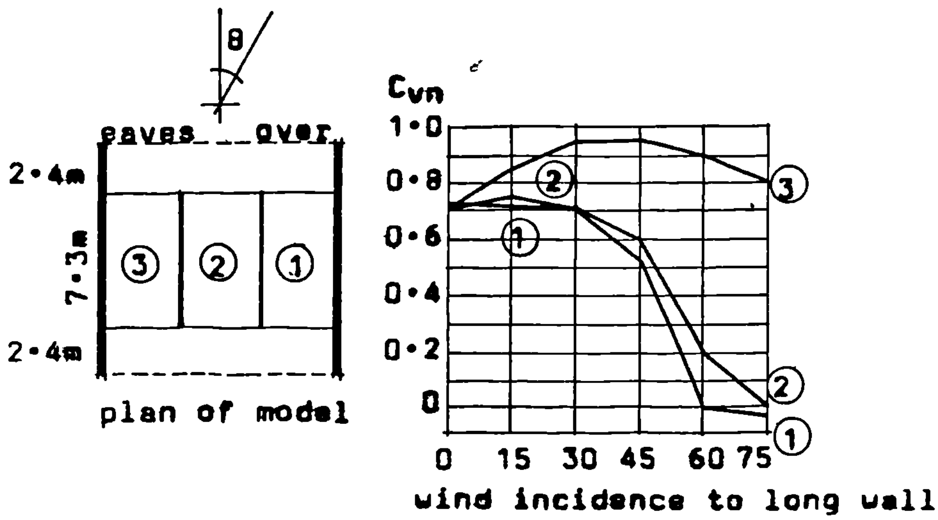


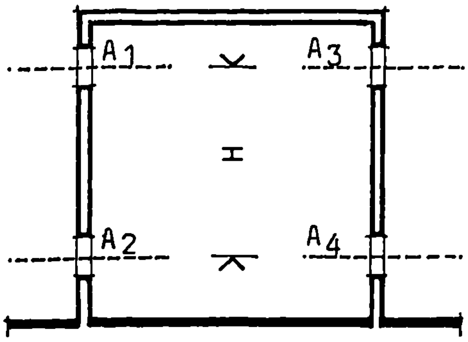
Figure (4.18b) Mean wind speed coefficients at varying incidence through a low set house with extended eaves and end walls and two internal partitions. (18)

velocity coefficient increases for the first model. On extending the end walls and the overhang, the air speed falls in the central and nearer cells but increases in the farther cell.

The use of the velocity coefficient method has the limitation of the need for wind tunnel studies on each model of interest, with accurate modelling when complex openings are invloved. Yet, the simplicity of the velocity measurements and calculations make its use possible, even at the early sketch design stage, provided the velocity coefficients are already determined. The ease of assessing air velocity at any point of interest helps to relate the calculation directly to physiological body cooling, and correspondingly to the thermal comfort within the space. Considering the type of space and the functional zoning within it, it seems possible to establish comprehensive C_v data which can halp in determining air speeds in standard zones of the anticipated occupancy.

4.3.3 The Resultant Natural Ventilation

Air flow within a building is generated by the pressure difference between its cells and the outside environment. The generating forces may be thermal or inertia, or both acting at the same time to produce the resultant air flow. The gradient obtained across a given opening may be considered a function of the algebraic sum of the pressure differences due to each force seperately. The maximum air flow will be expected when the two forces act together in the same direction. The general characteristics of natural ventilation can be illustrated by the simple example in fig.(4.19) comprising a single cell with no internal divisions. Assuming the openings are fairly large, and the wind blows with a constant magnitude from a fixed direction, the flow will be similar to that for wind only when small



Arrangement of openings in simple buildings

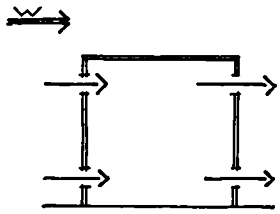
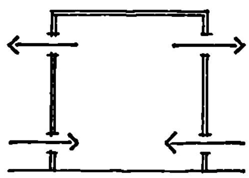
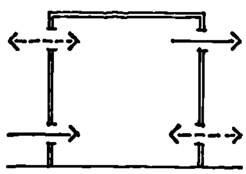
Conditions	Schematic	Formula
B wind only		$Q_W = C_D A_W U_r (\Delta C_p)^{\frac{1}{2}}$ $\frac{1}{A_W^2} \doteq \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$
A temperature difference only		$Q_B = C_D A_b \left(\frac{2\Delta\theta g H}{\bar{\theta}}\right)^{\frac{1}{2}}$ $\frac{1}{A_b^2} = \frac{1}{(A_1+A_3)^2} + \frac{1}{(A_2+A_4)^2}$
C wind and temperature difference together		$Q_T = Q_B$ For $\frac{U}{\sqrt{\Delta\theta}} < 0\cdot26\left(\frac{A_b}{A_W}\right)^{\frac{1}{2}}\left(\frac{H}{\Delta C_p}\right)^{\frac{1}{2}}$ $Q_T = Q_W$ For $\frac{U}{\sqrt{\Delta\theta}} > 0\cdot26\left(\frac{A_b}{A_W}\right)^{\frac{1}{2}}\left(\frac{H}{\Delta C_p}\right)^{\frac{1}{2}}$

Figure (4.19) Cross ventilation of single cells (56).

temperature differences exist, but as temperature difference increases, air flow through upper openings due to wind pressure is reduced and the outward flow is increased. At lower openings a reduction in the out-flowing air will occur, while the in-flow will be reinforced. As the air temperature increases and wind pressure decreases, the flow approaches that for the temperature difference alone. A reasonable approximation may be achieved by considering the flow rates due to each mechanism, and applying the greater as the resultant ventilation (56).

On calm days wind has very low speed[1], hence thermal forces dominate the ventilation process. These forces are dependant on both the temperature difference between the internal and external spaces and the pressure head, ie the vertical distance between the inlets and outlets. So, air flow due to thermal forces will be of importance only when at least one of these factors has a significant magnitude. In multi-storey slabs of low-cost residential units, very high ventilation rate is a common feature during the overheated periods where air mixing can be considered perfect, hence temperature difference between inside and outside the building will range from 1·0 to 3·0°C, figs.(4.4 & 4.5). Ceiling height in these types of residential units ranges between 2·7 and 3·0 m, with window sill heights ranging between 0·9 and 1·2 m. Neither the temperature difference nor the pressure head have a magnitude great enough to generate air flow. This illustrates the significance of the slightest breeze in alleviating uncomfortable environmental conditions. Thus it is important to examine the effect of wind flow patterns on buildings as they influence the physical internal environment.

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1 On a calm day wind speed is less than 0·25 m/s, table (4.10).

4.4 Wind Patterns and Building Forms

The importance of wind driving ventilation and shaping buildings in the hot countries of the Middle East has been evident throughout their architectural history. The form of the Ancient Egyptian house was characterised by the 'Malqaf'[1], fig.(4.20), or air scoop, on the roof (206, 11). This feature has been used in Egypt since these early times and its use spread eastward to reach the Persian Gulf (68), Iraq (6), Pakistan (226) and Iran (23). The Mid-Eastern houses oriented their 'Iwans'[2] in the direction of the beneficial wind.

Wind speeds and directions for each month are required if accurate information is to be obtained about air flow patterns around and within buildings. However, if the concern is for air flow for structural and environmental safety (145, 215), other parameters concerning gust characteristics are required. Generally, wind information available from the meteorological stations is not directly applicable to ventilation and pressure calculations. Modifications due to wind configuration from natural and man made obstacles should be allowed befor using this data. Meteorological stations are usually located[3] near airports, in rural open spaces and in coastal areas where there are very few obstacles. As wind moves over a built up area,

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1 The 'Malqaf' is a device used for the first time in the Ancient Egyptian house to catch cool air high above the roof. Al-Zogbi (11) reports on many house models in the Egyptian Museum. It consists of an air inlet with inclined roof and vertical opening oriented towards the desirable wind and directing it down to the living level(P457).

2 'Iwan' is a high, pointed arch commonly used in Islamic houses to cover the living spaces.

3 These locations are chosen to produce data for the weather in general, and the parameters concerning navigation and aviation in particular.

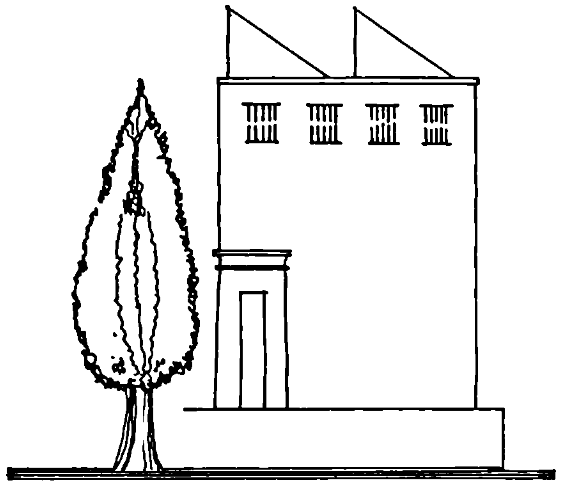

Figure (4:20) Reconstruction of the house of Netamun. The house of Nakht from a drawing in his papyrus.

buildings cause interference and modifications in both direction and magnitude occur. A high building projecting over its surroundings will form an obstacle to the wind and deflect the air along various streams and channels, producing conditions at street level which may differ markedly from those experienced among buildings of uniform height. The pressure difference developed around such a building will affect in turn the pressure system around other nearby buildings. Penwarden et al (216), White (265), Wise (267, 268) and Hunt (144) report the effect of such buildings on the environment in their vicinity where pedestrians suffer from unacceptable wind conditions. Many of the reported cases have been rectified, some more successfully than others. However, the extra cost and time involved in modifying the solutions could have been avoided if, during the design stage, the architects were aware of the possible wind conditions. It is more convenient to alter the lay-out and design of buildings in accordance with the wind criteria while schemes are still on the drawing board. The aim of the designer should be the creation of a pleasant environment both inside and outside his buildings, including acceptable wind conditions. Faced with the many changing parameters of wind configuration with buildings, the most satisfactory solution can be achieved by testing 3-dimensional models[1]. At present wind tunnel tests seem to offer the most reliable means of solving the many problems related to the wind environment in and around buildings. Full scale models are usually too expensive, and often require waiting until the building is completed. They are time consuming and have very limited range of modifications. Full scale measurements are however essential to validate the wind tunnel results, and provide a

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1 Flow visualisation devices which produce flow patterns similar to those predicted by potential flow theory are available. Such patterns are extremely misleading as they lack the essential characteristics of air flow around buildings, eg seperation, shear layers and a broad turbulent wake.

guide for the applicability of results from other wind tunnel tests. Studies by White (265), using wind tunnel techniques, to investigate the proposed 18 storey office block for the town centre development at Corby resulted in modifying it to a low rise, 4 storey, block providing equal accomodation.

The observable effects of wind were classified by Admiral Sir Francis Beaufort in 1806 tp provide a means of estimating wind[1] conditions at sea, and his scale of wind forces (table (4.10)) is still in use today.

A generalised design method, applicable to standard situations would be of special importance to designers, This would enable architects to predict the likely wind effects on occupants and design accordingly.

