DAYLIGHT AND SOLAR DATA

Paul J Littlefair and Sheila M Secker*
Building Research Establishment, Garston, Watford, WD2 7JR
*160 Longhurst Lane, Mellor, Stockport, SK6 5PJ

In building design the ability to predict the effects of daylight is of increasing importance. Daylight can be an important factor in building energy efficiency; in some buildings lighting may account for half the energy cost. This paper describes the weather data that are available for daylight prediction. First of all the requirements for data are evaluated. For many energy applications, the key quantity is the percentage of the working year a given design illuminance is exceeded by daylight. This requires external daylight illuminance data, together with a knowledge of sky luminance distribution. The paper then outlines the available data on daylight in the UK, including the Meteorological Office measurements and more recent data from Garston and Nottingham. These do not cover the whole of the UK, and so the paper also describes prediction methods to evaluate daylight availability where no measured data exist. These may be simple formulae based on solar altitude; complex models which can also predict sky luminance distribution; or luminous efficacy values to obtain daylight data directly from solar radiation data.

1. INTRODUCTION

1.1 Background

The recent interest in daylight has centred around its use as one of an array of new energy efficiency techniques in buildings. Although only some 5% of UK primary energy is consumed by lighting, in some types of building, such as office blocks, it can account for some 30-60% (1) of primary energy consumption (a fair reflection of energy cost). To illustrate the energy effects of the decision whether to use daylight, Crisp (2) classified the 'low-energy' buildings investigated as case studies (3) by the RIBA energy group, and found that in general the shallow plan, daylit, naturally ventilated buildings had around half of the predicted primary energy consumption (in W/m^2) of the deep plan, air-conditioned buildings with extensive artificial lighting.

New technology has been developed which can promote the efficient use of daylight. A breakthrough here has been the availability of new forms of lighting control, such as daylight-linked photoelectric switching, time switching, and localised manual control (4). An example case study has been reported by Portsmouth City Council (5), who installed a control system in an open plan office which combined all three of these operations, and reported nearly 40% saving in lighting energy use compared with traditional switching.

Although these new forms of lighting control are by now accepted technology nevertheless prediction methods are still required to better assess the cost-effectiveness of control energy savings in a particular building; which demands an accurate knowledge of daylight levels at the control points. Other applications in building design, such as the calculation of the energy effectiveness of increased glazing area or installation of solar shading, also require a quantification of indoor daylight levels and their impact on artificial lighting use and internal gains.

1.2 Requirements for daylight calculations

In general, daylight levels inside a building depend on two main factors; the building details (window size, internal reflectances, obstructions, etc) and external daylight availability, typified by external illuminance levels and sky luminance distributions. This paper concentrates on external daylight data.

Daylight levels are constantly changing, both annually and diurnally and as weather conditions alter; one important consequence of the time variation of daylight is that it is not possible to meaningfully quote a single internal daylight illuminance for a building. Moreover, as daylight cannot be stored, time integrated data of the 'degree day' type are usually inappropriate, except where plant growth or damage to art objects are important issues. Instead a range of illuminances needs to be specified. For building energy related calculations, the most suitable quantity is usually the cumulative distribution of internal illuminances; typically the percentage of the working year a given design illuminance is exceeded. This quantity can be related to the energy used for artificial lighting in a daylit building. For example, the energy saved by a basic on-off photoelectric control will simply be proportional to the percentage of working year its switching illuminance is exceeded. For dimming control the situation is more complicated, but savings can still be related to the cumulative distribution (7). For manual switching, Hunt's method (6, 8, 9, 10) can be used.

Average illuminances for each month and hour can also be used for checking the consequences of daylight design, and assessing the seasonal and diurnal variations in daylight levels. They can also be related to lighting energy use (11).

In each case internal illuminances are required. These can be obtained from the corresponding external illuminance data provided some assumption is made about sky luminance distribution. References 12, 13, 7 and 10 give appropriate methods for internal illuminance calculation.

Traditionally in the UK a CIE standard overcast sky luminance distribution has been assumed. Under a CIE overcast sky the daylight factor (the ratio of internal to external horizontal illuminance) can be calculated for any point inside a building (12-13). Internal illuminances can then be calculated by multiplying the daylight factor by horizontal external diffuse illuminance data.

Unfortunately this approach cannot account for the effects of orientation which occur on non-overcast days. These are important; for example a south facing window receives over twice as much daylight (including direct sunlight) as a north facing one. Correction can be made by multiplying the daylight factor by an orientation factor. Table 1 gives orientation factors which can be used (11). Alternatively the vertical external illuminance data from Garston (7) can be used as the starting point for calculation, multiplied by a ratio which depends on daylight factor.

Alternative luminance distributions such as the BRE Average Sky have now been developed which can be used to calculate internal illuminances. These are described in sections 3.2 and 3.4.

