CHAPTER 4

CLIMATIC DATA FOR BUILDING THERMAL DESIGN

eather data are one of the foundation stones of our (building services) industry since it is the building and its services which protect us from its extremes and create an appropriate internal environment. Without accurate weather data, we could neither design efficient or effective services nor predict energy use." – (CIBS, 1984, Forward by P. G. T. Owens)

Climatic conditions have a major effect on building loads, HVAC equipment performance and building energy consumption. The amount of energy use in a building is a direct result of the climate, the building use and the building form. This chapter studies building climatic design and outdoor design conditions so as to investigate the climatic conditions of Hong Kong. Basic design weather data for HVAC applications in Hong Kong are established and the Hong Kong climate is analysed using statistical and graphical methods.

4.1 Building Climatic Design

The practices of climatic design for buildings is explained and the considerations for the quality of weather data are described.

4.1.1 Practices of climatic design

The external character of a geographical location is prescribed by its climate. A basic rule for building energy efficiency is to gain the maximum benefit from the climatic conditions since the HVAC system is working to maintain the desired indoor environmental conditions under the influence of the external weather (Watson and Labs, 1983).

Understanding climate

A building can be considered as a limatic modifier’ which shields the indoor environment from the external climate. The conditions of weather that shape and define local climates are called elements of climate (Givoni, 1976, Chp. 1), which may include weather parameters such as temperature, humidity, air movement and solar radiation. Weather data form the basis of HVAC design and provide information for studying the climatic context. Weather files are generated from climatic data and used in building energy analysis. The climate-specific properties of building energy consumption can be studied by evaluating the weather data. The process of identifying, understanding and controlling the climatic influences at the building site is perhaps the most critical part of building design (NSW Public Works, 1993, pp. 307).

Defining a climate

Depending on the application, different data will be used for defining the climatic characteristics. Not all meteorological data are of value for HVAC design and building energy analysis. Building designers are usually interested in those climatic elements which affect indoor comfort and the heat transfer through building fabric and via ventilation. The climatic elements crucial for building thermal design include:

- Site information (such as latitude and longitude).
- Temperature data (such as dry-bulb temperature (DBT)).

- Humidity or moisture data (such as wet-bulb temperature (WBT), dew-point temperature (DPT) and relative humidity (RHM)).
- Solar radiation data (such as global solar radiation (GSR)).
- Cloud cover data.
- Wind data (such as wind speed and wind direction).

No matter what sort of weather data are used, they should represent the severity issue of the climate and its long-term effects. Clarke (1985, pp. 215) pointed out that the data should represent the conditions under which the building will be required to function and should have some quantifiable severity measure which establish their suitability for selection. Normally, the climatic data for buildings are selected from standard weather databases.

Weather databases

With increased interest in solar energy in the twentieth century, climatic data for solar system design were investigated. A weather database, known as OLMET’ (which emphasized solar data), were rehabilitated and developed in USA (NCC, 1978 & 1979). This database was later utilised to establish weather datasets for building energy simulation since the data types required are similar (NCC, 1976 & 1981; Crow, 1981). Another database, known as the ERC Meteorological Database’, was set up in 1982 for the locations in UK (Page, Gibbons and Lowe, 1985). Depending on the energy simulation method used, either full hourly weather data, reduced hourly data, or inned’ data will be used for the analysis. Unfortunately, the quality of weather data usually varies widely because of the historical problems in meteorology – lack of complete hourly data, incompatible formats and absence of standard selection criteria. Building designers, compounded with voluminous weather data, find it very difficult to understand and assess the properties and validity of these data, not to mention accuracy and suitability.

4.1.2 Quality of weather data

A system of quality control is often implemented for computerised climatic measurements to ensure internal and temporal consistency of the data (Chin and Kwok, 1974, pp. 7-10). The uality' of weather data mentioned here does not mean the error checking and consistency maintenance by meteorologists. It refers to the breadth and type of weather data provided by the weather station. The weather data kept at different countries may be quite different from each other (Page and Thompson, 1982). Certain weather data are basic in all weather stations (such as air temperature); other elements are observed only if there is a proven need for them (such as solar radiation). The inherent properties and sources of weather data should be considered when making analysis and generating weather datasets. Good communication between meteorologists and engineers is important to ensure that the right data are being measured, maintained and used.

Period of weather records

The number of years that weather data are available will determine the breadth of the weather database. In principle, as many years as possible should be considered for a proper analysis (Thom, 1960). The longer the period of records is, the better and more persuasive the results will be (since shorter periods will exhibit variations from the long-term average). For engineering applications, it is believed that weather data based on not less than 30 years are conservatively stable (Crow, 1981). The 30-year monthly weather summary is therefore often reported by weather stations as a long-term climatic index (ROHK, 1987-1992). However, in practice, the length of climatic records depends very much on the availability of weather data at a location. Complete weather data for 30 years are often lacking (especially in developing countries) and the measurements in early years may not be detailed enough. The result is that only one or two decades of weather data are present in many locations and the long-term weather data are often dictated by the best available information (see also Section 5.1).

Measuring intervals and weather parameters

Having a reasonable length of continuous climatic records is not enough; the weather data should be measured at small time intervals. Generally, hourly data are more useful than daily, weekly or monthly data. If the required data are not present at the weather station but can be estimated using other measured data and properties, then some works can be done to generate the data from the basic parameters (such as moisture content and enthalpy). The requirements of weather data for HVAC design and energy analysis should be fully understood in order to assess the quality of the weather data. Weather parameters which are seldom measured nowadays, such as daylight data and diffuse solar radiation, may be needed as more attentions are paid on their analysis for building energy efficiency.

A painstaking task

Constructing climatic data for HVAC applications involves much more than acquiring the required raw information from the weather station. Checks are required for missing data and erroneous data. Corrections and interpolations are required to convert the data to the desired time standards and quality (Keeble, 1990). The basic raw data need to be re-constructed into suitable formats required by the design process or simulation tools (Donn and Amor, 1993). Enormous efforts, using a combination of experience, engineering judgement and local knowledge of the particular location and climate, are needed to develop the design data and weather files. Therefore, the task should not be overlooked. To help understand the design weather data, the principle of outdoor design conditions is described and explained in the next section.

4.2 Outdoor Design Conditions

The basic principle of outdoor design conditions is described and the concept of risk assessment in design weather is studied.

4.2.1 Basic principle

Outdoor design conditions are weather information for design purposes showing the characteristic features of the climate at a particular location. They are usually determined by statistical analyses of long-term weather data and may include information on air temperature, humidity, wind, rainfalls and solar data. Gabrielsson and Wiljanen (1994) found that so far no clear guidelines have been presented for specifying the weather for load calculations, especially in summer conditions, apart from the rather incomplete ones in ASHRAE and similar handbooks. Generally, the weather for load calculations is specified for summer (cooling design) and winter (heating design) conditions. Winter is easier since temperature is the main parameter (Thomas, 1955; Thom, 1957; Williams, 1962); for summer, the humidity and solar data involved complicate the analysis.

Design temperatures

Outdoor design temperatures which indicate the extreme conditions for thermal load calculations are the most important parameters (Holladay, 1947 & 1973; Jamieson, 1955). The choice of these design temperatures depends on the assignment of design requirements and contingency involved. Thom (1957) pointed out that the assignment of the prescribed design requirements is an engineering problem while the determination of the contingency is a climatological problem. Current methods for determining outdoor design temperatures are similar in basic principle. Design temperatures for the summer and winter periods are specified respectively by the highest and lowest temperatures likely to be encountered at a specific frequency of occurrence. Choice of the frequency level are empirical; the decision is often based on considerations for local practices, numerical neatness and their effects on overload capacity and operation (Jamieson, 1955).

Effect of humidity

WBT, DPT and RHM are three common variables to express humidity level of the ambient air [*]. They are used in conjunction with DBT to represent the state conditions of moist air. The pair DBT and RHM is commonly used for indoor design conditions while the pair DBT and WBT is popular for outdoor conditions. The effects of WBT and humidity on HVAC system design and operation are not well understood (Burger, 1993). WBT of outdoor air is important principally in determining the cooling load produced by ventilation or leakage air (Kusuda and Achenbach, 1966). In general, DBT affects the sensible component of building loads while WBT dictates ventilation component associated with building loads. Coincident values of DBT and WBT are needed for a realistic appraisal of psychrometric conditions of the outside air.

Coincident dry-bulb and wet-bulb temperatures

Building load and energy consumption at an hour are calculated with a pair of coincident outdoor DBT and WBT. Usually the maximum DBT is coincident with a WBT slightly below the maximum WBT and vice-versa. Kusuda and Achenbach (1966) pointed out that the coincident occurrence of extreme values of DBT and WBT will be less frequent than the independent occurrence of these same values. The assumption of maximum DBT and WBT coincidence can result in weather-oriented loads up to one-third or greater (ASHRAE, 1979). Generally, three pairs of DBT and WBT values can be used (Wickham, 1982) [†]:

- Design DBT (DDB) with design WBT (DWB).
- Design DBT (DDB) with its coincident WBT (CWB).
- Design WBT (DWB) with its coincident DBT (CDB).

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[*] Wet-bulb temperature and relative humidity are chosen by the author as the major weather variables for humidity level in this thesis.

[†] Coincident wet-bulb (CWB) is the mean of all wet-bulb temperatures occurring at the design dry-bulb (DDB);coincident dry-bulb (CDB) is the mean of all dry-bulb temperatures occurring at the design wet-bulb (DWB).

ASHRAE (1993, Chp. 24) recommended the design DBT be used with the coincident WBT for computing building cooling loads, unless it has been indicated that the application is more sensitive to humidity. For example, evaporative cooling systems which are affected by high WBT require special attention to design WBT (Crow, 1972). When calculating building cooling loads, it is advisable to determine whether the structure is most sensitive to DBT (i.e., extensive exterior exposure) or WBT (i.e., outside ventilation) (ASHRAE, 1979). Wickham (1982) has developed similar concept for Australia but it is recommended that the DDB/DWB pair is for the summer conditions, the DDB/CWB pair for dry-bulb sensitive cases and the CDB/DWB pair for wet-bulb sensitive cases. There is no definite answer to the selection unless the nature and significance of the application and weather parameters are understood.

4.2.2 Risk assessment

Outdoor design conditions affect building loads and economical design. The effect of incorrect selection of outdoor conditions can be dramatic when system and plant operation are considered (Lam and Hui, 1995a). If some very conservative, extreme conditions are taken, uneconomic design and oversizing may result. If design loads are underestimated, equipment and plant operation will be affected. If a climatic factor influential to the system has not been considered properly, the building may not be able to handle the actual operating conditions effectively (such as high humidity). The precise effects on building load and energy performance are difficult to assess since other contributing factors are involved, such as sizing methodology, operation strategy, system reliability and controls of indoor environmental conditions. Williams (1962) pointed out that determination of a satisfactory outdoor design temperature depends upon a judicious economic balance between thermal input-dissipation characteristics of a building and vagaries of the thermal extremes.