4.4.1 Wind Characteristics

In the architectural sense the term wind usually refers to the air moving parallel to the Earth's surface in the lowest part[2] of the atmosphere. It is convenient to classify wind by the nature and magnitude of the thermal convections involved, dealing on the one hand with the global atmospheric circulation, and on the other with the local winds which, in the main, are induced by the temperature difference caused by local irregularities in terrain. These local winds are often more significant than the more

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1 It is interesting to note that during those times wind was the main energy source for transportation, especially for long distances.

2 The lower part of the atmosphere is below altitude 20 km, the study of which is known as meteorology. However, building, architecture, town planning, and environmental engineering are concerned with the lowest 600 m, except for more ambitious architects like Frank Lloyd Wright, who extended his activity to a one mile tower (sketch design).

Table (4.10) Summary of wind effects on people, based on the Beaufort scale. After Penwarden and Wise (216) and White (265).

Beaufort No.	Conditions	Wind speed m/s	Effects
0	-Calm; smoke rises vertically.	>0·2	No noticeable wind.
1	-Light movement; direction of wind shown by smoke drift, not wind vanes.	0·3-1·5	No noticeable wind.
2	-Light breeze; leaves rustle, ordinary vanes moved by wind.	1·6-3·3	Wind felt on face.
3	-Gentle breeze; leaves and small twigs in constant motion, wind extends light flag.	3·4-5·4	Hair is disturbed.
4	-Moderate breeze; raises dust & loose paper, small branches are moved.	5·5-7·9	Disturbs light dresses.
5	-Fresh breeze; small trees in leaf begin to sway, crested wavelets form on inland waters.	8·0-10·7	Wind felt on body, drifting snow becomes airborne, limit of agreeable wind on land.
6	-Strong breeze; large branches in motion, whistling heard in telegraph wires.	10·8-13·8	Umbrellas used with difficulty, hair blown straight, difficult to walk steady, wind noise in ears unpleasant, windborne snow overhead.
7	-Near gale; whole trees in motion.	13·9-17·1	Inconverience felt when walking against wind.
8	-Gale; breaks twigs off trees.	17·2-20·7	Impedes progress, great difficulty with balance.
9	-Strong gale; slight structural damage occurs - chimney pots and slates may be removed.	20·8-24·4	People blown over by gusts.

widespread circulation system. Air is in motion due to the horizontal pressure difference caused by heating and cooling of the atmosphere[1]. As air has mass and is in motion on the surface of a spinning sphere, it consequently behaves in accordance with the laws of mechanics. Generally the resultant horizontal deflecting force on the moving air mass will be the algebraic sum of the rotational and centrifugal forces. The deflecting forces are additive when the wind flow is clockwise in the southern hemisphere, or anticlockwise in the northern, and vice versa. The frictional force is generated as soon as motion starts, so that equilibrium is eventually reached with the wind direction tilted towards the lower pressure. The frictional force steadily decreases with height from maximum at the surface to zéro at the gradient height, so that not only does the wind speed increase with height, but also its direction shifts with increasing altitude, to become nearly parallel to the isobars. The curve of the wind vectors on the horizontal plane is known as 'Ekman Spiral'. The layer of the atmosphere in which wind shifts in this way is known as the 'Ekman Layer' fig. (4.21). The actual shift is about 30^{o} over land, decreasing to about 15^{o} over the sea where the frictional forces are lower. Recent research in this area (141, 133) established the existence of a surface layer, 10 to 30 m high, adjacent to the ground, over which the wind properties and direction remain constant.

A sheet of air moving over the Earth's surface is reluctant to rise in the face of an obstacle, but if the obstaclé's nature is suitable, the air will tend to flow around rather than over it. Generally, if there is a gap in the line of the obstruction air will tend to flow through it causing an increase in wind speed. Similarly, wind coming

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1 The general atmospheric circulation has been discussed previously in Section 2.2.4, emphasis on that of hot and moderate climates in Section 2.3.2, while the Egyptian conditions have been examined in Section 3.2.4.

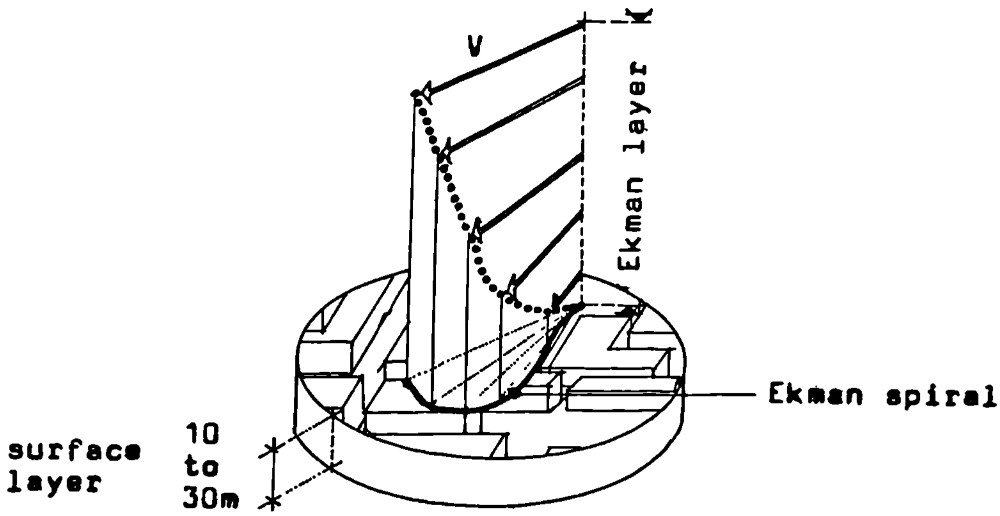

Figure (4.21) Wind speed increase with height and its direction shifts with height.

from the sea will be canalised between headlands and will tend to flow along the estuary, sea loch or valley[1] where it may give local wind directions at water level somewhat varying from mean wind speed.

Wind velocities vary in magnitude and direction at all times randomly with reference to a fixed point in the atmosphere. In the case of turbulent flow the process is called a stochastic process. Fortunately it has been found possible to separate the turbulent flow properties into mean, $\overline{V}$, and fluctuating, $V' = \Delta\overline{V}$, components. Their algebraic sum is equal to the latitudinal velocity component V, fig.(4.22a), and is expressed as follows:

$$V = \overline{V} + \Delta\overline{V} \qquad (4\text{-}14)$$

The mean velocity ($\overline{V}$) in the above equation can be regarded as steady for most architectural cases, with the unsteady, time dependent part ($\Delta\overline{V}$) being incorporated in the fluctuating part. Therefore, most of the flow and interaction phenomenon can be usefully described in terms of the steady time average mean characteristics.

As wind moves from smooth to rough terrains, the velocity is reduced due to the presence of natural and man-made obstacles. The reduction occurs in the lower part of the atmosphere which in architectural aerodynamics is regarded as the boundary layer. Turbulence characteristics and mean velocity distributions across this layer, which ranges in depth from about 250 to 600 m, profoundly influence wind effects on buildings. Architectural aerodynamics is so intimately related to the characteristics of the boundary layer that a review of wind flow around and within building

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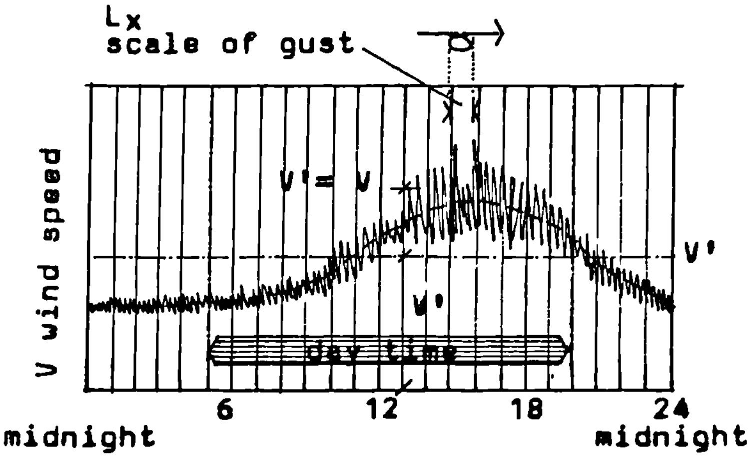
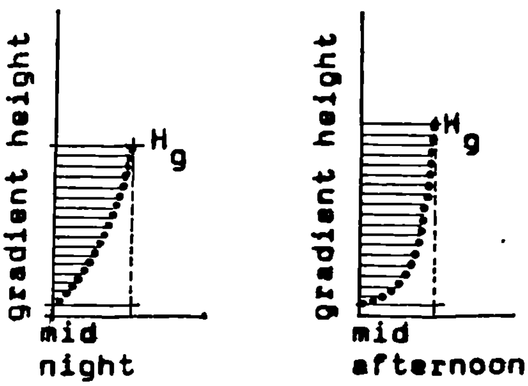
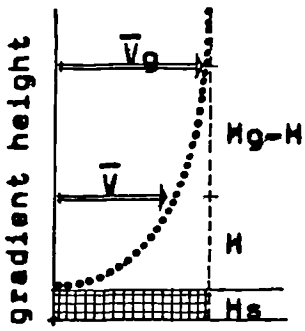
1 Wind blows up the Nile Valley (north to south) according to this phenomenon. Egyptians travel northward with the current and southward utilizing the prevailing winds.



a) Diurnal variation in wind velocity on a clear day, summer.



b) Velocity profiles



c) Velocity gradient

Figure (4.22) Temperature effect on velocity gradient.

should be preceded by an understanding of the characteristics of that layer. The vertical distribution of mean velocity, turbulence intensity[1] and height scale of turbulence for strong winds determine the flow characteristics for most considerations of wind effects on buildings. Unfortunately no analytical formulation relating surface roughness to the vertical distribution of mean velocity and turbulence parameters exists. The most used form of the distribution of mean wind speed, $\overline{V}$, with height, H, is a 'power law' expression:

$$\overline{V}/\overline{V}_g = (H/H_g)^{\alpha} \qquad (4\text{-}15)$$

where g refers to the reference gradient value and α is an expression depending on the surface roughness as in table (4.11). However, within the rough surface itself the air speed will be approximately constant (141, 245, 133, 69) and is referred to as the standard height (H_s) table (4.11) above which the velocity profile is given by

$$\overline{V} = \overline{V}_g \times H_s \times (H/H_g)^{\alpha} \qquad (4\text{-}16)$$

The standard height may be taken as the rooftop level of buildings in the vicinity of the tower or group of buildings. Wind below the standard height behaves in a highly irregular manner and it is not feasible to prescribe any empirical or theoretical profile, Moreover, for the same reasons, it is not recommended to simulate the gradient speeds in the wind tunnel for wind speeds lower than 10 m/s (133, 70).

Meteorological data are obtained from measuring stations

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1 The intensity of turbulence is a measure of the main fluctuation over the mean velocity, hence, turbulence intensity = $(\Delta\overline{V}^2)^{\frac{1}{2}}/V$. The longitudinal scale of turbulence is a measure of the length of eddy or gust (L_x).

Table (4.11) Surface roughness; the parameters of the power law (133).