TABLE 1 - Total and Diffuse Orientation Factors for an 09.00-17.00 Working Day

Orientation	Total	Diffuse
North	0.77	0.97
East	1.02	1.15
South	1.67	1.55
West	1.08	1.21

In general, before internal illuminances can be calculated some sort of external daylight data needs to be obtained. In addition to the time variation mentioned above, there are also systematic geographical variations in daylight availability (6). Thus it is possible that the benefits of daylighting may vary significantly from region to region within the UK. The next section reviews the available external daylight data.

2. AVAILABLE DATA ON DAYLIGHT

For many years the external meteorological data which were used as the basis for daylight design in Britain were those recorded at the National Physical Laboratory, Teddington from July 1933 to October 1939. These values were analysed and reported upon by McDermott and Gordon-Smith (14).

In 1947 the Meteorological Office began recording of global sun and sky illuminance on the horizontal plane at Kew Observatory. This was followed later by recording at London weather Centre (from 1950), Lerwick (1958), Eskdalemuir (1958), Bracknell (1965), Jersey (1969), and Aldergrove Belfast (1969). The measurement of diffuse (sky) illuminance started at Kew in 1962 and Bracknell 1966. Records ceased on 31 December 1977. Some of the data have been published in the Monthly Weather Reports of the Meteorological Office, but frequently corrections to the data were published up to twelve months later. The detailed observational data can be consulted at the Meteorological Office or obtained on computer print/out tape. These values

values have now been analysed by the Building Research Establishment and the results published by Hunt (15). His report provides a great deal of up-to-date information about the daylight availability at Kew and Bracknell for the period 1964-1973, and slightly less detailed for the other five stations.

Figures 1-4 are taken from this report. Figures 1 and 2 show mean diffuse and global external illuminances at Bracknell for each hour and month of the year. Figures 3 and 4 contain cumulative distributions, showing the percentage of a working year different daylight illuminances are exceeded. Figure 3 shows the effect of location on global illuminance availability. Figure 4 uses data from one location (Kew) to indicate the effect of choice of working hours on daylight availability.

Despite the Meteorological Office work, there still remains a large area between London and southern Scotland, containing a not inconsiderable proportion of the 'built environment' of Britain, for which there is no long continuous record of illuminance data. A literature search has revealed only a few other investigations of daylight conditions namely:

(1) at Edinburgh by the National Physical Laboratory and reported upon at the CIE Conference 1948 (16)

(2) at Plymouth from 1930 to 1941 and 1947 to 1949 by Atkins et al (17)

(3) at East Grinstead, St. Albans and Leeds by the Central Electricity Generating Board in the 1950s

(4) at Nottingham between May 1978 and July 1979, and from June 1984, by Tregenze (18-20)

(5) at Garston by the Building Research Establishment from 1981-1984 (7, 21)

3. PREDICTING DAYLIGHT IN THE REGIONS

3.1 Use of available data

Thus there is a shortage of measured daylight data for most parts of the UK. The data from the six sites monitored by the Meteorological Office (Jersey, Kew, London, Aldergrove, Eskdalemuir and Lerwick) plus Nottingham and Garston can be used. Although for other locations interpolation can be used, it clearly cannot allow for local differences in microclimate. Application of the data is limited because (a) diffuse illuminances are not generally available and (b) there is a large area of central and northern England which is not covered. Clearly more measurements are desirable. At the time of writing we understand that new measurements are planned at Sheffield, and it is hoped that the data will be available soon. 1991 has been designated 'International Daylight Measurement Year' by the CIE and more measurements should be made then. Meanwhile various methods exist to predict daylight availability and these are examined below. No method is as good as directly measuring the daylight, but they can often give a reasonable approximation to real illuminances.

3.2 Allowing for latitude

Geographical variations in daylight availability can be treated as combinations of latitude related variations and climate related variations. This separation turns out to be important because latitude related variations are much easier to predict. The simplest approach is to use a formula which relates average global horizontal illuminance E to solar altitude Ys such as that proposed by Chroscicki (22) and illustrated in Figure 5;

$$E = \frac{89.1 \sin Ys}{1 + 0.2 \operatorname{cosec} Ys} \quad \text{kilolux}$$

The use of this type of formula can allow for the regional variations in illuminances that are due to differences in solar altitudes at different latitudes. However it cannot allow for climate related variations. In this case Chroscicki's formula fits Kew data very well but may overestimate illuminances in the cloudier areas of Scotland. Kittler (23) has reviewed alternative formulae based on solar altitude which can be used for different climatic zones.

A different method which can allow for latitude variations in the same way is the BRE Average Sky (24-26). It consists of a series of equations (26) which relate time averaged sky luminance distribution to solar altitude. From this sky luminance distribution average daylight illuminances on any plane, internal or external, can be calculated for each month and hour of the year. Thus the Average Sky is more powerful than the formulae already described, because it can be used to find daylightavailability inside buildings as well as on external planes. However, like the external illuminance formulae, it is only capable of allowing for latitude related variations, and not climate related variations in either global illuminance or sky luminance distribution.