Optimum design and risk level

It is difficult to establish and evaluate a set of recommended design values without a qualifying statement which explains their impacts. The isk' of failure and substandard performance should be understood by designers, and where possible, the significance level should be determined in consultation with the client and future end-users. Thom (1960) found that the selection of this probability is not a climatological problem but is an engineering problem which involves many factors such as economy, use, customer satisfaction. In essence, risk assessment, design conditions and building performance form a riangle' of the building design optimisation. Only with a clear idea of the consequences of design conditions can designers weigh up the contributing factors in the life-cycle analysis of the building.

Rational design data

When performing building energy analysis, the building inputs are checked rigorously but the weather inputs are often taken for granted. No clear indications now exist on how to assess and explain the design weather data. Generally, the usefulness of the design weather data is based on the assumption that the frequency level of a specific temperature over a suitable time period will repeat in the future (ASHRAE, 1993, Chp. 24). But there is no uniform basis for defining the system reliability of each design weather variables and their impacts on building performance. The design load in theory is the load which is only exceeded a reasonably small percents of time (such as 1%, 2.5% or 5%) over the expected lifetime of the building. The crux of design load calculation is not to simulate any particular real behaviour, but to minimise the risk of system failure under the worst likely conditions. Erbs (1984) pointed out that the choice of calculation procedures, target conditions and associated lists of material property values reflects the need for robust methods of risk assessment. Mason and Kingston (1993) have suggested the use of energy simulation programs to size air conditioning plant based on the level of indoor temperature exceeded the design conditions. To achieve optimum system design and performance of buildings, there is a need to rationalise the outdoor design data (Lam and Hui, 1995). Study of the design weather data for Hong Kong will be explained in the next two sections.

4.3 Weather Data of Hong Kong

The existing weather data of Hong Kong are investigated and a weather database for HVAC applications and building energy analysis is established. Outdoor design conditions for Hong Kong are determined by analysing the local weather data.

4.3.1 Existing weather data

Hong Kong is at latitude 22° 18' north and longitude 114° 10' east with an elevation of 33 metres above sea-level [*]. The Royal Observatory Hong Kong (ROHK) is responsible for measuring and maintaining the meteorological records. Official weather data were published annually since 1884, except the seven years 1940-1946 during the World War II (ROHK, 1987-1992; ROHK, 1947-1986). Early data for the years 1884 to 1939 were summarised by Peacock (1952) and ROHK (1963). Hourly data on temperatures, humidity, cloud cover and wind are available for a reasonable period of time. But, like many other places in the world, there is a lack of hourly solar radiation data [†]. Daily total horizontal global solar radiation (GSR) have been recorded at the King Park Meteorological Station of ROHK since June 1958 but hourly GSR measurements only started in December 1978. The direct and diffuse components of GSR are not measured by ROHK (Lau, 1989) but measurements for these components have been started to improve the situation (Lam and Li, 1993).

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[*] This refers to the main weather station at the headquarters of the Royal Observatory Hong Kong at Tsimshatsui, Kowloon, Hong Kong.

[†] The available solar data for Hong Kong have been studied and reported by Lau (1989), Peacock (1978) and Sham (1964). Statistical analyses have been carried out by Leung and Cheung (1979), Leung (1980) and by Leung and Yan (1981) based on some limited amount of data.

Weather database for Hong Kong

Although the basic meteorological measurements are available from ROHK for more than a century, there are very few research work done to generate weather information for building design. It is found that existing weather data of Hong Kong for HVAC applications are sparse and very limited (Lam and Hui, 1995a). To improve the situation, the latest and most detailed weather data were collected from ROHK; a weather database was established to provide essential climatic information, monthly weather summary and hourly weather data (see also Section 5.3). When developing the weather database, the main emphasis is put on HVAC applications and energy calculations. Table 4.1 gives a list of the hourly weather data currently maintained. The important weather data of Hong Kong are summarised in Appendix II (monthly summary of DBT, WBT, DPT and GSR are provided).

Table 4.1 Hourly Weather Data Collected from ROHK

Weather Data	Unit	Period of year	Numbers of year
Dry-bulb temperature (DBT)	^oC	1960-94	35
Wet-bulb temperature (WBT)	^oC	1960-94	35
Dew-point temperature (DPT)	^oC	1960-94	35
Global solar radiation (GSR)	MJ/m^2	1979-94	16
Wind speed (WSP)	m/s	1968-94	27
Wind direction (WDR)	ten degrees	1968-94	27
Atmospheric pressure (ATP)	mbar	1960-94	35
Cloud amount (CLD)	oktas	1961-94	34
Duration of bright sunshine (SUN)	scale 0 - 10	1960-94	35
Relative humidity (RHM)	percentage	1968-94	27
Vapour pressure (VAP)	hPa	1968-94	27

Note: 1. All the above data are measured at ROHK Headquarters, Tsimshatsui (Latitude 22° 18’, longitude 114° 10’ and elevation 33 m) except GSR and SUN which are measured at King Park Meteorological Station (Latitude 22° 19’, longitude 114° 10’ and elevation 66 m).

Supporting programs for weather data analysis

To facilitate the analysis of weather data, the author has developed some supporting computer programs (written in BASIC language) to carry out the statistical analyses. Two of these supporting programs used in this Chapter are:

- *STAT’* – This program performs statistical calculations on hourly data to determine monthly and yearly values of descriptive statistics, including mean, median, daily total, standard deviation and root mean square difference. Degree-days, design days and coefficients for cross-correlation and auto-correlation can also be calculated.

- *REQ’* – This program calculates the frequency distribution of weather variables. Frequency occurrence of either one single variable or two variables can be determined.

Figure 4.1 shows a brief overview of the STAT’ and REQ’ programs. Further details about the supporting programs can be found in Lam and Hui (1995b).

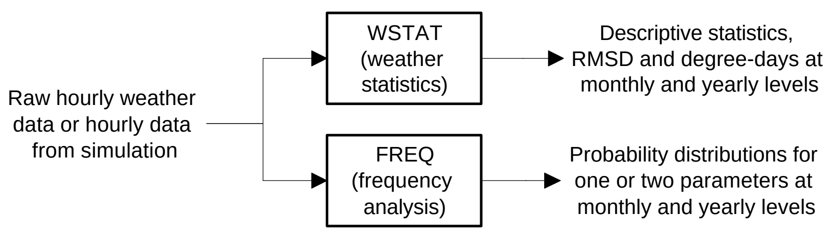

Figure 4.1 *Overview of the STAT’ and REQ’ Programs*

4.3.2 Develop design data for Hong Kong

The available methods and outdoor design data which may be useful for Hong Kong have been investigated by Lam and Hui (1995a). It is found out that the general design data provided in engineering handbooks are not detailed and accurate enough for design evaluations and building energy analysis. The design data used by practising building designers vary from case to case (JRP, 1991, pp. 51-67).

Summer and winter months

To establish the design data for Hong Kong, the first thing to do is to determine the summer and winter months which indicate respectively the cooling and heating seasons for thermal design. A common approach is to select four calendar months with the highest long-term monthly average DBT as the summer period, and three months with the lowest average DBT as the winter period (ASHRAE, 1993, Chp. 24). This approach has been used to consider the long-term monthly averages of DBT, WBT and GSR. Table 4.2 shows the monthly averages of long-term DBT, WBT and GSR in Hong Kong.

Table 4.2 Monthly Averages of Important Weather Data of Hong Kong

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
DBT (°C)	15.7 XII	15.9 XI	18.4 IX	22.0 VII	25.8 V	27.6 III	28.6 I	28.2 II	27.5 IV	25.0 VI	21.3 VIII	17.6 X	22.8
WBT (°C)	13.1 XII	13.8 XI	16.6 IX	20.1 VII	23.7 V	25.4 III	26.0 I	25.8 II	24.7 IV	21.5 VI	17.7 VIII	14.4 X	20.3
GSR (MJ/m²)	11.53 XI	10.79 XII	11.10 X	13.20 VIII	16.05 V	16.21 IV	18.92 I	17.26 II	16.29 III	15.67 VI	13.33 VII	11.87 IX	14.37

Note: 1. Monthly average dry-bulb temperature (DBT) and wet-bulb temperature (WBT) are based on data for the 48-year period from 1947 to 1994. The monthly average global solar radiation (GSR) is based on data for the 37-period from 1958 to 1994.

2. The Roman numerals under each number are the rankings for the respective monthly values in descending order.

It can be seen from Table 4.2 that the rankings of DBT and WBT are identical, whereas the rise and fall of GSR do not always follow the temperatures. Based on these three climatic variables, June, July, August and September are selected as the summer months. For the winter period, DBT and WBT indicate December, January and February as the winter months while GSR indicates January to March. It is believed that DBT and WBT have greater influences, and consequently, December, January and February are selected as the winter period.

Outdoor design temperatures

Analyses for the summer, winter and whole-year periods have been conducted on the hourly temperatures of Hong Kong for the 35-year period from 1960 to 1994. Significance levels in percentage frequency as suggested by ASHRAE (1993, Chp. 24) are considered more systematic and flexible for risk analysis. Outdoor design temperatures of Hong Kong at significant levels from 0.1% to 10% are determined and summarised in Table 4.3 (both the design and coincident temperatures are provided in the table). Common practice in HVAC design usually takes the summer 2.5% and winter 97.5% for comfort air-conditioning. For critical processes, the summer 1% and winter 99% are often used for the design temperatures.

Discussions with the practising building services engineers in Hong Kong indicate that, with a lack of accurate design data, most designers take the outdoor design temperatures of 33 ^{o}C DBT/ 28 ^{o}C WBT for summer and 10 ^{o}C for winter as the rule of thumb (this is a the same as the general data suggested by CIBS (1984)). As compared with the results in Table 4.3, the 33 ^{o}C DBT/ 28 ^{o}C WBT rule is approximately equivalent to taking 0.5% design DBT and 0.5% design WBT for the summer months. This is considered conservative and uneconomic for general design purpose. The 10 ^{o}C DBT for winter lies between 97.5% and 95% design DBT for the winter months; this is considered not stringent enough. There is scope for reducing cooling plant size and achieve better energy efficiency if proper design data are used for summer. For winter conditions, the effect of slightly higher design temperature is not significant in Hong Kong.