Category	Definition	α	Hg m	Hs m
A	Exposed open terrain with few or no obstructions, eg sea coast and flat plains.	0·1	250	0-5
R[1]	Open terrain with scattered obstructions, eg airports, open parkland with isolated structures. A reference terrain for measurement of zonal wind speed.	0·15	300	2-10
B	Terrain with numerous closely spaced obstructions including small wooded areas and the outskirts of large cities.	0·22	350	5-15
C	Terrain with large structures, includes large city centres, eg Cairo.	0·3	400	10-20 [2]

1 R is considered to be the reference terrain to which all other categories should be referred. This terrain has the characteristics of those surrounding most of the meteorological stations. For example, Ezbekieh in Cairo, falling in category C, should be referred to the reference terrain before applying the meteorological record

2 The height may be changed according to the average roof height surrounding the tower or group of buildings.

located at airports or places which correspond to open site conditions and have the same character as terrain category R, table (4.11). The reference mean wind velocity[1] depends on the purpose for which it will be used, and for this section will be considered as the daily mean with hourly change in direction. This is measured at a standard 10 m height. The velocity profiles for other types of terrain can be expressed in terms of the reference terrain R by using the gradient height terms as shown in table (4.11). The gradient velocity for all types of terrain is the same, facilitating the conversion from one type of surface roughness to another. Handa (133) derived an expression for the relationship between them as follows:

$$\bar{V}_{AH} = C_{AH} \times \bar{V}_{R10} \qquad (4\text{-}17)$$

$$C_{AH} = 1{\cdot}13 \times (H/5)^{0{\cdot}1}$$

$$\bar{V}_{BH} = C_{BH} \times \bar{V}_{R10} \qquad (4\text{-}18)$$

$$C_{BH} = 0{\cdot}83 \times (H/15)^{0{\cdot}22}$$

$$\bar{V}_{CH} = C_{CH} \times \bar{V}_{R10} \qquad (4\text{-}19)$$

$$C_{CH} = 0{\cdot}68 \times (H/20)^{0{\cdot}3}$$

The design curves for the speed coefficients C_{AH}, C_{BH} and C_{CH} are presented in fig.(4.23). Knowing the value of the reference wind velocity $\bar{V}_{R10}$ at the reference height of 10 m for open site conditions, ie the meteorological wind speed record, the wind velocity for any other type of terrain at a specific height H can be calculated.

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1 For wind loading considerations it is usually measured at 10 m height, at 10 minute intervals, and correlated to gust speed (201, 254).

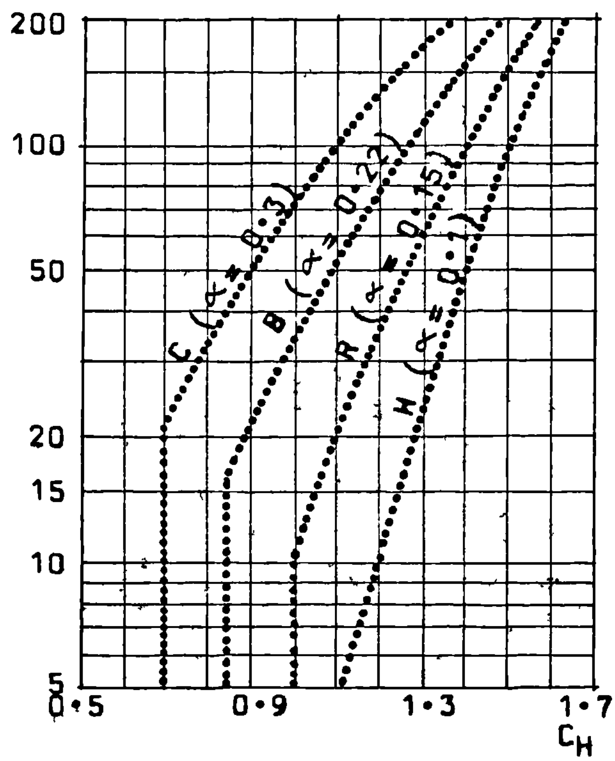

Figure (4.23) Speed coefficient for different surface roughness (133).

$$C_Z = \frac{\overline{V}_Z}{\overline{V}_{R10}}$$

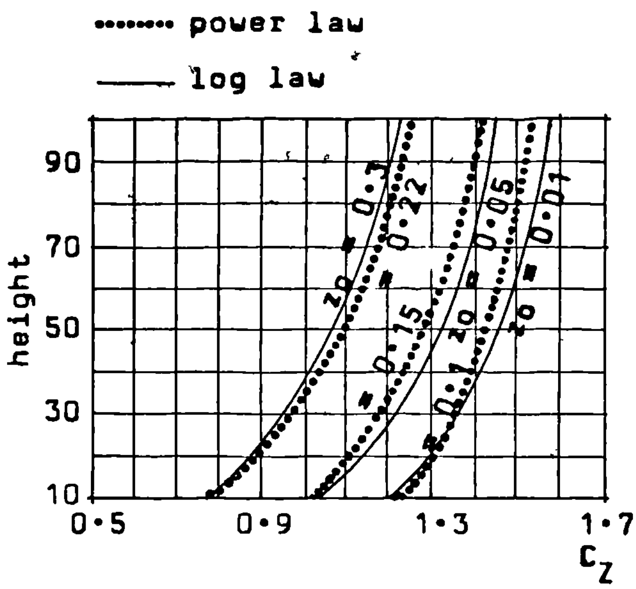

Figure (4.24) Comparison between logarithmic and power law profiles (133).

The other method in use for representing the velocity gradient is the logarithmic law and is given by:

$$\bar{V}_H = V_F \times 1/K \times \ln(H/H_o) \qquad (4\text{-}20)$$

where:

V_F = friction velocity

K = Karman constant, value = 0·4 (98)

H_o = varies between 0·1 cm and 3·0 m, depending on the surface roughness, and is approx 10% of the average obstacle height.

The use of the log law is advocated because of its application in wind tunnel work and meteorology. However, in practice there is no pronounced difference between them, Fig.(4.24), and the power law is chosen for its easy application in building aerodynamics.

Temperature gradient in the boundary layer may affect the velocity gradient profile and the changes between super-adiabatic and inversion conditions are illustrated by the diurnal variation in surface wind occurring in clear summer weather, fig.(4.22b). During the day the rapid heating of the ground will lead to super-adiabatic conditions resulting in an increase in gradient height, high surface velocities and a high intensity of turbulence. At night clear skies permit heat to radiate quickly from the ground, leading to inversion conditions and allowing the gradient height to decrease, the velocity profile to become very steep, the surface velocity to fall to very low values, and the turbulence to become negligible. Unfortunately, there are no suitable means available for simulating these conditions in the wind tunnel or in wind calculations.

Before proceeding to the more specific section, discussing air circulation around and within buildings, it is important to understand the flow properties likely to be met.

Air flow fields can be divided into three regions, as in fig.(4.25)a,b&c , and can be described as follows:

a) Free stream flow - This is the flow ahead of and outside the immediate influence of the body. Most importantly, this is the region where mean shear rates are negligibly small.
b) Shear layers - These are regions of high mean shear rate. A boundary layer of fluid through which the mean velocity at the outer edge is a very important shear layer. When a boundary layer separates from a surface or at an edge, it becomes a free shear layer separating free stream flow on one side from a wake flow region on the other.
c) Wake flow - This region is usually developed[1] behind a separating shear layer having low velocity, eddies, vortices or reverse flow.

Air flows as stream lines,,defined as being tangential to the instantaneous direction of the flow. For steady flow conditions where there is no flow across the stream lines, the path of a typical trail of smoke is coincident with the stream line. Hence, it is possible to use smoke, bubbles of dye tracers to provide visualisation of the flow pattern, fig.(4.25).

In the free stream flow, the relationship between pressure and velocity in different parts of a fluid field can be obtained by analysis of the dynamics of a particle of the fluid. This is usually referred to as Bernoulli's equation. Assuming a steady flow of inviscid[2] and irrotational[3] fluid

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1 Two boundary layers which meet at the trailing edge of a streamlined shape also develop a type of wake flow.
2 Viscous forces are negligible.
3 Elements of fluid undergo zero rotation as they deform in the flow.

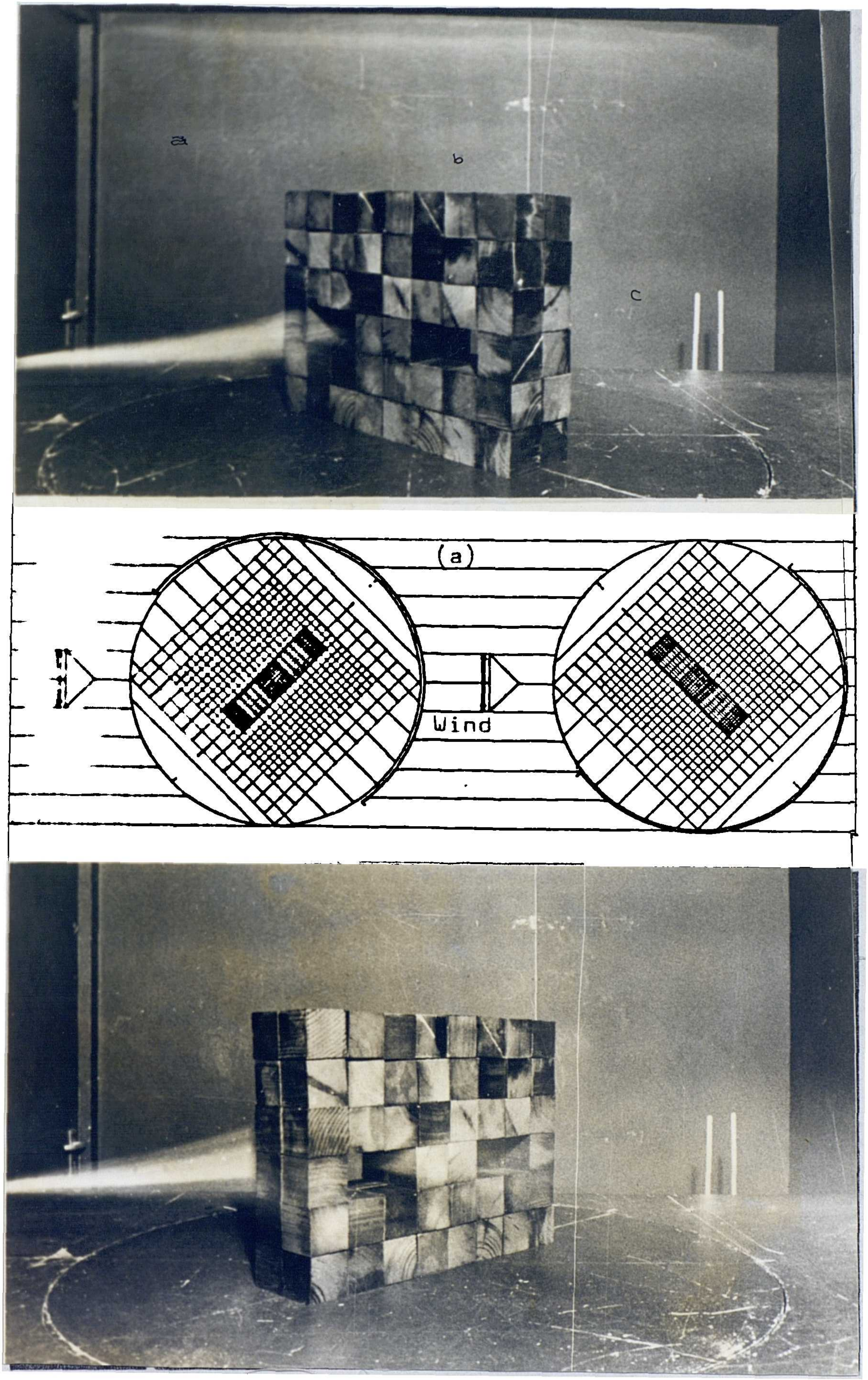

Figure (4.25) Visualisation of the flow pattern showing flow fields a) free stream, b) shear layer and c) wake flow.

Bernoulli's equation can be written as:

$$P_1 + \tfrac{1}{2}\rho\overline{V}_1^2 + \rho g H_1 = P_2 + \tfrac{1}{2}\rho\overline{V}_1^2 + \rho g H_2 \qquad (4.21)$$

where:

P	=	static pressure
H	=	height above a horizontal datum
g	=	gravitational acceleration
ρ	=	fluid density

In the boundary layer the gravitational term is negligibly small, so air may be regarded as homogeneous and incompressible, thus equation (4-21) can be rewritten:

$$P_1 + \tfrac{1}{2}\rho\overline{V}_1^2 = P_2 + \tfrac{1}{2}\rho\overline{V}_2^2 = \text{constant} \qquad (4\text{-}22)$$

Bernoulli's equation is applicable only to steady free stream flows and specifically excludes shear and boundary layer flows where rotation also occurs.

4.4.2 Induced Circulation Around Buildings

Due to the numerous factors governing the wind/building configuration, a complete description of wind flow patterns around all types of buildings is out of the scope of this part, and only those factors governing ventilation problems, with reference to simple shapes and groups of buildings, will be described.

The building is a three dimensional object allowing free air flow around its surfaces. Air flow can be considered to develop due to two separate mechanisms or pressure fields which cause high wind speeds near the edges and at ground level. The first type of flow is caused by the pressure distribution on the windward face of a building. This is related to the local wind dynamic pressure, which increases with height for winds normal to the building.

In general, pressure on this face is above the atmospheric pressure. The maximum occurs at stagnation point[1] where the wind is brought to rest. The pressure contours follow a well defined pattern centred around this point, fig.(4.26). Close to the corners, accelerating flow may produce small areas where the pressure is below the atmospheric. The resulting pressure gradient induces flow vertically down the face below the stagnation point. This flow rolls up into a standing vortex, fig.(2.25), causing high wind speeds in this region. Configuration of up-stream buildings can be critical for this flow and the effect will be discussed in the next section.

The second type of flow is caused by the pressure difference between the low pressure wake regions and the relatively high pressure regions on the windward side. Flow directly between these two regions through openings, arcades or around the corners can cause very high local speeds with the down flow on the windward face of the building, accelerating the flow. The taller the building, the higher the velocities induced through voids in the building and around its corners, fig.(4.28). Considering both flow direction and pressure pattern along the building face, one might question the locations of openings, and their design details, for many existing buildings[2]. Near ground level the three regions in which increased speeds are likely to occur are vortex flow (A), cornerstream (B) and through flow (C), fig.(4.28). The side wall, the roof

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1 The stagnation point is the point on the windward side where the wind comes to rest and all its kinetic energy is transferred into pressure. It can be as high as 80% of the building height.

2 At Leicester University innovative window design has been introduced on all faces, fig.(4.27). This is likely to function as a good ventilator on a hot summer day on the windward face except for the central region. On the adjacent sides the same window may provide unsatisfactory ventilation conditions.

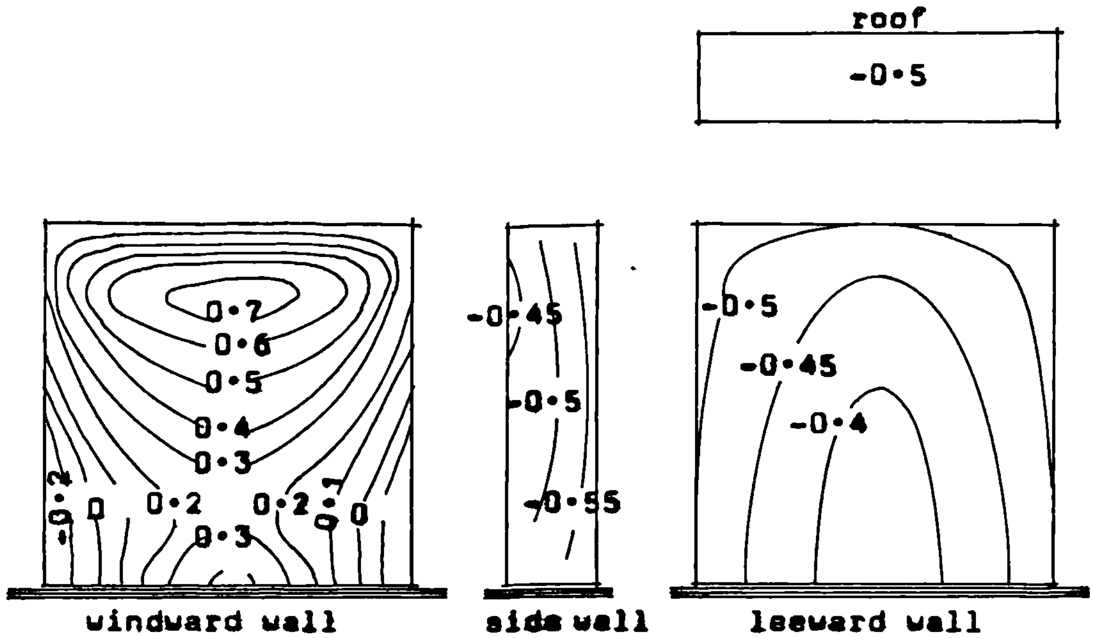
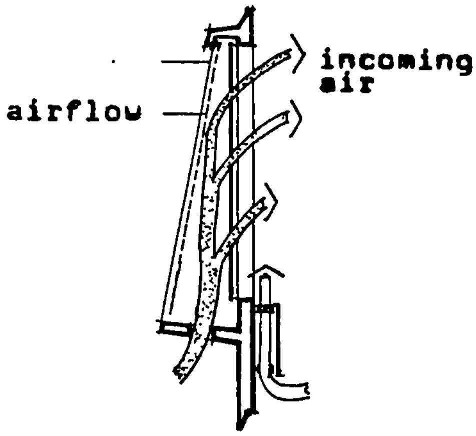
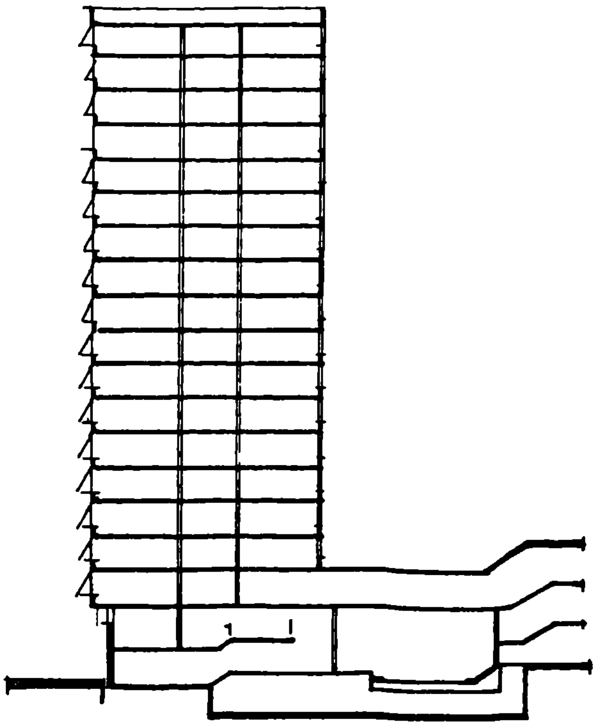


Figure (4.26) Typical pressure distribution on the surfaces of height 0·4m and width 0·4m, with a low building 0:3m upwind. Pressures expressed as coefficients $C_p = (p-p_0)/\frac{1}{2}\rho V_H^2$ where p is the pressure at the surface, p_o is the static pressures in the wind tunnel air stream, is air density, V_H is the wind speed at building height H, and $\frac{1}{2} V_H^2$ is the dynamic pressure of that wind at roof level.



section
through the
window panel



cross section through the glass
tower, Attenborough building,
Leicester University.

Figure (4.27) The Leicester University builidng for faculties of arts and social sciences.

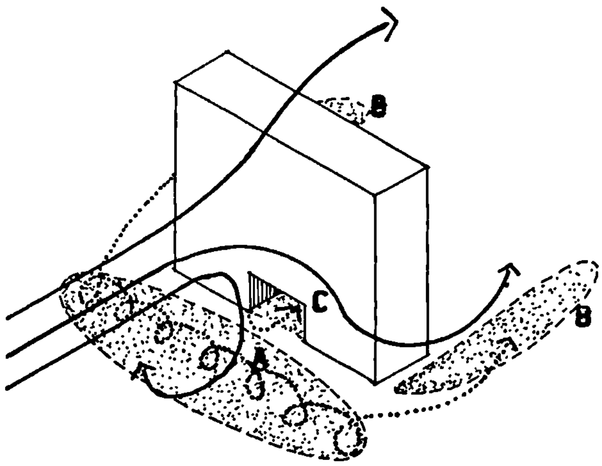


Figure (4.28) The regions with high wind speed.
A - Vortex flow
B - Corner stream
C - Through flow

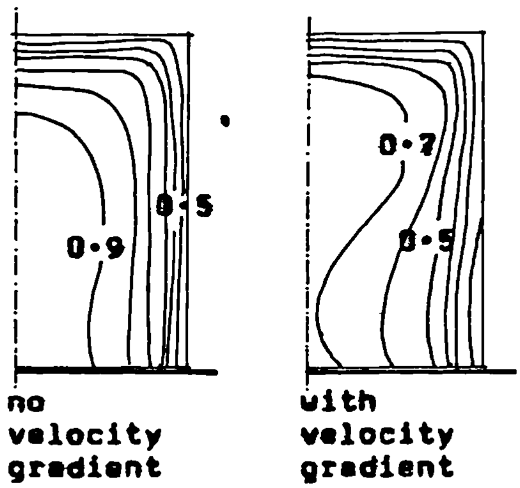


Figure (4.29) Values of pressure coefficient on windward face of an isolated cube.

and the leeward wall all experience suction. At the same time an upward flow occurs towards the regions of high suction on the leeward side. Close to the side walls and roof air flows in a reverse direction, ie back towards the windward edges where the flow separates from the surface of the building. Within the wake region downwind of the building there is a turbulent flow of air, but mean speeds are generally low. A gas introduced into these regions is diffused into the separation cavity and is not transported to the upwind face because transport cannot occur across the stream of separation in the upstream direction.

When seperation and reattachment occur on a surface, strong mean pressure gradients develop and intense vortex motion is generated within a separation cavity. The vortex formation shown for a flat roof in fig.(4.30), according to a wind tunnel test by the author, illustrates this phenomenon. The pressure distributions reported by Cermak (64), BRE (46) and Handa (133) may be the cause of roof damage in many buildings (266). Roof parapets on tall buildings provide protection by keeping the vortex core at a greater distance from the roof surface.

In the case of wind flow normal to the building, the down-stream reattachment distance is dependent on the frontal ratio. Evans (99) reports this phenomenon for different roof shapes and aspect ratios. The reattachment distance seems to be a function of the windward face proportions; increase in the width or height is followed by an increase in the reattachment distance. The change in height effect is more pronounced than that for a change in width fig. (4.31). Flow seperation over the roof of a tall building is frequently a source of trouble from smoke and other effluents (216).