Table 4.3 Outdoor Design Temperatures of Hong Kong

	Summer months (June to September)					
Sign. level	10%	5%	2.5%	1%	0.5%	0.1%
DDB (oC)	30.8	31.5	32.0	32.6	32.9	33.6
CWB (oC)	26.5	26.7	26.9	27.0	26.9	27.0
CDB (oC)	30.0	30.6	31.0	31.3	31.7	32.2
DWB (oC)	26.9	27.2	27.5	27.8	28.0	28.5
	Winter months (January, February and December)					
Sign. level	90%	95%	97.5%	99%	99.5%	99.9%
DDB (oC)	12.2	10.8	9.5	8.2	7.4	5.7
CWB (oC)	9.4	8.2	6.7	6	5.4	3.8
CDB (oC)	13.0	11.5	10.4	9.1	8.9	6.6
DWB (oC)	8.8	7.3	6.2	5.0	4.3	2.8
	Whole year high temperature					
Sign. level	10%	5%	2.5%	1%	0.5%	0.1%
DDB (oC)	29.3	30.4	31.2	32.0	32.4	33.2
CWB (oC)	26.1	26.3	26.6	26.9	27.0	26.8
CDB (oC)	29.0	29.7	30.2	30.8	31.4	32.0
DWB (oC)	26.3	26.7	27.0	27.4	27.7	28.2
	Whole year low temperature					
Sign. level	90%	95%	97.5%	99%	99.5%	99.9%
DDB (oC)	15.3	13.6	12.1	10.3	9.1	7.0
CWB (oC)	12.7	11.0	9.4	7.6	6.6	5.2
CDB (oC)	15.7	14.0	12.7	11.1	10.6	8.2
DWB (oC)	12.5	10.4	8.7	6.9	5.9	4.0

Note: 1. Sign. level = significant level; DDB is the design dry-bulb and CWB is the coincident wet-bulb temperature with it; DWB is the design wet-bulb and CDB is the coincident dry-bulb with it.

2. The design temperatures were determined based on hourly data for the 35-year period from 1960 to 1994.

Other design data

There is no definite rule on what types of data are required for expressing outdoor design conditions. To establish the design data for Hong Kong, the author has studied the data and recommendations in ASHRAE (1993, Chp. 24), CIBS (1984), Chinese General & Research Institute of Nonferrous Metal Industry (1989) and Wickham (1982). The following information is considered most useful for building design: (a) annual extremes (maximum and minimum) of DBT, (b) diurnal range (mean daily range of DBT) and (c) wind data (prevailing wind direction and wind speed). Recommended outdoor design conditions for HVAC applications in Hong Kong are given in Table 4.4. Design temperatures for comfort HVAC and critical processes which are the two most common design situations are given.

Table 4.4 Recommended Outdoor Design Conditions for Hong Kong

Location	Hong Kong (latitude 22° 18' N, longitude 114° 10' E, elevation 33 m)			
Weather station	Royal Observatory Hong Kong			
Summer months	June to September (four hottest months), total 2928 hours			
Winter months	December, January & February (three coldest months), total 2160 hours			
Design temperatures:	For comfort HVAC (based on summer 2.5% or annualised 1% and winter 97.5% or annualised 99.3%)		For critical processes (based on summer 1% or annualised 0.4% and winter 99% or annualised 99.6%)	
	Summer	Winter	Summer	Winter
DDB / CWB	32.0 ^{o}C / 26.9 ^{o}C	9.5 ^{o}C / 6.7 ^{o}C	32.6 ^{o}C / 27.0 ^{o}C	8.2 ^{o}C / 6.0 ^{o}C
CDB / DWB	31.0 ^{o}C / 27.5 ^{o}C	10.4 ^{o}C / 6.2 ^{o}C	31.3 ^{o}C / 27.8 ^{o}C	9.1 ^{o}C / 5.0 ^{o}C
Extreme temperatures:	Hottest month: July mean DBT = 28.6 ^{o}C absolute max. DBT = 36.1 ^{o}C mean daily max. DBT = 25.7 ^{o}C		Coldest month: January mean DBT = 15.7 ^{o}C absolute min. DBT = 0.0 ^{o}C mean daily min. DBT = 20.9 ^{o}C	
Diurnal range:	Summer	Winter	Whole year	
- Mean DBT	28.2	16.4	22.8	
- Daily range	4.95	5.01	5.0	
Wind data:	Summer	Winter	Whole year	
- Wind direction	090 (East)	070 (N 70° E)	080 (N 80° E)	
- Wind speed	5.7 m/s	6.8 m/s	6.3 m/s	

Note:
1. DDB is the design dry-bulb and CWB is the coincident wet-bulb temperature with it; DWB is the design wet-bulb and CDB is the coincident dry-bulb with it.
2. The design temperatures and daily ranges were determined based on hourly data for the 35-year period from 1960 to 1994; extreme temperatures were determined based on extreme values between 1884-1939 and 1947-1994.
4. Wind data are the prevailing wind data based on the weather summary for the 30-year period 1960-1990. Wind direction is the prevailing wind direction in degrees clockwise from north and the wind speed is the mean prevailing wind speed.

4.4 Analysis of Hong Kong Weather

The general weather conditions of Hong Kong are described and the key weather statistics are determined. Frequency distributions of the weather parameters are developed. Graphical methods are used to show the year-round climatic properties of Hong Kong.

4.4.1 General weather conditions

According to the climatic classification of Barry and Chorley (1992, pp. 342), the weather of Hong Kong can be classified as wa' (humid subtropical climate). In the winter months between November and February, Hong Kong experiences a winter monsoon mainly coming from the north and northeast directions with cold and dry air from the continental anticyclone (in Mainland China). The spring season is short and usually characterised by cloudy skies, periods of light rain and sometimes very foggy and humid conditions. In the summer months between May and September, the monsoon blows usually from the south and southeast directions. The weather is mainly tropical, hot and humid with occasional showers or thunderstorms. The autumn is short as it lasts from mid-September to early November. The winds become more easterly in direction. The amount of cloud in the sky and humidity decrease rapidly at this time and so does the frequency of cyclones.

Weather statistics

To quantify the weather conditions, major descriptive statistics for DBT and WBT have been determined and they are summarised in Table 4.5. The descriptive statistics for GSR, wind speed, relative humidity and dew-point temperature are given in Table 4.6 *.

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* A statistical package, known as the *Statistical Package for the Social Scientists* (SPSS), has been employed for performing part of the statistical analysis in this study (Norusis, 1993a).

Table 4.5 Descriptive Statistics for Hourly Dry-bulb and Wet-bulb Temperatures

Statistics	Dry-bulb temperature			Wet-bulb temperature		
	Summer	Winter	Annual	Summer	Winter	Annual
Maximum	35.0 °C	28.2 °C	35.0 °C	29.8 °C	24.3 °C	29.8 °C
Minimum	19.6 °C	4.2 °C	4.2 °C	14.8 °C	- 0.8 °C	- 0.8 °C
Mean	28.2 °C	16.5 °C	23.0 °C	25.5 °C	13.8 °C	20.3 °C
Median	28.1 °C	16.7 °C	24.0 °C	25.7 °C	14.0 °C	21.5 °C
Mode	28.0 °C	17.0 °C	28.0 °C	26.0 °C	14.0 °C	26.0 °C
S.D.	1.937 °C	3.287 °C	5.430 °C	1.358 °C	3.581 °C	5.454 °C
Skewness	0.067	- 0.238	- 0.439	- 1.513	- 0.307	- 0.615
Kurtosis	- 0.085	0.109	- 0.714	4.357	- 0.161	- 0.627

Note:
1. The summer period refers to the four months from June to September and the winter period refers to the three months January, February and December.
2. The maximum and minimum in above are the maxima and minima of hourly values, not instantaneous absolute values.
3. S.D. is the standard deviation for the hourly data.
4. The statistical data are determined for the 35-year period 1960-94.

Table 4.6 Descriptive Statistics for Hourly Global Solar Radiation, Wind Speed, Relative Humidity and Dew-point Temperature

Statistics	Global solar radiation	Wind speed	Relative humidity	Dew-point temperature
Maximum	4.51 MJ/m²/hr	23.5 m/s	100 %	28.3 °C
Minimum	0.0 MJ/m²/hr	0.0 m/s	18 %	- 9.2 °C
Mean	0.53 MJ/m²/hr	3.04 m/s	78.2 %	18.78 °C
Median	0.01 MJ/m²/hr	3.0 m/s	80 %	20.3 °C
Mode	–	0.5 m/s	83 %	25.1 °C
S.D.	0.84 MJ/m²/hr	1.92 m/s	12.61 %	6.19 °C
Skewness	1.468	1.256	1.244	0.063
Kurtosis	1.596	0.684	- 1.020	- 0.835

Note:
1. The maximum and minimum in above are the maxima and minima of hourly values, not instantaneous absolute values.
2. S.D. is the standard deviation for the hourly data.
3. The statistical data are determined for the 35-year period 1960-94.
4. The mode for the hourly global solar radiation is invalid because of the zero values at night time.

Basically, four important aspects can be observed from the statistics:

- *Central tendency* – Mean (arithmetic), median and mode are the usual indices for central tendency [*].

- *Extremes* – The maximum and minimum values are extreme conditions for assessing the severity of the weather.

- *Spread* – The standard deviation indicates the spread of the data.

- *Shape* – The skewness [†] and kurtosis [‡] are indicators of the shape of data distribution as compared with a standard ell-shape’ normal distribution.

From Table 4.5, the long-term means of DBT and WBT are 23 ^{o}C and 20.3 ^{o}C, respectively. Study of the statistics for these temperatures indicates that DBT and WBT spread wider in winter than in summer; for the whole year, the temperature data tend to cluster more on higher temperatures. Study of the year-round humidity level and DPT in Table 4.6 shows that the year-round humidity level is high (annual mean RHM is 78.2%). Statistics for the hourly GSR data in Table 4.6 show an annual average of 0.53 $MJ/m^2/hr$ (or 12.7 $MJ/m^2/day$) which indicates plenty of sunshine in Hong Kong; hourly wind speed varies from 0 m/s to 23.5 m/s, but with a mean of only 3.04 m/s.

Evaluation of the shape of distributions (by skewness and kurtosis) requires more care since the statistical indices are affected by other factors, like

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[*] The mode is the most frequently occurring value; the median is the value above and below which one-half of the observations fall; the (arithmetic) mean is calculated by dividing the sum of all data by the total number of data.

[†] Skewness is a measure of the degree of symmetry about the central point of the data. If the tail (region with less cases) is toward larger values on the right, the distribution is positively skewed, denoted by a positive skewness. If the tail is toward smaller values on the left, then the distribution is negatively skewed, with a negative skewness.

[‡] Kurtosis indicates the extent to which observations cluster around a central point (i.e., how flat or peaked a distribution is). If cases cluster more than those in a normal distribution (that is, the distribution is more peaked), the distribution is called *leptokurtic*, denoted by a positive value of kurtosis. If cases cluster less than the normal distribution (that is, it is flatter), the distribution is termed *playkurtic*, with a negative kurtosis.

irregularities and multiple crests. The skewness for annual DBT, WBT and DPT are all negative which implies that the temperature distributions are skewed negatively with more data at high temperatures. It is interesting that the summer WBT is highly *leptokurtic* (with kurtosis = 4.357) which indicates that most WBT concentrates on a narrow range in summer. GSR and wind speed have positive kurtosis but not as large as the summer WBT. The summer and annual DBT, winter and annual WBT, annual RHM and annual DPT have negative kurtosis which shows that their distributions are flattened.