When a building of height H is sheltered by another of equal or greater height, and at a distance not more than

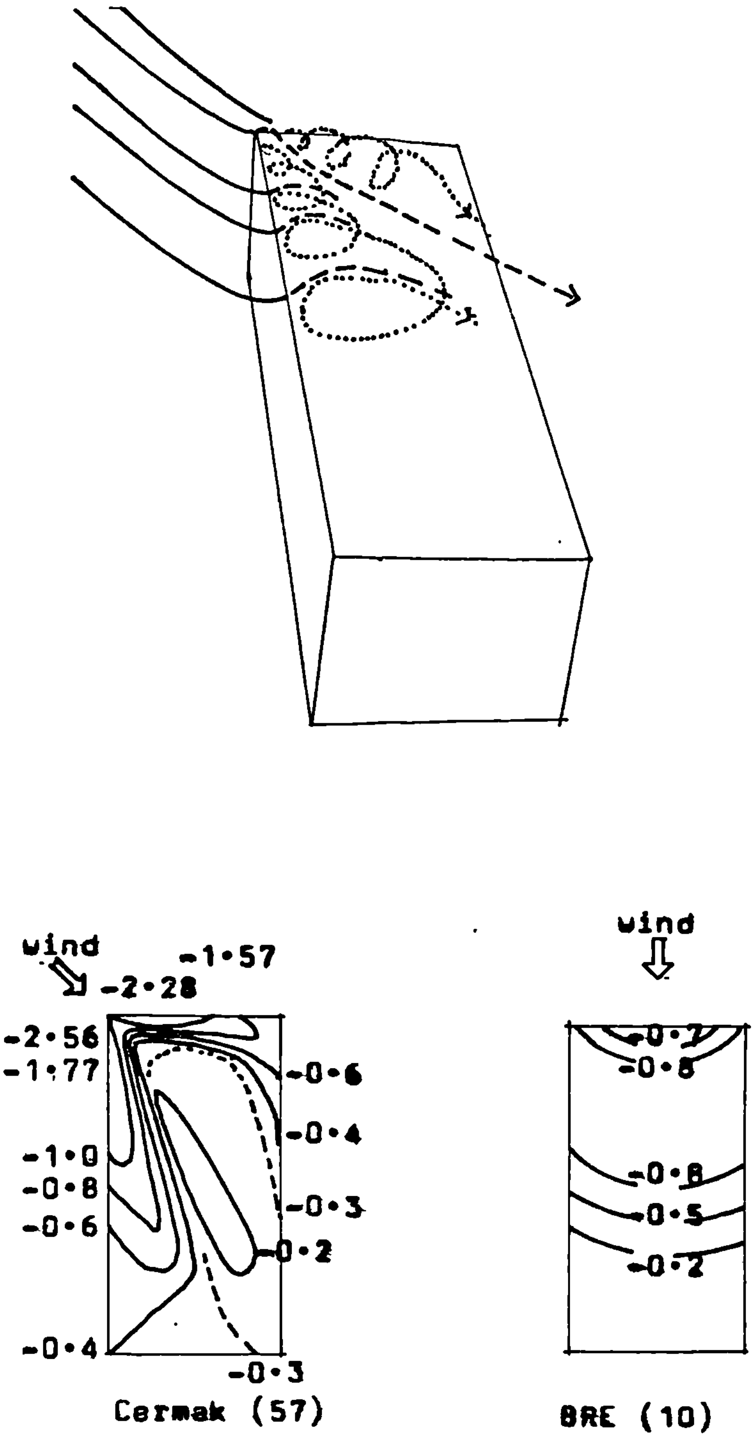


Figure (4.30) Effect of vortex formation on the mean pressure distribution over a flat roof.

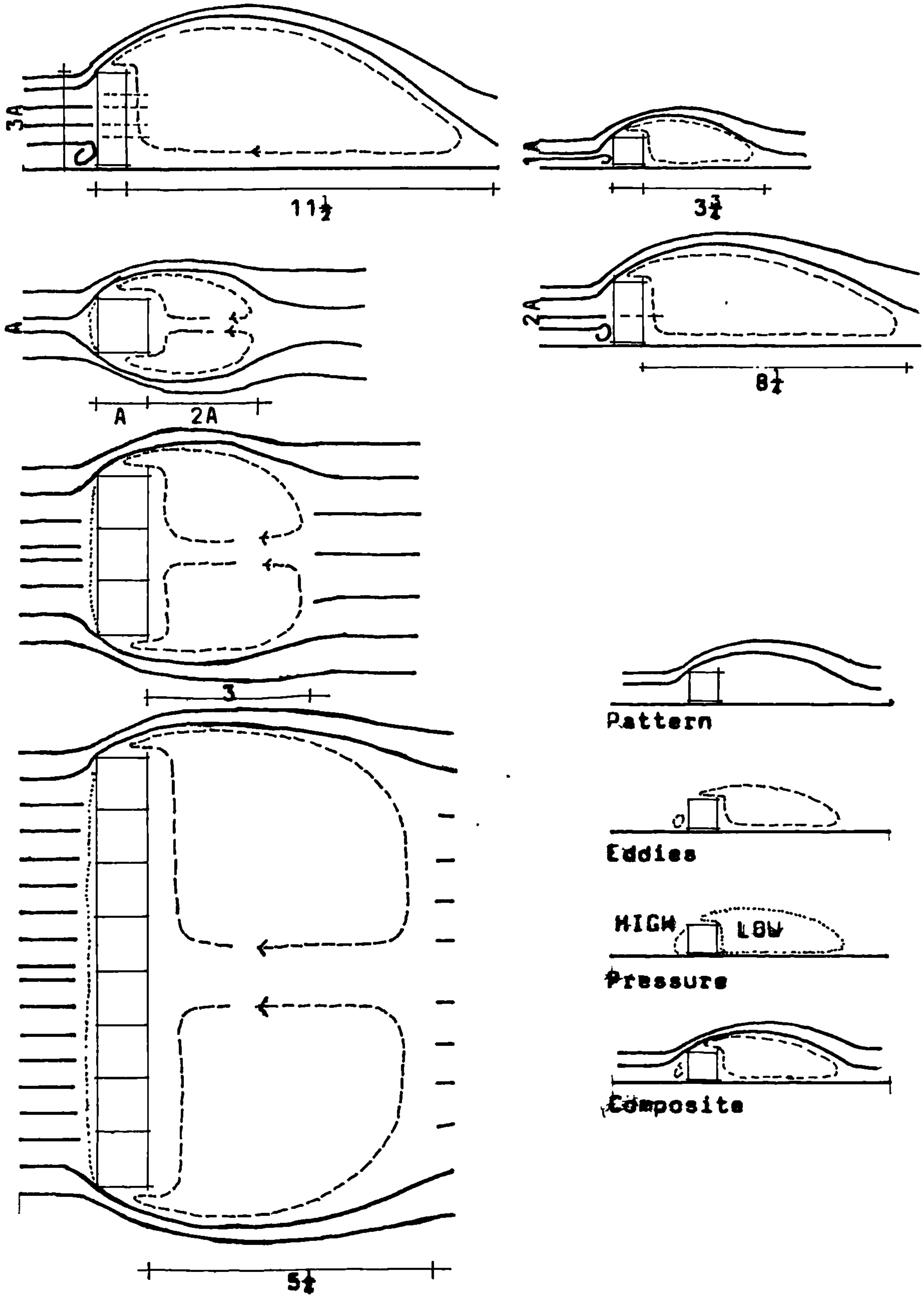


Figure (4.31) Evans observations of the aspect ratio (height, width) parameters on the reattachment distance (99).

3H, the horizontal wind load on the building due to wind from the direction of the shelter will be reduced by a factor of 0·1. Rows of buildings facing the wind cause a reduction in air velocity around and behind them. However, if two tall buildings are positioned close together at right angles, fig.(4.32c), wind velocities up to 80% higher than the free stream can be expected in the gap zone. The velocity is increased by the increase in their heights because of the increase in the down flow along their faces. When a low building is located in the wind shadow of a tall building, fig.(4.32a), the increase in height of the tall block could increase the reversed air flow in a direction opposite to that of the wind, through the low building. This is usually caused by the lower part of a large vortex returning through the low building.

Belts of trees, fences and wind breaks which obstruct wind flow reduce the air speed in the lower layer of the atmosphere and produce shelter. The shelter provided by a screen is defined as a percentage of the free stream velocity. This is expressed as follows:

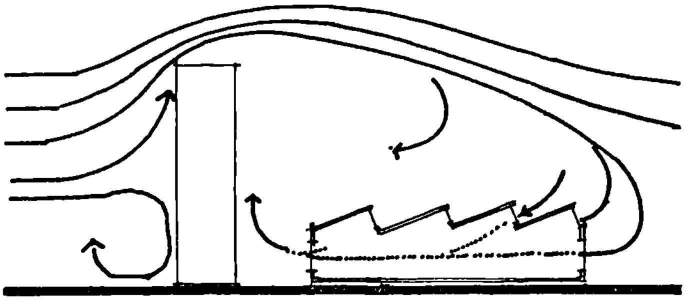
$$\text{(shelter) } S = (V_s/V_o) \times 100 \qquad (4\text{-}23)$$

where V_s = mean wind speed at a point with shelter
V_o = mean wind speed at same point without shelter

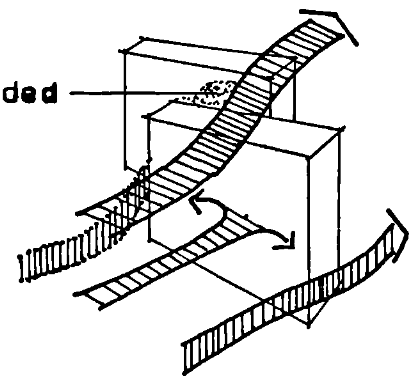
The two parameters used to describe the shelter effect are:

i) length of the zone of shelter
ii) reattachment distance

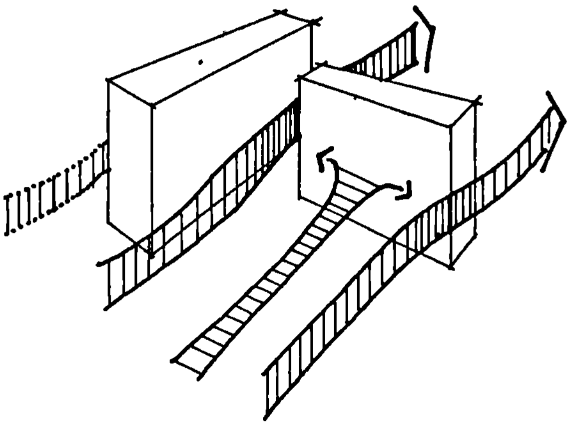
Both these parameters are better described in terms of the shelter barrier height. The length of the zone of effective shelter seems to agree closely with the reattachment



a) Air flow distribution about a high building with a low building to the leeward side.



b) Air flow distribution about two tall buildings parallel to each other.



c) Air flow distribution about two tall buildings close together at right angles.

Figure (4.32) Air flow around tall buildings.

distance[1]. Olgyay (206) reports the shelter effect of a plate. cylinder, triangular shape and trees, each giving a shelter ranging between 7 and 25 times their height. Penwarden and Wise (216) indicated that for wind flow over a row of low rise buildings pedestrian areas are generally sheltered, with wind speed ratios in the range of 0·5 - 0·7 of that at the top of surrounding buildings.

Olgyay (206) presented a series of flow visualisations in two dimensions. The group model consisted of six blocks arranged in three rows at different spacings. The main conclusion resulting from this was that the pattern of gridiron with buildings aligned with the wind direction provides more shelter to subsequent rows of buildings, while the staggered pattern gives better ventilation. It was recommended that an inter-block distance of seven times the building height should provide satisfactory ventilation fig.(4.33).

Soliman (245) reports the work of Vincent and Bailey who, in a series of wind tunnel experiments, considered two buildings in a row. The geometrical values considered in this study were the building shape (roof), the group form (height) and the distance of separation. They concluded that an upstream low block would reduce the pressure difference across the high building by about 20% maximum. Increasing the upstream block height to equal or exceed that of the downstream will decrease the pressure. The effect is magnified by decreasing the seperation distance and the windward wall pressure of the downstream block was less than that of the leeward wall.

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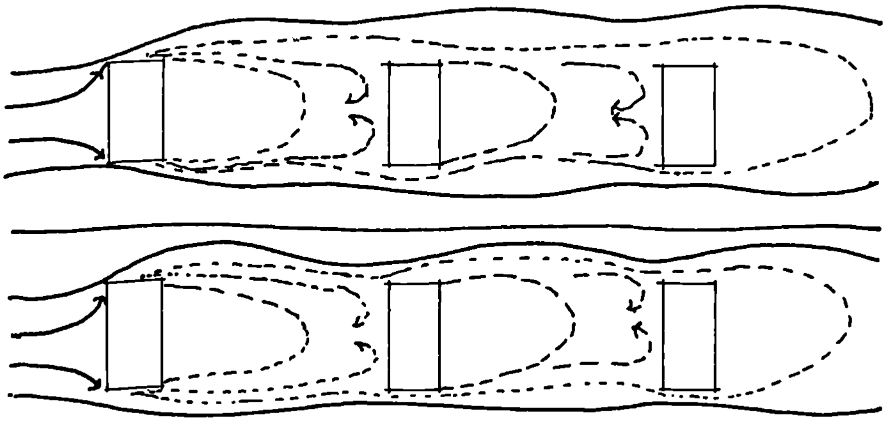
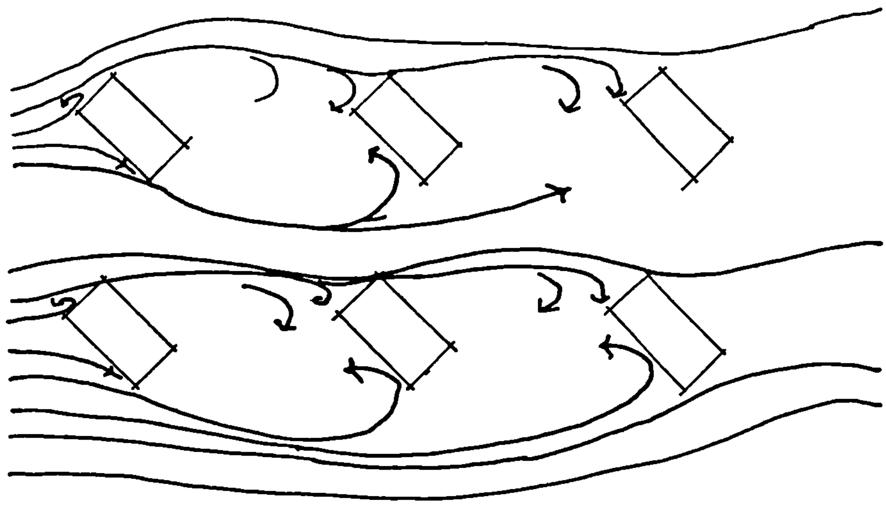
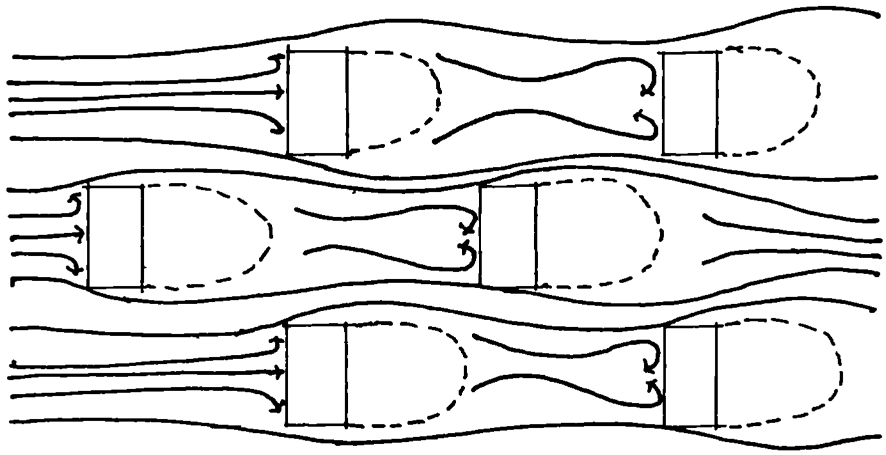
1 When a flow is forced to separate from a boundary layer by a discontinuity or adverse pressure gradient, the flow will reattach itself to the boundary at a position depending on the flow and the obstacle's properties.



a) gridiron layout



b) inclined blocks layout



c) checkerboard layout

Figure (4.33) Diagrams of wind flow around housing layout. After Olgyay (206).

Givoni (121) investigated the effect of building grouping geometry on air flow pattern and natural ventilation. His blocks were arranged in either two or three rows, normal to the wind. In the two-row cases the separation distance was varied between 0•75 and 3•25 times the height, while in the three-row the distance was 0•75 to 1•25 times height with 0•25 times height intervals in both cases. He observed increases in the air speed between blocks in two rows with the increase in distance, while the internal air speed in the leeward block showed a decrease followed by an increase. When the lateral distance between the blocks of the same row was increased both internal and external air speeds increased to reach a maximum, followed by a decrease to the original value when the lateral distance equalled zero. Air speed inside seemed to be a function of the block properties and of the openings details. This will be discussed in the next section.

Wise (268) carried out a study of a combination of a slab building with an upstream low rise building. The geometrical parameters were:

i) the distance, L
ii) the slab building thickness, W
iii) the slab building height, H.

The results are illustrated in figs.(4.34, a and b). The main conclusion reached was that the velocity, V_A, at one point between the two buildings, and near to the ground is a complex function of the wind speed at the top of the slab building, V_H, the height, H, and the thickness, W, as well as the low building height, h. The following expression was obtained:

$$R_H = V_A/V_H$$

$$= 0{\cdot}24((a/H)^{0\cdot28} + (L/H)^{0\cdot4} + (W/H)^{0\cdot8})$$

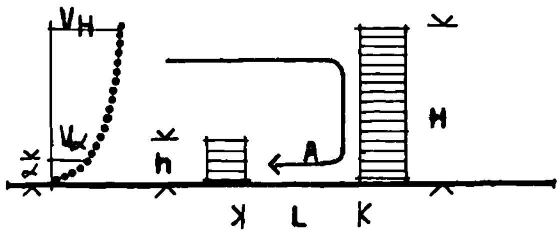


Figure (4.34b) Parameters affecting the flow pattern around a slab building with low rise building upstream.

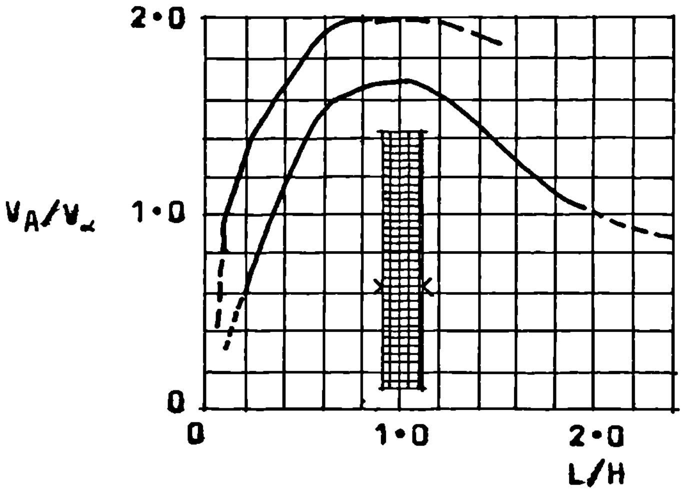


Figure (4.34a) The variation of V_A/V_α with L/H,, Wise (268).

The above equation was found to be applicable within the following limits only:

$H/a > 33$; $W/H > 1$; $L/H > 1$; and $H/h > 8$.

Values of R_H in the three high speed regions near the ground are given in fig.(4•35).

Soliman (245), in a series of wind tunnel experiments, investigated the wind pressure effect on building groups. Examining the flow regime over a group of identical cubes he concluded that the change of the flow regime from isolated roughness to wake interference regime is a function of the separation distance and the reattachments, while the second change of the regime from wake interference to skimming flow will be governed by the cube height which satisfies the conditions of maintaining one stable vortex, fig.(4:36). The governing conditions for each of the three flow conditions may be expressed as:

i) for the isolated roughness flow regime -
$S_c/H > E_t/H$

ii) for the wake interference regime -
$E_v/H < S_c/H < E_t/H$

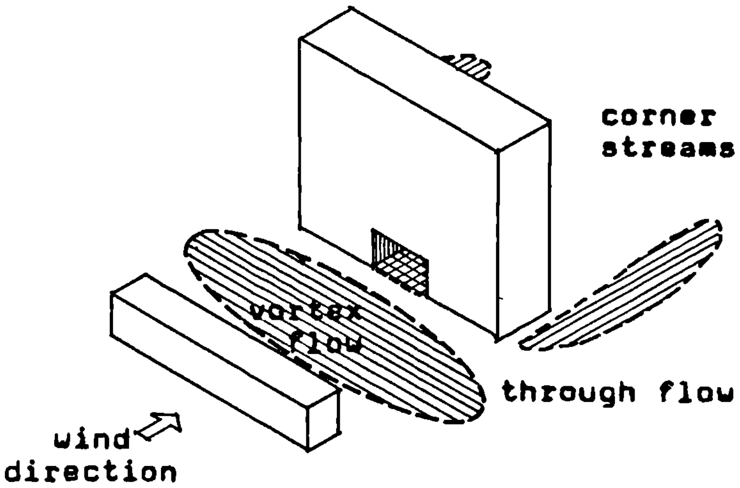
iii) for the skimming flow regime -
$S_c/H \leqslant E_v/H$

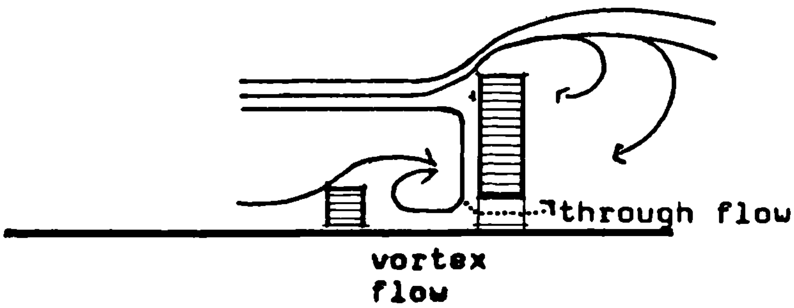
where:

S_c = clear spacing between buildings

E_t = sum of the seperation and reattachment distances, E_u and E_d respectively, around the isolated cube

E_v = stable vortex dimension in the flow direction





Region	R_H
Vortex	0·50
Corner	0·95
Through	1·20

Figure (4.35) Regions of increased wind speed at pedestrian level around tall building. The table shows some typical speed ratios.