Comparison with ASEAN

The OTTV standards of ASEAN and Hong Kong have been compared in Section 3.3.3. It will be interesting to see how their climates compare with each other. Figures 4.2 to 4.4 show the monthly averages of DBT, WBT and daily total GSR of ASEAN and Hong Kong [*]. It can be seen from Figures 4.2 and 4.3 that Hong Kong has a clearer seasonal change than ASEAN. The temperatures in Hong Kong in summer time (June to September) are close to ASEAN (monthly average DBT from about 26 ^{o}C to 29 ^{o}C), but temperatures in winter and intermediate seasons are much lower than ASEAN. The tropical climate of ASEAN requires only cooling throughout the year but the Hong Kong climatic cycle requires that both heat gains and heat losses must be considered. There is a short and mild winter between November and February during which heating may be required in some air-conditioned buildings in Hong Kong (such as hotels). When the DBT and WBT profiles are considered, it can be seen that the DBT and WBT in Hong Kong follow closely with each other, but the DBT and WBT relationships vary throughout the year in some ASEAN countries (such as Bangkok and Singapore).

[*] The data for Hong Kong are taken from the monthly averages in Table 4.2 and the data for ASEAN are from the summary data reported in Deringer and Busch (1992).

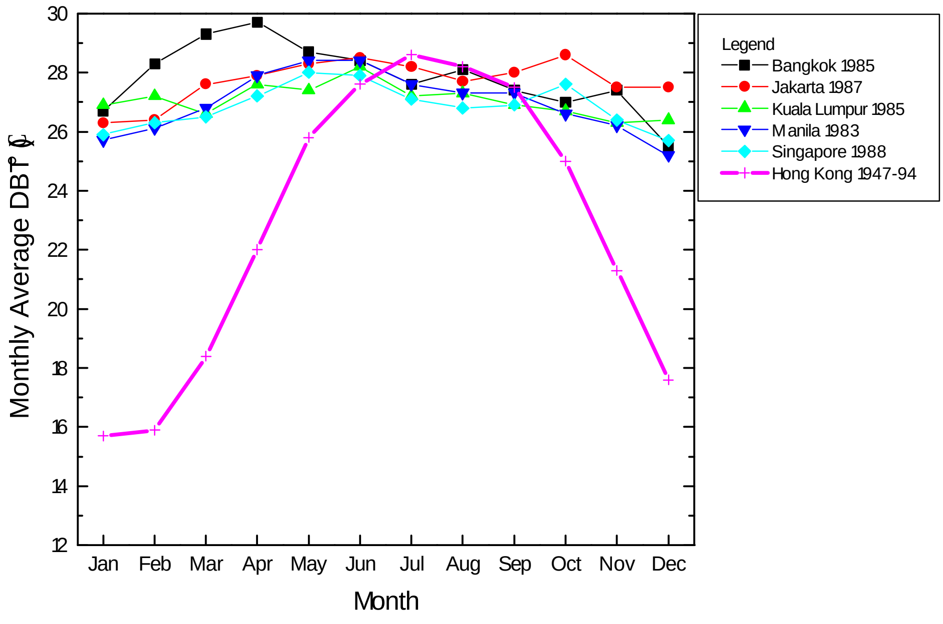

Figure 4.2 *Monthly Average Dry-bulb Temperature for ASEAN and Hong Kong*

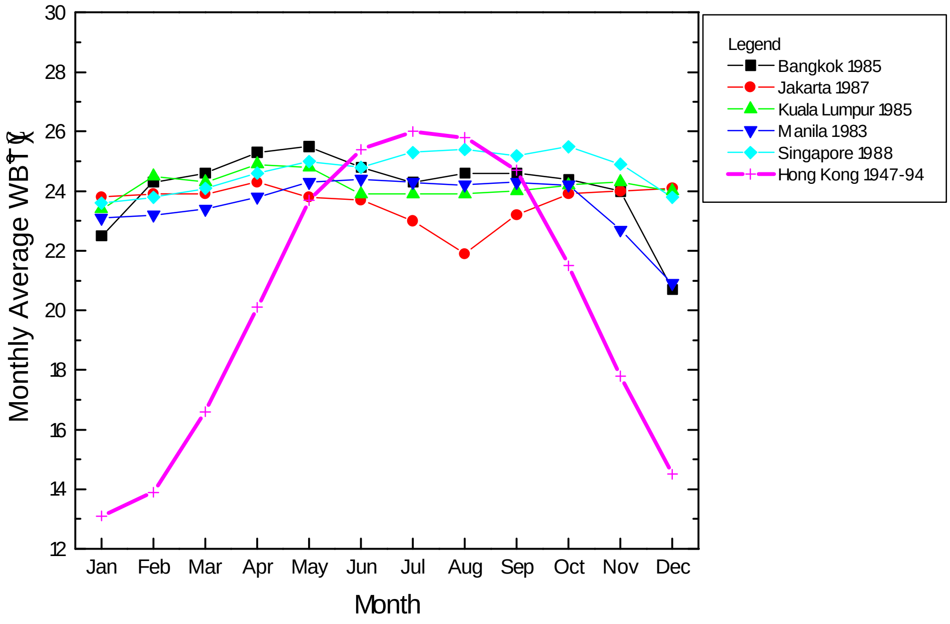

Figure 4.3 *Monthly Average Wet-bulb Temperature for ASEAN and Hong Kong*

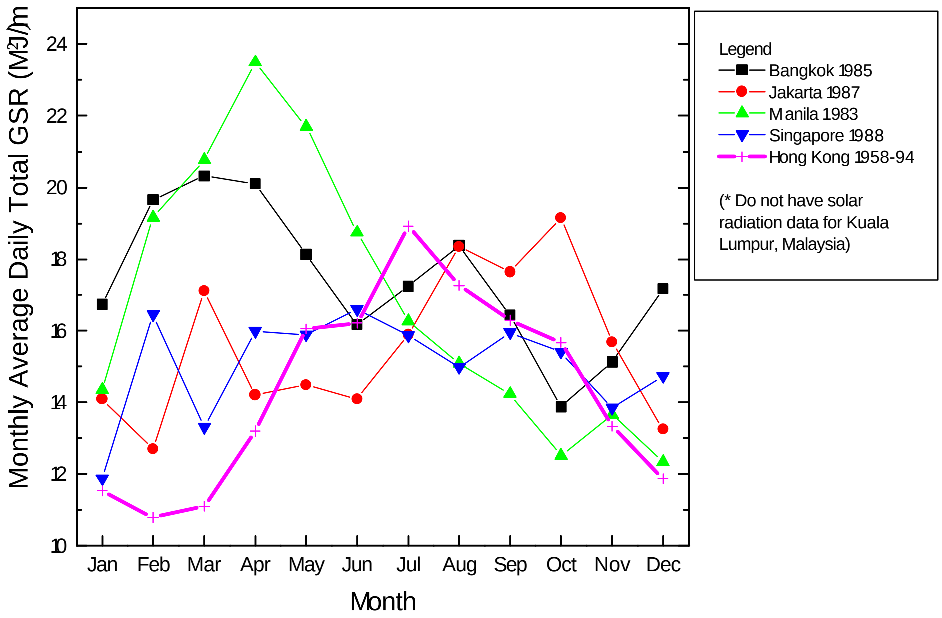

Figure 4.4 *Monthly Average Daily Total Global Solar Radiation for ASEAN and Hong Kong*

The monthly solar radiation as shown in Figure 4.4 are more varying in these countries. Hong Kong indicates a peak solar radiation in July but there are different peak solar months in ASEAN (March for Bangkok, October for Jakarta, April for Manila and June for Singapore). Since solar component is a dominating factor in the OTTV standards (see Section 3.3.3), the properties of solar radiation data should be examined with great care. The building systems (such as envelope and HVAC system) should be carefully designed if they are to take full advantage of the interactions of solar heat gains during winter and intermediate seasons. Assessment of the weather data can provide a useful check for the reasonableness of the parameters in the building energy standards and of the results in building energy performance analysis. To better understand the climatic cycle and properties of Hong Kong, frequency distributions of the major weather parameters are examined in detail in the next section.

4.4.2 Frequency distributions

Graphical representation is a simple and direct way to analyse and interpret climatic data. The frequency distributions of four major weather parameters (DBT, WBT, GSR and RHM) have been studied and plotted in graphical form to help understand the climatic properties. The probability distribution functions (PDF) of hourly DBT and WBT of Hong Kong are shown in Figures 4.5 and 4.6, respectively. The distributions for the summer months, winter months and whole year are given.

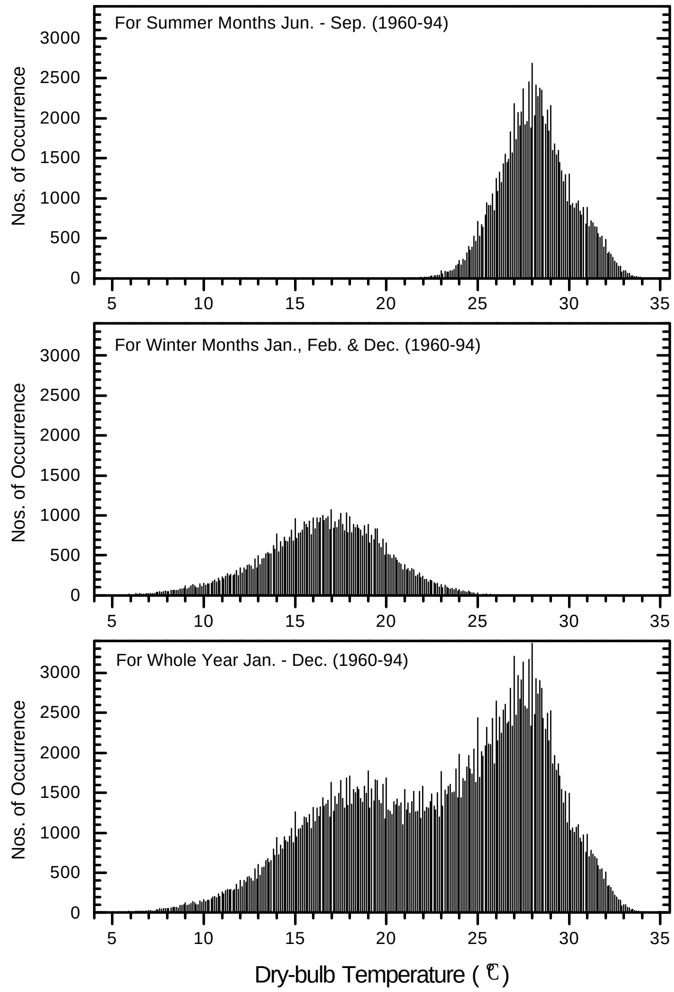

Figure 4.5 *Probability Distribution Functions of Hourly Dry-bulb Temperature*

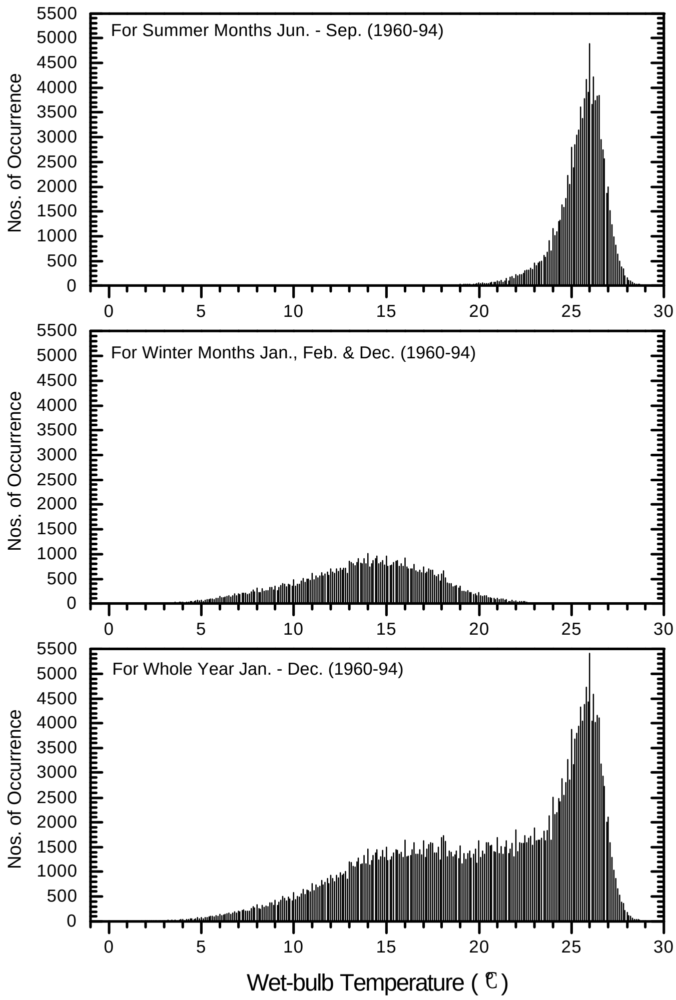

Figure 4.6 *Probability Distribution Functions of Hourly Wet-bulb Temperature*

It can be seen from Figure 4.5 that the PDF of summer and winter DBT are symmetric with mean temperatures at 28.2 ^{o}C and 16.5 ^{o}C, respectively. The PDF of whole-year DBT shows two marked peaks (one higher than the other) and is strongly influenced by the summer distribution. As for WBT in Figure 4.6, the summer WBT is skewed to the right with a sharp rising peak centred at 26 ^{o}C while the winter WBT is more widely spread with a mean at 13.8 C only. The resultant whole-year WBT tends to cluster at temperature between 24 ^{o}C and 27 ^{o}C but it has a mean of only 20.3 ^{o}C.

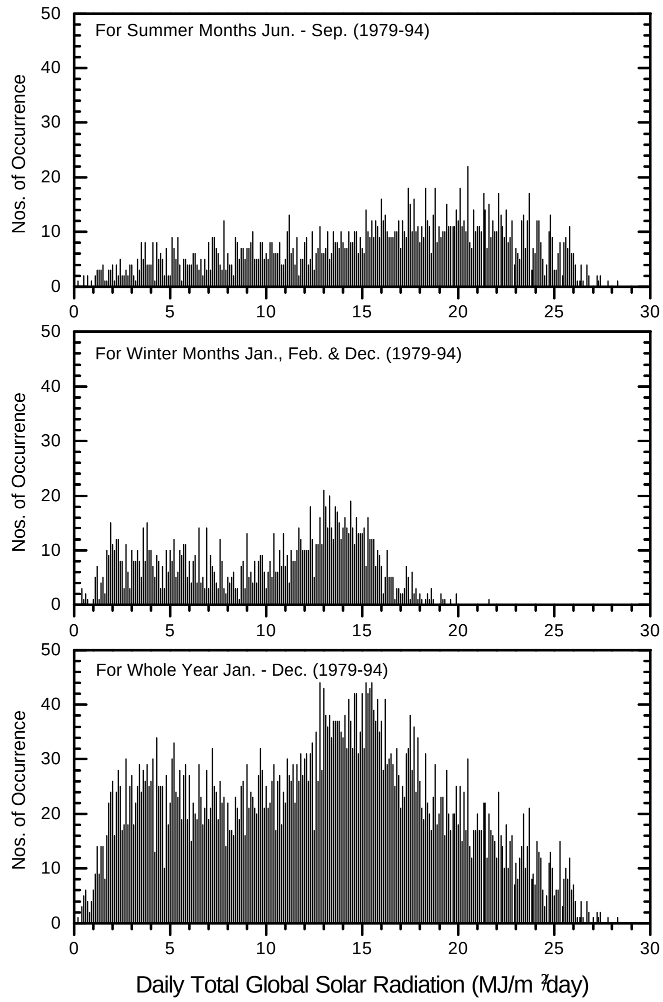

Figure 4.7 *Probability Distribution Functions of Daily Total Global Solar Radiation*

Figures 4.7 and 4.8 show the PDF of daily total GSR and hourly relative humidity, respectively. Daily total GSR for winter and for the whole year are quite similar with two crests roughly centred at about 4 and 14 $MJ/m^2/day$. GSR for summer has one crest at about 20 $MJ/m^2/day$ slightly skewed to the right. This indicates that there is large solar heat gain during summer and a short period in winter. The PDF of RHM for summer, winter and whole year are skewed to the right with data at the region from 60 % to 100 % all the time.

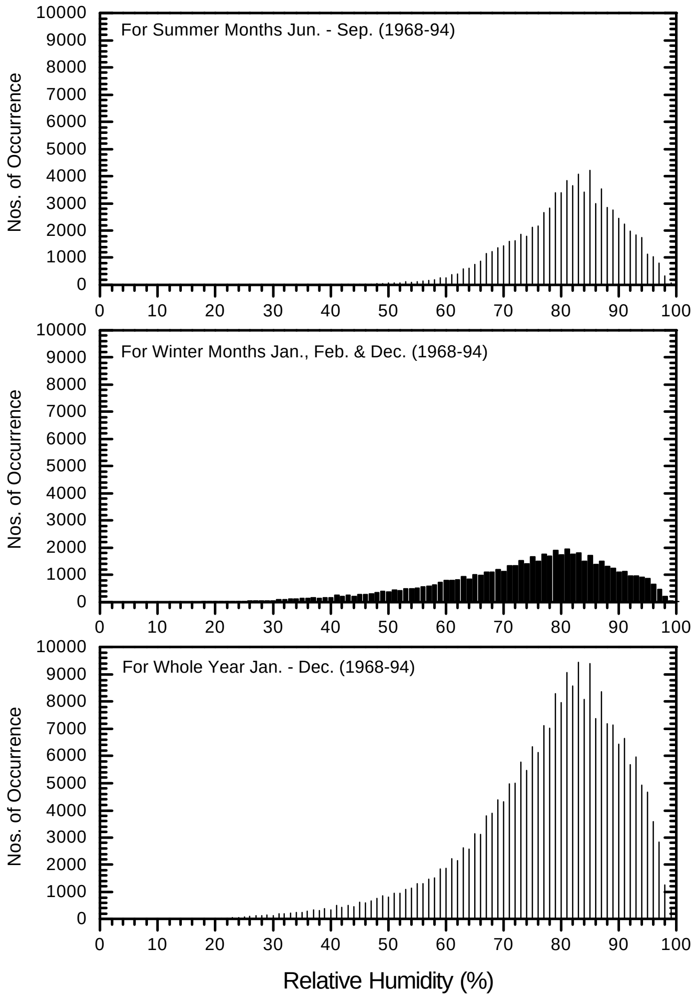

Figure 4.8 *Probability Distribution Functions of Hourly Relative Humidity*

The distribution charts can help visualise and understand the statistical figures (such as in Tables 4.5 and 4.6). They are very useful to designers who want to glance through the major climatic elements and principles for a location. Development of suitable frequency charts can also provide information for setting up a simple method for evaluating the design conditions and their implications to building performance as demonstrated in the following paragraphs.

Cumulative distribution functions

By converting the PDF charts into cumulative values, it is possible to analyse the outdoor design temperatures (DBT and WBT) effectively in a graphical form, since the cumulative frequency of occurrence is the opposite of the significance level commonly used in the design temperatures (see Section 4.2.1). Figures 4.9 and 4.10 show the cumulative distributions functions (CDF) of long-term hourly DBT and WBT of Hong Kong, respectively (summer, winter and whole year are shown). The abscissa on the left is the cumulative frequency of occurrence while that on the right is the significant level of design temperatures which ranges from 100% to 0%.

It can be seen from Figures 4.9 and 4.10 that the summer DBT, winter DBT and winter WBT is similar to the -curve' of a normal distribution function while the whole-year DBT and WBT (solid lines) are slightly distorted at high temperatures. The two extreme ends of the CDF are most interesting since the design temperatures can be determined by looking closely at these two regions. Figures 4.11 and 4.12 show the magnified views of the CDF for summer (the high end) and winter (the low end) design temperatures, respectively. The design DBT and WBT (DDB and DWB) are drawn in solid lines in Figures 4.11 and 4.12 while the coincident DBT and WBT (CDB and CWB) are given as squares and triangles, respectively. These charts are very useful since they can be used to determine the design temperature at various significant levels and to understand the relationships between the design and coincident temperatures.