Figure (4.36a) The main three flow regimes.(245).

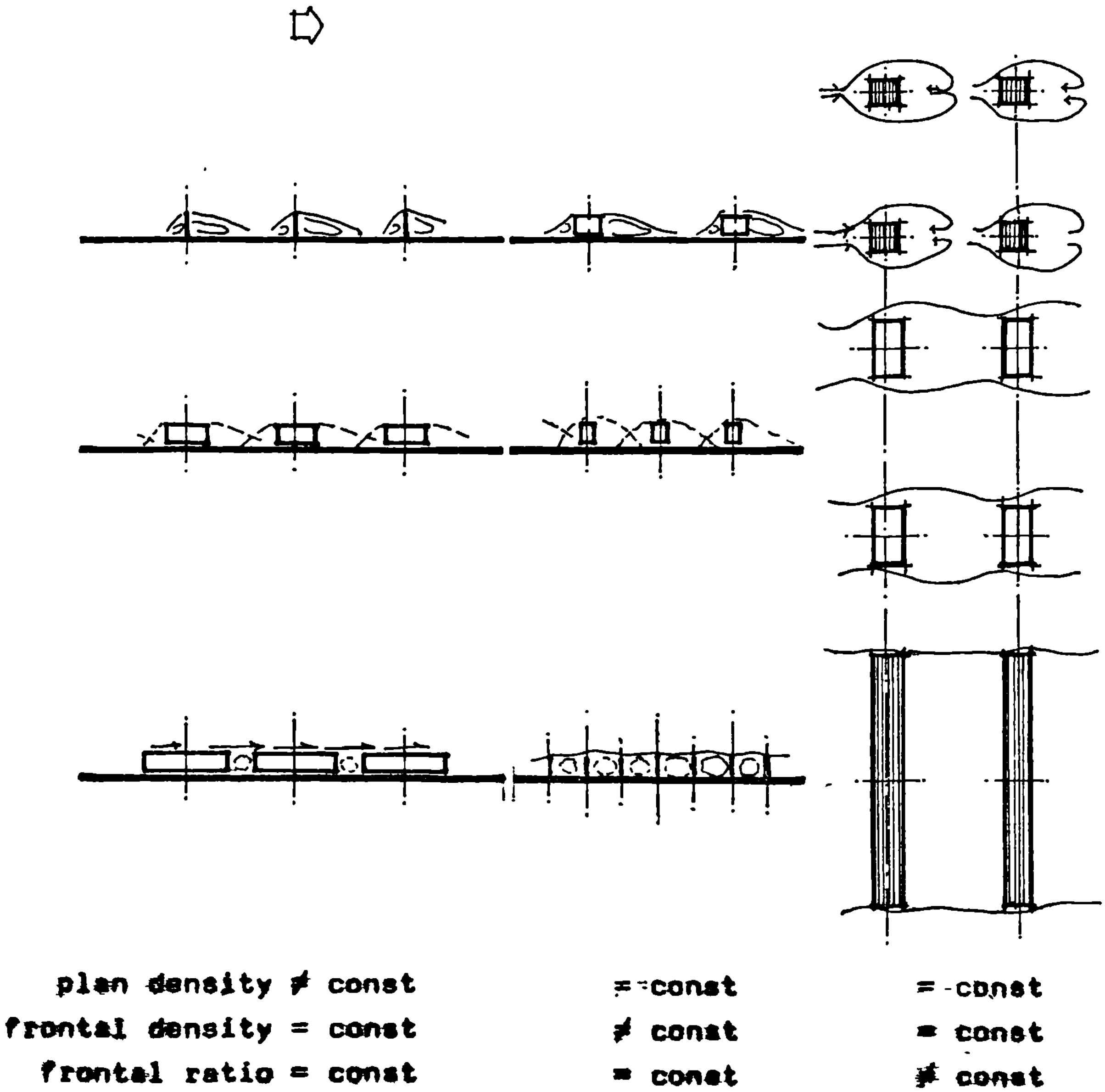


Figure (4.36b) Examples showing that the three flow regimes are not a sole function of plan density, frontal density or frontal ratio (245).

E_v is related directly to the grove height and the skimming flow regime will occur at $S_c/H = 1{\cdot}5$. This ratio is the dominant parameter for groups of buildings with a wide range of frontal aspect ratios, and may alter the flow regime from the isolated regime to either the wake interference or the skimming flow. However, none of the three flow regimes is a sole function of the plan area density, λ_p, the frontal area density, λ_f, or the frontal aspect ratio, A_f, as illuatrated in fig.(4.36).

4.4.3 Induced Circulation Within Buildings

It is of great importance to ensure good ventilation of spaces inside a building in order not to disturb the function for which it was built. The arrangement of openings in the high and low pressure zones and the orientation of the window inlets can help to improve the air flow conditions. For the evaluation of the ventilation systems a distinction should be made between the desirable and undesirable wind, based on wind velocity and its general characteristics such as cool or hot, pollution, and diurnal variation. The calculation of ventilation using either pressure coefficient, C_p, or velocity coefficient, C_{vn}, has been described in section 4.3, and the advantage of the velocity method for estimating ventilation conditions during the over heated period has been stated. Therefore, consideration of the previous work concerning ventilation evaluation due to wind speed is important for the thesis of this section.

In a series of flow visualizations in a two dimensional wind tunnel Olgyay (206) examined the flow pattern inside single cell models. The parameters he considered were inlet-outlet relative area, inlet-outlet relative vertical distance, the presence of a partition, and the effect of some attachments (louvers etc). The main conclusions drawn by Olgyay from this study were:

i) The inlet-outlet area: with the inlet smaller than the outlet Ventori effect dominates with high speeds; using the opposite arrangement the speeds (within the flow stream) were not satisfactory.
ii) Inertia effect: when the openings were symmetrical the flow was straight; with asymmetrical arrangement of openings the flow was deflected.
iii) Partition effect: introducing a partition into the flow stream will reduce speed, deflect and produce turbulence in the flow, hence it is recommended to avoid partitions transverse to the flow.
iv) Location of outlets and inlets: outlet location is irrelevant to the incoming wind flow pattern.
v) The inlet position governs the flow pattern.
vi) Effect of attachments: solid overhang at ceiling height will improve ventilation performance. However if window overhangs are supplied for reasons other than ventilation, eg shading devices, they should be perforated.
vii) The type of window deflects and modifies the incoming flow.

Investigations by Straaten (249) showed the complex influence of the geometry of the openings on the discharge coefficients in a row of buildings, and may be summarised as follows:

i) Relative shape and sequence of aligned openings: smaller openings downstream than upstream converted a substantial amount of the kinetic energy into static pressure around the outlet; an outlet the same size or larger than the inlet reduces the kinetic energy loss and secures high velocity within the stream.
ii) Alignment of openings with the flow stream secures minimum energy losses due to forced change in flow direction.

iii) Surfaces close and parallel to the flow stream cause a substantial conservation in energy within the stream, with minimum turbulent mixing. This is referred to as 'wall effect'.

iv) Close spacing of similar sized, aligned openings can cause a significant reduction in static pressure in the space between the openings. This results in an increased discharge through the upstream opening. The effect appears to occur when the ratio of downwind spacing to the hydraulic radius[1] of the opening is less than 80, and is most pronounced when this ratio is less than 30. However this situation does not occur frequently in buildings.

v) Increasing the wall thickness or reveal depth: has the effect of restricting stream expansion, therefore delaying flow separation from the duct walls and reducing energy losses.

vi) Wind tends to maintain its direction while passing through a clear opening in a windward wall. This has two effects; first the effective area of the opening is reduced by a factor which is approximately the cosine of the angle of incidence of wind to the opening; secondly, as rooms are usually rectangular in shape the stream is more likely to suffer energy losses due to flow deflection.

Givoni (119, 123, 120) examined the factors affecting ventilation in a single cell in a series of wind tunnel experiments. The parameters he considered are window orientation, size, inlet-outlet position and presence of a partition. He concluded that:

i) Better ventilation conditions are obtained when the

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1 The hydraulic radius of the duct being the duct area divided by its perimeter.

air stream has to change direction within the room than when the flow is direct from inlet to outlet.

ii) In rooms with one opening there is an appreciable effect when the window size is increased while the provision of two openings with a projection may amplify the effect.

iii) Average indoor velocity depends mainly in the smaller opening, whether inlet or outlet makes little difference.

iv) Cross ventilation will double the average and maximum velocities.

v) Sub-division reduces internal velocities; the nearer the partition to the inlet the greater the reduction.

vi) Application of fly screens along the whole balcony in front of the opening gives better ventilation conditions than applying them directly on the window.

4.4.4 Considerations for Air Flow Patterns Within Buildings

Air movement within the built environment is governed by two main forces:

1 It will tend to follow its original direction and will be governed by its inertia forces until they are lost due to friction or obstruction, or overcome by other forces.

2 When the inertia force diminishes or is smaller than the force generated by the difference in pressure, air flow direction will be controlled by the outlet.

The first force can be considered as a natural one depending mainly on the characteristics of the prevailing wind. However, it can be modified by design effects in the window detailing region. The second force will depend mainly in the designer's mastery of space detail design and outlet positioning. The following notes should be considered when designing for naturally ventilated buildings:

i) Using a smaller size inlet with larger outlet will allow utilization of the 'Venturi effect'.

ii) Inlet and outlet symmetrically placed will result in straight flow patterns between the openings with very little air interference in other parts of the space.

iii) Asymmetrical flow patterns will occur when asymmetrical openings or obstructing partitions are provided. Partitions outside the flow stream will not affect the flow, while those in the stream will deflect it and may reduce the local air speed. However, the average air speed may remain the same, or even increase.

iv) In multi-storey buildings the flow direction in the vertical plane will depend on the location of the opening in the windward face. The air flow pattern may be considered as a function of the distance between the opening and the stagnation zone. The general belief that high inlets deflect incoming air towards the ceiling, and low inlets will deflect the flow towards the floor applies only for single storey blocks, fig.(4.37). Therefore the provision of special windows, external attachments and internal features may modify the flow pattern. High ceilings in floors above the stagnation zone may reduce the desirable effect of ventilation substantially by allowing air to flow away from the living level. The effect of the locations of openings on the windward face on the air flow through the building will be further examined in the wind tunnel, Chapter 6.

v) The flow outside groups of buildings will follow three regimes, ie isolated roughness, wake interference and skimming flow, fig.(4.36). A courtyard can be considered as two rows of short span enclosed by