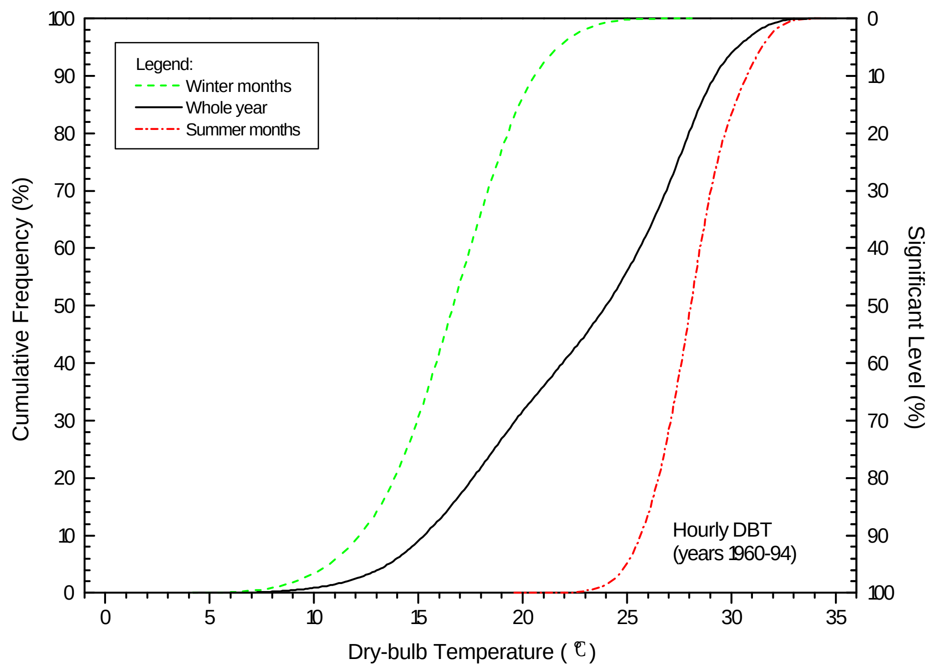

Figure 4.9 *Cumulative Distribution Functions of Hourly Dry-bulb Temperature*

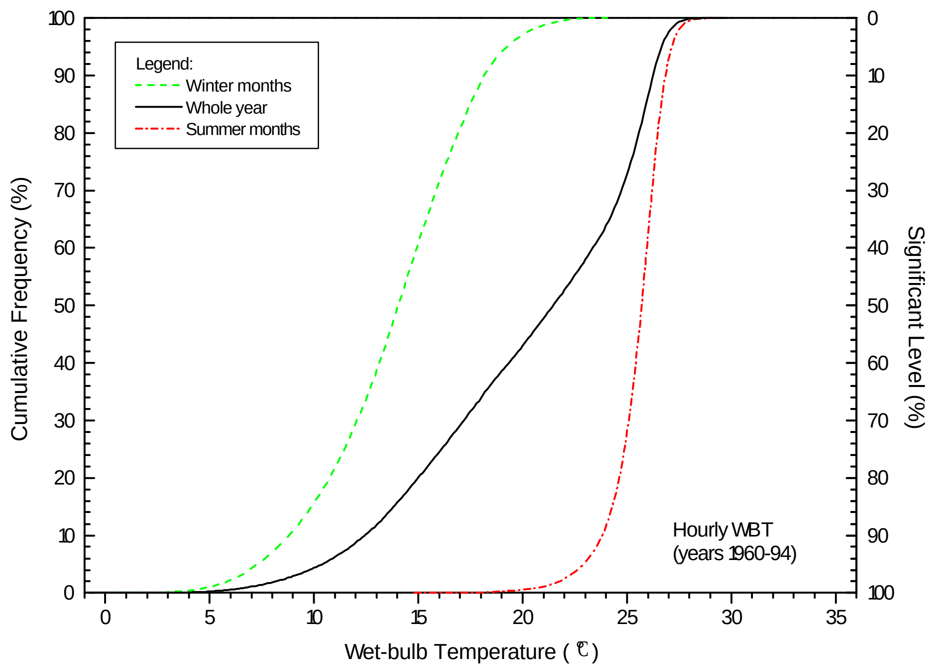

Figure 4.10 *Cumulative Distribution Functions of Hourly Wet-bulb Temperature*

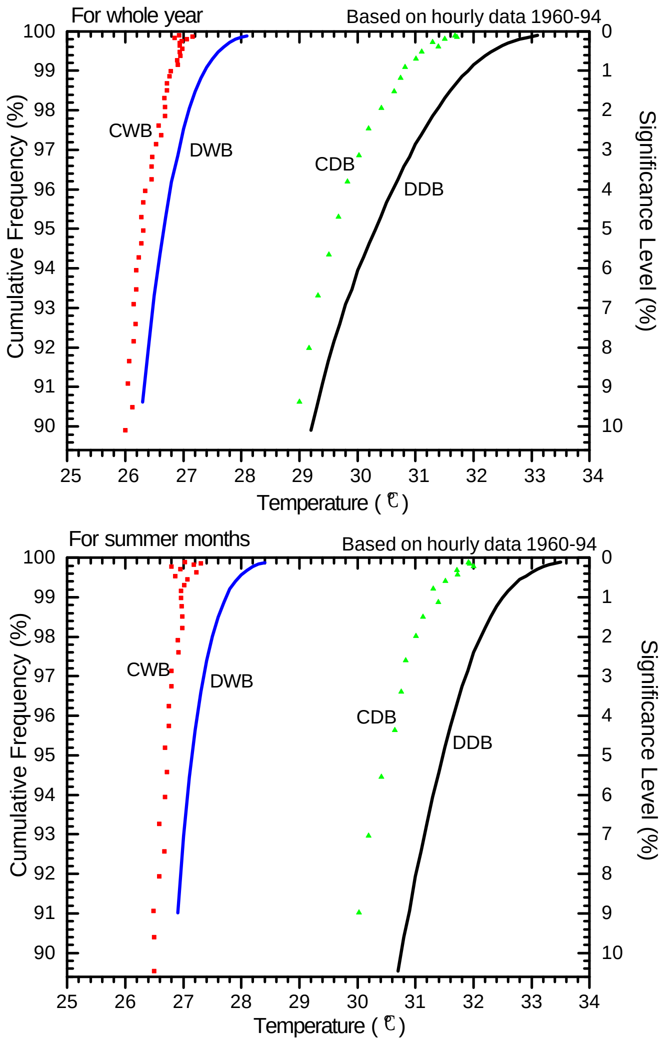

Figure 4.11 *Cumulative Frequency for Summer Design Temperatures*

It can be seen from Figure 4.11 that for summer design purpose the coincident temperatures are higher than their respective design temperatures (CDB is higher than DDB and CWB is higher than DWB for both whole year and summer months). Whereas, from Figure 4.12 for winter design purpose, the coincident values are lower than their corresponding design values. This indicates that independently determined design temperatures are more stringent than their corresponding coincident values. The difference between the design and coincident temperatures at various significant levels can be read directly from the figures.

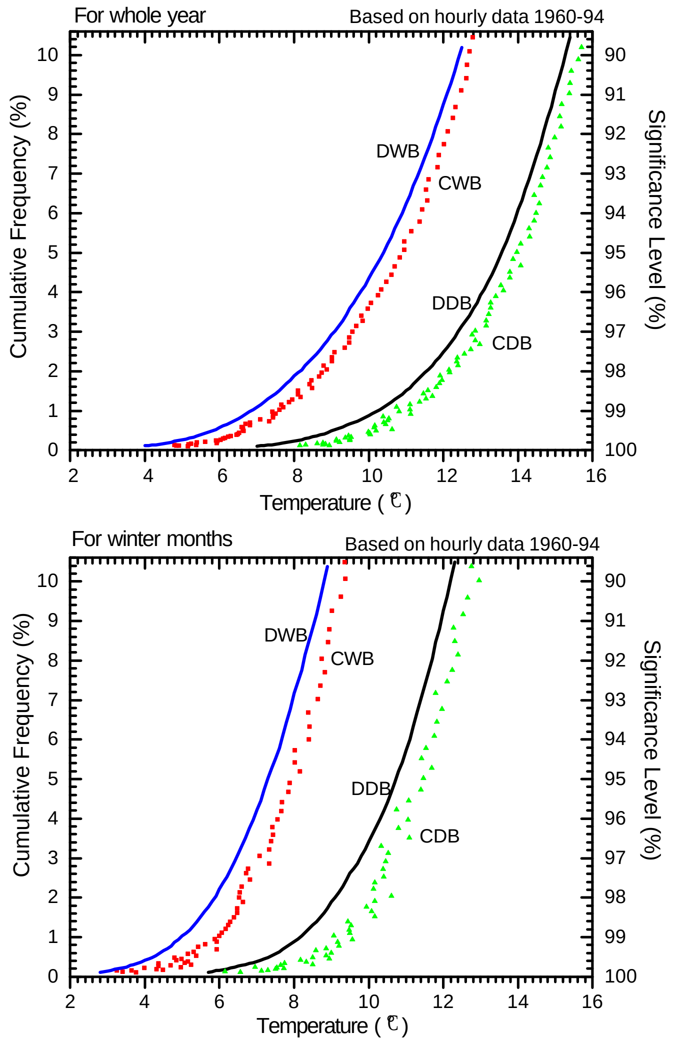

Figure 4.12 *Cumulative Frequency for Winter Design Temperatures*

It should be noted that the frequency levels determined from summer and winter months are not the same as the annualised (whole-year) values. Conversion between the summer/winter frequency of a design temperature and the equivalent annualised frequency level can be made by using the graphs of Figures 4.11 and 4.12. For example, at summer frequency of 2.5%, the DDB is 32 ^{o}C (it can be read from the lower graph of Figure 4.11). From the DDB curve of the whole-year period in the upper graph of Figure 4.11, a DBT of 32 ^{o}C would mean about 1% annualised value. Similar techniques have been employed by Mason (1988 & 1993) for evaluating the design conditions in Australia.

4.4.3 Building thermal design by graphical methods

Climate analysis often involves presentation of the annual patterns of the main climatic factors in various forms (Givoni, 1992; Loftness, 1982). Building designers are interested in both seasonal and diurnal variations. It will be useful for them if the weather data can be presented throughout the day and throughout the year (Brealey, 1972). To help designers analyse the climatic variations in Hong Kong, some graphical methods for climatic analysis have been used to develop characteristic charts showing the seasonal weather behaviours of Hong Kong. It is hoped that the information presented here can demonstrate a useful approach for assessing building thermal design and its energy implications. Techniques described in this section are only some of the methods the author thinks useful and effective for the conditions in Hong Kong. There are many other options for graphical climate assessment, such as those in Loftness (1982) and Watson and Labs (1983). Application of these methods will require evaluation of their efficiency under the climate concerned.

Year-round contour maps

A year-round contour map (also called sopleth' chart), has been generated to show the diurnal variations of weather parameters in Hong Kong throughout the year. Figures 4.13 to 4.16 show respectively the year-round contour maps of DBT, WBT, relative humidity and GSR of Hong Kong (these contours are plotted using the long-term monthly averages of the weather parameter at each hour of a day). These charts are useful for finding what design recommendations or corrective measures are needed to achieve efficient building design and operation.

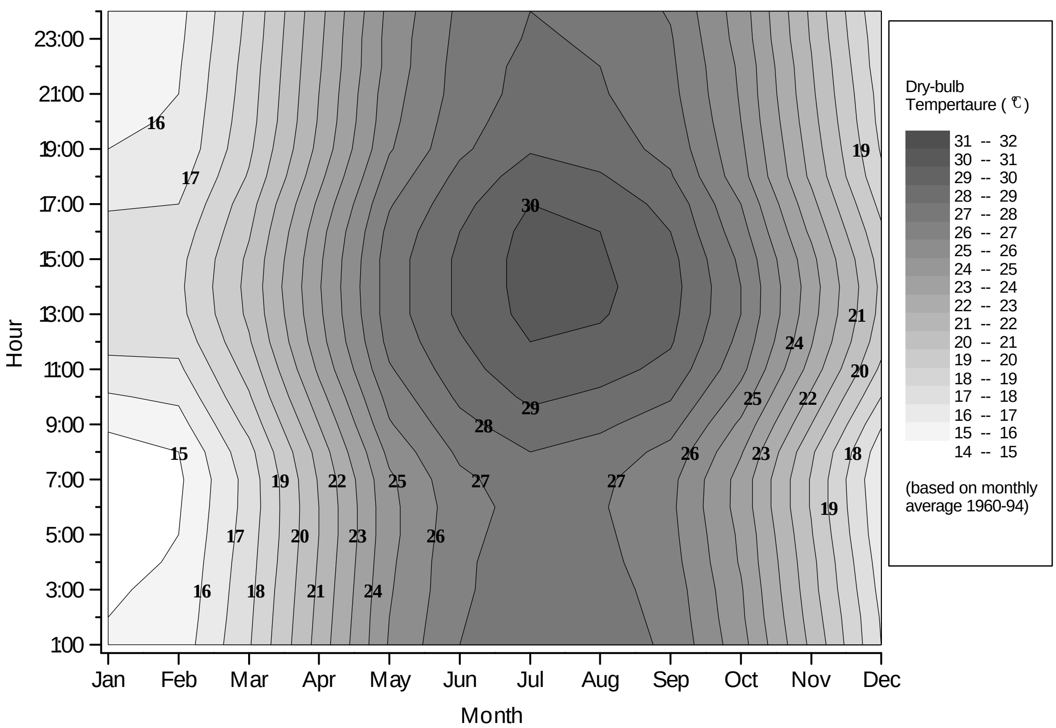

Figure 4.13 *Year-round Contour Map of Dry-bulb temperature*

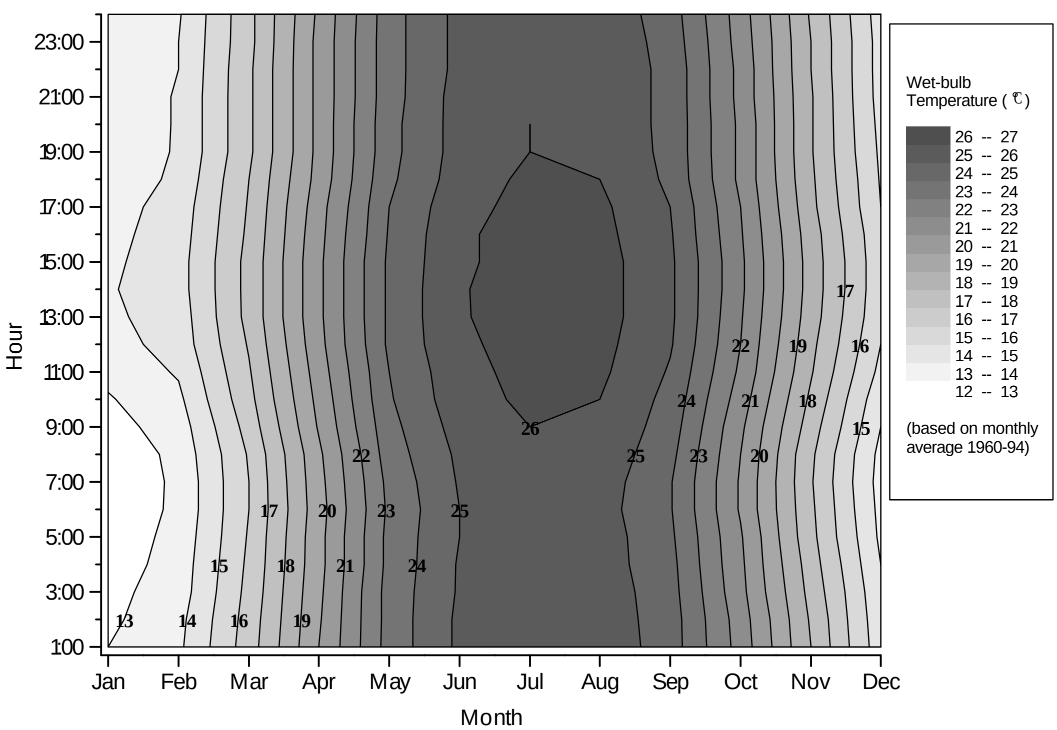

Figure 4.14 *Year-round Contour Map of Wet-bulb temperature*

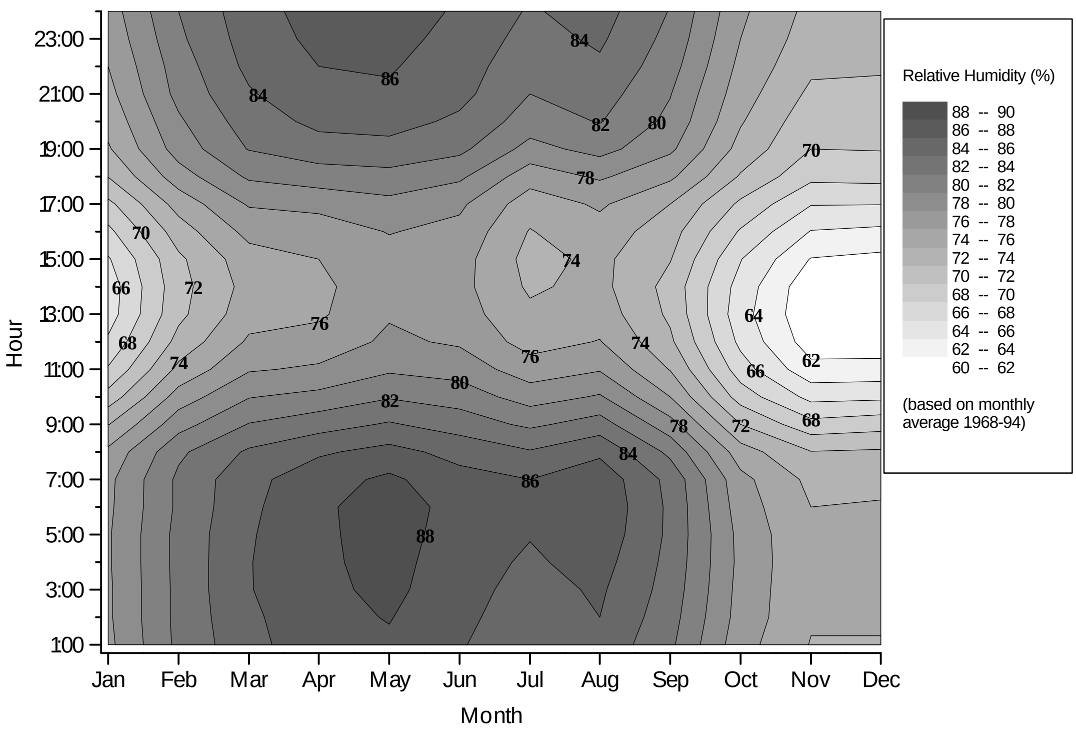

Figure 4.15 Year-round Contour Map of Relative Humidity

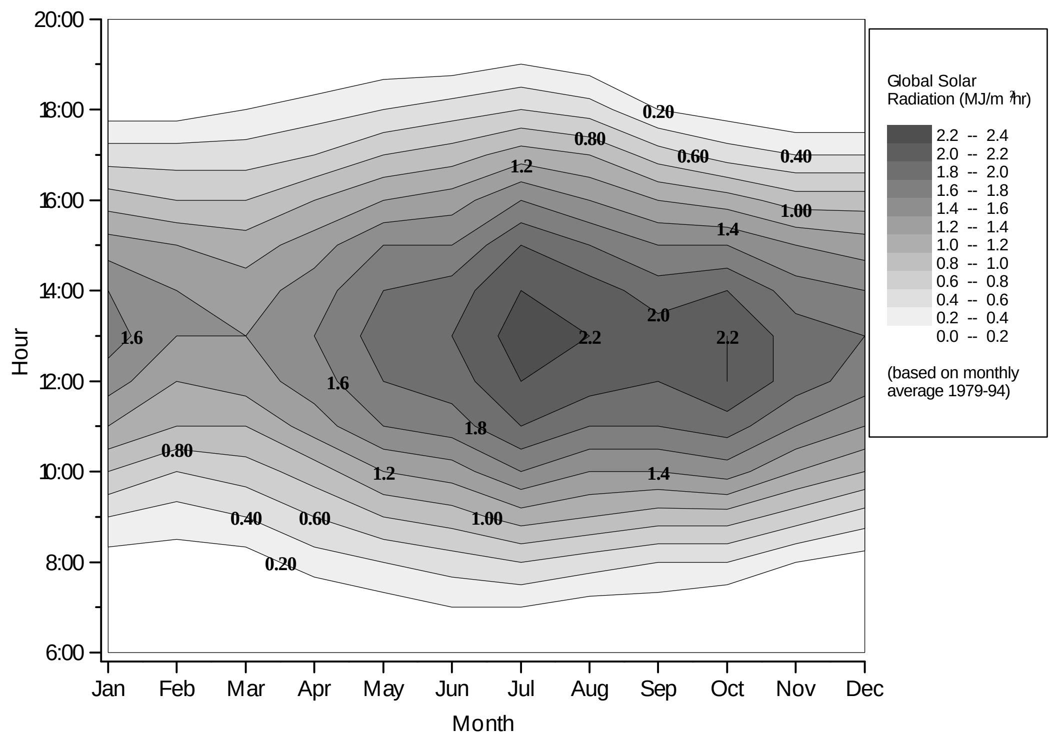

Figure 4.16 Year-round Contour Map of Global Solar Radiation

It can be seen from Figures 4.13 and 4.14 that the climatic variations of DBT and WBT are quite similar. Analysis of the DBT pattern indicates that the hottest time is the hours from 12:00 noon to 5:00 pm in the months of July and August where the average DBT is above 30 ^{o}C. The WBT pattern shows that WBT is high (above 26 ^{o}C) in the mid-day of June to August. The contour map of relative humidity in Figure 4.15 indicates that the humidity level is high in the mid-seasons from March to June at hours 1:00 am to 7:00 am in the morning and 9:00 pm to 11:00 pm at night. The GSR variations in Figure 4.16 exhibit a maximum in the middle of a day from 11:00 am to 3:00 pm. It is interesting that another peak of the GSR contours can also be found in January.

Frequency analysis on psychrometric chart

As discussed before in Section 4.2.1, the coincidence of DBT and WBT is difficult to assess only from the outdoor design conditions. To study the effects of coincidence of DBT and WBT data, simultaneously occurring hourly DBT and WBT pairs have been used to plot on a psychrometric chart the frequencies of occurrence of the DBT and WBT pairs. Figures 4.17 to 4.19 show such plotting constructed in one-degree intervals for the summer, winter and whole-year periods, respectively. This type of frequency charts was proposed by Kowalczewski and Cunliffe (1967), and has been used for assessing the year-round climate and characteristics of building energy consumption (Holmes and Adams, 1977).