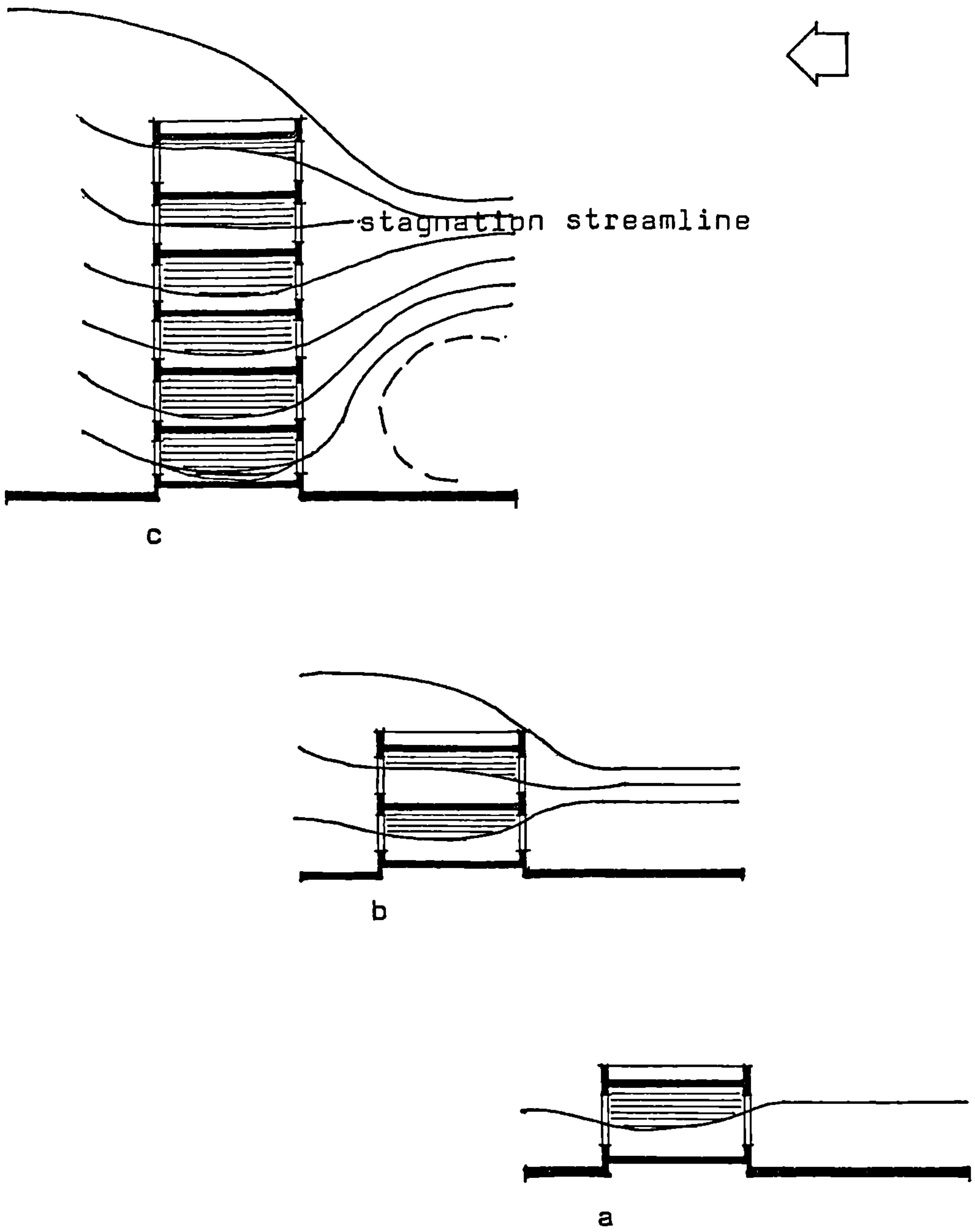

Figure (4.37) The effect of building height on ventilation conditions within the built environment.

two endwise buildings[1]. The conditions inside courtyards with depth greater than the vortex length need further investigation and will be visualised in the wind tunnel, Chapter 6.

vi) The porosity of the building's windward face seems to affect both the air flow on and across that face and through the building, as well as the wake length behind the building. Newberry, Eaton and Mayne (202) recommended the use of models with some permeability which are expected to bring wind tunnel results closer to the conditions of the full scale. This factor will be considered later in the model design stage of the wind tunnel experiments, Chapter 6.

vii) Architectural features and projections on the facade can affect the air flow and the pressure distribution across the faces of a building, particularly the windward one. These can modify the effect of surface flow pattern on the internal air movements; Handa (133) has investigated their effects, and designers should consider these when dealing with buildings having such features.

viii) The effect of deflected stream on the average air velocity within the built environment can be seen in table (4.12). It shows that deflected air flow will secure a higher average air velocity than the straight flow despite the higher local velocity and higher air change rate provided by the latter.

ix) Spaces with windows in one wall only may have little effect on internal air velocity[2], but when the wind

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1 Lawson (166) suggests that acceptable conditions occur when the enclosed area divided by the square of the height of the buildings forming the walls is less than 20. This relationship has no consideration to the court proportions and the conditions of the three flow regimes.

2 Warren investigated the turbulent flow effect on air flow within a single-opening space (261). He found it is possible to have considerable air flow within the space provided a turbulent flow is prevailing.

Table (4.12) The effect of window location and wind direction on average air velocity (percentage of external velocity). After Givoni (122).

inlet width	outlet width	windows:	in opposite walls		in adjacent walls	
		wind:	perpendicular	oblique	perpendicular	oblique
1/3	1/3		35	42	45	37
1/3	2/3		39	40	39	40
2/3	1/3		34	43	51	36
2/3	2/3		37	51		
1/3	3/3		44	44	51	45
3/3	1/3		32	41	50	37
2/3	3/3		35	59		
3/3	2/3		36	62		
3/3	3/3		46	65		

is oblique[1] on that wall the inner air will start moving due to the pressure generated across the window. Warren (261) studied the effect of window vane which seemed to secure considerable air flow within the space.

x) Satisfactory ventilation is possible in apartments where air has to pass from one space to another provided the air paths between them remain open when ventilation is required.

xi) For general design purposes the ability of specifying wind in terms of average speed suggests the use of an average wind speed map[2] for rough estimation in the very early design stages, fig.(4.38).

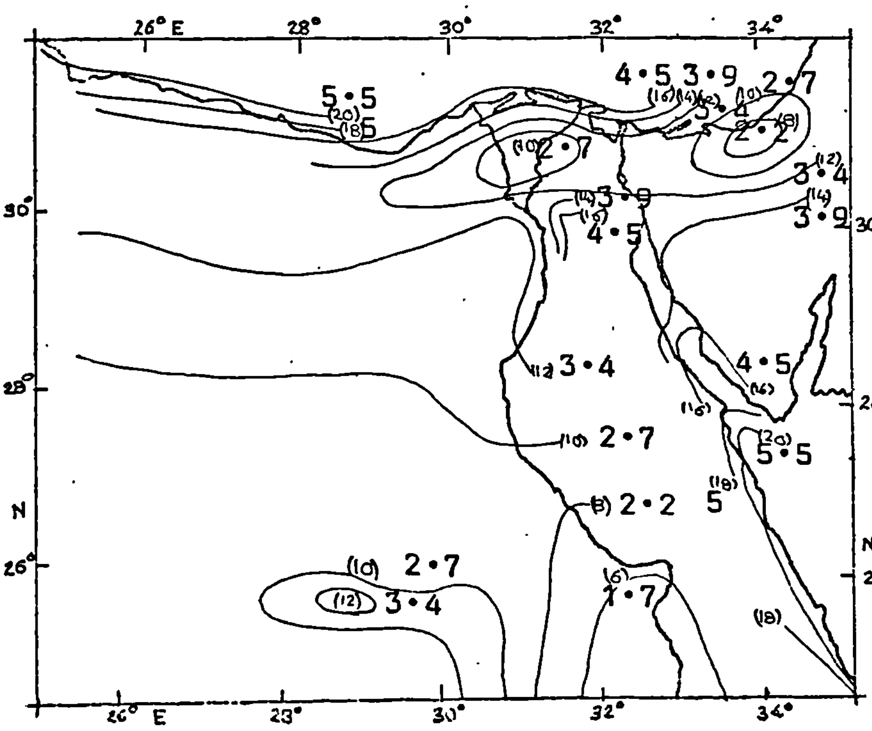

Figure (4.38) Mean annual wind speed m/s (km/h).

1 The angle between the window and the wind should be in the range of 20 - 70°.
2 Lacy gives an example of these maps for the United Kingdom (164).

4.5 Summary of Design Considerations for Natural Ventilation

Ventilation has a very important part to play in building design in the hot regions of the world. In buildings it is required to satisfy the three major needs of health, comfort and structural safety. The importance of each of these depends on the prevailing climatic conditions. In cold climates where energy conservation is of prime importance satisfying health needs as well as humidity control within the structural shell should accompany any consideration for reducing ventilation. These conditions may be the same during underheated periods in other kinds of climates. In hot climates thermal comfort and structural cooling are the most important needs to be satisfied while health needs are catered for within the thermal comfort ventilation requirements. However, health ventilation for odour should be satisfied under all climatic and environmental conditions, otherwise occupants may sacrifice the comfort aspects to remove odours. Ventilation for comfort should follow the space function. In hot climates ventilation over all utilized areas is desirable, while in cold climates it is not. Effects of air movements on natural ambient air temperature can be seen in table (4.3), and can be accurately estimated using the Standard Effective Temperature (SET) in Appendix 3.

Rationalized structural cooling is of special importance in hot dry climates. This can be seen in the work of Kuba (162) in the Sudan and in the work of the Egyptian General Organisation for Housing Building and Planning Research (136). Calculation of ventilation heat loss from structures can be done using equation (4-4), while the necessary ventilation rate to remove a known amount of heat can be calculated from equation (4-5).

Ventilation for humidity control is of special importance for both cold and hot humid climates. This can be calculated from equation (4-6) with water vapour production estimated from table (4.5).

The calculation method proposed for estimating ventilation performance in hot climates is based on the cooling effect of ventilation. This can be divided into two main steps:

i) Wind data modifications which should correspond to the terrain type and the opening height.

The meteorological data and information concerning the modification of this data to suit the particular location are needed for estimating the frequencies with which certain wind speeds occur within building development. The published meteorological wind records are usually measured at a height of 10 m and correlated to open sites like airports. They should be modified to the type of terrain in the district of the proposed building and to the height at which the openings will be provided. Equations (4-17), (4-18) and (4-19) will allow the modifications to terrain categories A, B and C respectively.

ii) Estimating full scale air speed inside the building and the air changes if required.

Full scale wind speed inside the space can be calculated using equation (4-13) to modify wind velocity to the required site, provided the velocity coefficient C_{vn} for this point is known.

$$\text{full scale wind speed} = C_{vn} \times \bar{V}_{10} \qquad (4\text{-}13)$$

Then if the air changes are required the full scale speed at the outlet can be multiplied by the outlet effective area. However, if the rate of air change is required the air change can be divided by the space volume. The velocity coefficient C_{vn} should be determined for the type and shape of the space with approximately the same type of window and the same height. The contemporary dwelling in Egypt will be analysed in Chapter 5 to establish the characteristics governing ventilation conditions within the typical residential units for low income groups in the Egyptian cities in general and Cairo in particular. These will be used as the basis on which the wind tunnel experimental programme is conducted. This programme aims to determine the velocity coefficient C_{vn} for multi-cell spaces and the factors which will affect air flow within these spaces. General flow patterns around buildings will be examined to identify the problems related to these types of buildings, before proceeding to investigate the flow pattern inside buildings in Chapter 6.