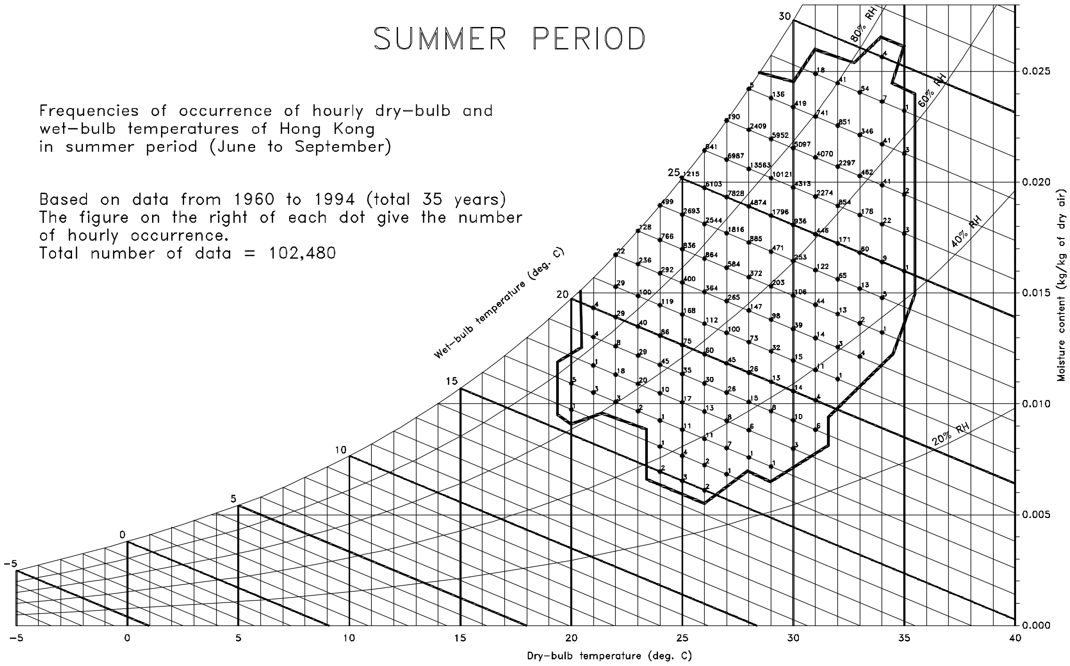

Figure 4.17 *Frequency Chart of Simultaneous Dry-bulb and Wet-bulb Temperatures of Hong Kong for the Summer Period*

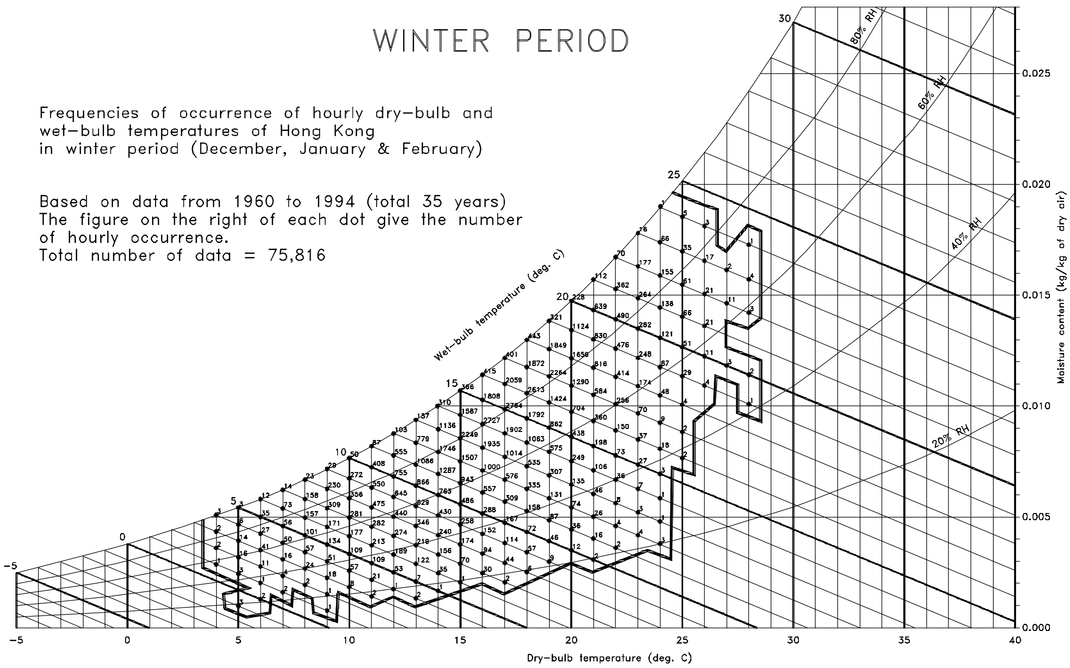

Figure 4.18 *Frequency Chart of Simultaneous Dry-bulb and Wet-bulb Temperatures of Hong Kong for the Winter Period*

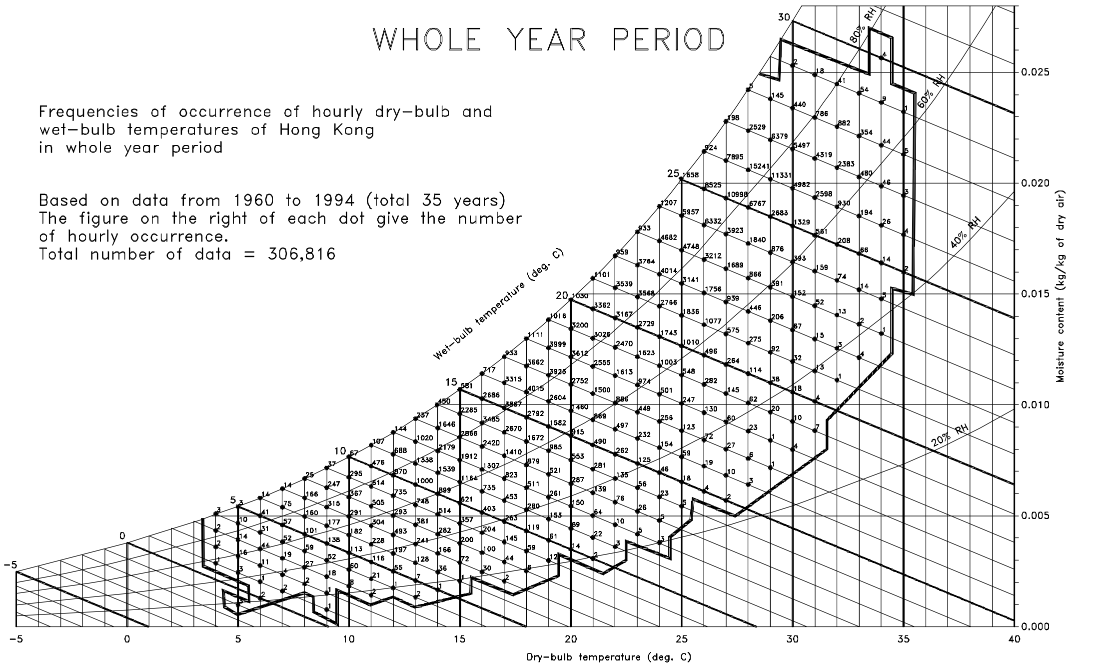

Figure 4.19 *Frequency Chart of Simultaneous Dry-bulb and Wet-bulb Temperatures of Hong Kong for the Whole-year Period*

The figure adjacent to each dot of the DBT / WBT pair in Figures 4.17 to 4.19 represents the number of hourly occurrences in the 35-year period 1960-1994. The temperatures indicated are class mid-values (that is, 20 ^{oC} represents the range between 19.5 ^{oC} and 20.5 ^{oC}). The probability of hourly DBT and WBT can be obtained by dividing the number of occurrences by the total number of data concerned. An utdoor air envelop’ (Wang, 1987, Unit 18) which indicates the span of the outdoor conditions has been drawn in thick solid lines on the chart to show the year-round outdoor conditions.

It can be seen from Figure 4.17 that in the summer months a small range of DBT and WBT values covers a large fraction of the entire distribution. For example, about 89% of the hours lie in the regime defined by DBT between 25 ^{oC} and 32 ^{oC} with WBT between 23 ^{oC} and 27 ^{oC}. The mode of coincident DBT and WBT for the summer months lies in the group with mid-values DBT of 28 ^{oC} and WBT of 26 ^{oC}. The number of occurrences of this group constitutes 13.2% of the total hours in the summer months. The range of RHM spans from 30% to 100% with most of the time at high humidity above 60%. The moisture level of the hours also indicates that latent cooling is an important consideration in HVAC system design and operation in Hong Kong. In Figure 4.18, the frequency chart of simultaneous DBT and WBT in the winter months spreads over a wider range. The RHM level ranges from 15% to 100% with the moisture content staying at lower values than in the summer months. The intersection of individual means of DBT and WBT (16.4 ^{o}C and 13.8 ^{o}C) is located at the centre of the winter outdoor air envelope since both winter DBT and winter WBT have a distribution close to normal.

The frequency chart for the whole-year period in Figure 4.19 indicates that the year-round weather conditions of Hong Kong, with other intermediate seasons considered, span a relatively small range in both temperature and humidity. Over 42% of the hours lie in the regime defined by DBT between 24 ^{o}C and 31 ^{o}C with WBT from 23 ^{o}C to 27 ^{o}C. The mode of coincident DBT and WBT for the whole-year period lies in the group with DBT of 28 ^{o}C and WBT of 26 ^{o}C, which is the same as the summer period. This implies that the year-round weather condition are strongly influenced by the summer distribution. By dividing the outdoor air envelope into different regions based on the properties of the outdoor air, it is possible to determine the schemes for different HVAC operations, such as economiser cycle (Lam and Hui (1995a). It is found that the minimum outdoor air is required for about two-thirds of a year and the economiser cycle (free cooling) can be used for about 30% of the time in Hong Kong. Other climate assessments can be made using these frequency charts, such as CIBS (1984, pp. 14-18) and Hughes (1989, Section 2). Kowalczewski and Cunliffe (1967) believed that this type of charts should retain usefulness even after the air-conditioning calculations are fully computerised.

Develop better understanding about weather

A building energy use is subject to a range of dynamic interactions affected by seasonal and daily changes in climate. Building design requires a seasonal analysis of the relationship between the patterns of energy supply and the patterns energy demand from the impacts of climate. It is possible for designers to take full advantage of the climate by intelligent use of building materials, architectural form and HVAC systems, if a more climate-sensitive approach is taken in the building design process. Graphical and statistical analyses are useful for climate assessment at the early building design stage.

The loads on HVAC equipment vary as the transmission of heat through the exterior building envelope and the difference in heat content between outdoor and indoor air are affected. It is often the case that the effects of weather on building energy use is masked by the various factors present in the analysis process. If design optimisation for the building and its HVAC systems is to be achieved, then a clear understanding of the characteristics of climatic patterns, building configurations and mechanism of energy simulation should be established. Roberts (1966) pointed out that although weather is the primary reason for air conditioning, this variable is the least understood. The thermodynamic properties of each climatic variable, such as temperature and solar radiation, on building components are fairly well established, but the analysis of the weather time series and the inter-relationships among the variables is still embryonic. The multi-variable weather time series involved is difficult to be modelled by simple methods. The analysis of the typical weather patterns and weather time series is the subject of the next chapter.