Another potential criticism of these methods is that they can in general only be used to predict average daylight illuminances; while for building energy use applications, for instance, the full range of daylight illuminances is required as characterized by the frequency or cumulative distribution. However new techniques have now been developed (11) which enable the cumulative distribution of daylight illuminances throughout the working year to be predicted using the BRE Average Sky.

3.3 Prediction from radiation data using luminous efficacy

Luminous efficacy methods are perhaps the most versatile and easily applied ways to calculate external daylight availability. They can in principle allow for most of the climate and latitude related variations. The luminous efficacy is simply the ratio of a daylight illuminance (in lux) to the corresponding irradiance (in W/m²). It is usually expressed in lumens per Watt (lm/W). Thus any irradiance data can be converted into illuminance data provided that the luminous efficacy is known.

For example, external irradiance data for the CIBSE Example Weather Year could be multiplied by a luminous efficacy to give external illuminances. However the appropriate luminous efficacy must be used in each case, ie for global, diffuse or direct solar data (see Table 2).

Within the UK, Meteorological Office radiation are available for 34 locations (27, 28). For all of these global horizontal irradiance has been recorded, plus diffuse horizontal irradiance at nine sites. Direct solar irradiance has been recorded at Kew and Easthampstead (Bracknell), and vertical total irradiances at Easthampstead. Independent irradiance data have also been obtained for tilted surfaces at Cardiff (29) and Birmingham (30).

Using luminous efficacy values all of the solar radiation data could be converted into daylight data and thus daylight illuminances would become available for a considerable number of locations where directly measured data do not exist. Unfortunately luminous efficacy values are themselves subject to variations (31), albeit smaller than the illuminance variations. A recent review of the subject (32) quoted values from various authors and for various sky conditions. The quoted global efficacies were found to range from 77 to 135 lm/W. Luminous efficacies can vary with solar altitude, atmospheric aerosol and water vapour content, and type and amount of cloud; and also according to whether diffuse, direct or global radiation is being considered. Illustrative values are given in Table 2.

TABLE 2 - Typical values of Luminous Efficacy (32)

	Luminous efficacy lm/W
Direct sun	55-90 at solar altitude 10° 100-110 at solar altitude 60°
Clear sky diffuse	120 - 140
Clear sky global	95 - 115
Overcast	105 - 120
Average diffuse	105 - 120
Average global	100 - 115

Thus it is essential that where luminous efficacy values are used they should be appropriate to the climatic conditions and type of data under consideration. A previous paper (33) calculated values for sites throughout the UK, and further research is currently underway at BRE to measure luminous efficacies and present them in appropriate formats. Meanwhile, the interested reader should consult the literature reviews (31, 32) mentioned above.

3.4 Prediction from other Meteorological Parameters

Daylight illuminances can also be obtained from other meteorological quantities instead of radiation data. The method developed at the Meteorological Office in 1961 by Taylor and Smith (34) used correlations of illuminance with sunshine and visibility data for Kew to derive illuminance data for 86 stations around Great Britain. The advantages of this method is that it enables use of relevant meteorological data which is recorded over a wide network of stations and long-period data exist. The estimated data published then gave the average daily total of daylight; a useful quantity for plant growth applications, but less relevant for lighting calculations in buildings.

More recently, in 1976, Smith (35) has produced another set of estimated illuminance data for 68 climatic areas of England and Wales, based on regression equations on sunshine for Kew and Eskdalemuir, taking account of the effect of the decrease in pollution on the Kew data. Values for each area were then calculated using sunshine averages. This data still indicates significant geographical variations and provides some information for the large tracts of Britain not covered by measurements.

A more recent method has been proposed by Aydinli (36, 37) and also by Page (38-40). Essentially it involves combining expressions for illuminances and irradiances under clear and overcast skies in proportion to observed sunshine probabilities for a particular site. Correction functions are used to allow for the extra irradiance on partly cloudy days. This method can allow for geographical variations due to latitude or sunshine, and also be used to obtain illuminances and irradiances on vertical planes and inside buildings. Thus a large number of luminous and radiant quantities can be calculated from the simple input parameters of sunshine probability and sun position.

This method has been extensively used for the prediction of solar radiation (40) and calculated values have been compared with irradiance measurements for a number of sites. However an exhaustive test of the daylight prediction algorithms against measured data has yet to be published and therefore their accuracy critically depends on the luminous efficacy values which are included in the calculation.

4. CONCLUSIONS

The increased interest in daylighting has led to a demand for methods of predicting daylight availability and lighting energy savings. This paper has outlined some of the techniques that are available, and the sources of basic data. More daylight data are required, especially for Northern England. Although ways of estimating daylight have been described, there is no substitute for measured data, and it is hoped that the forthcoming CIE International Daylight Measurement Year will help to remedy the situation.

ACKNOWLEDGEMENTS

The work described here forms part of the research programme of the Building Research Establishment of the Department of the Environment, and this paper is published by permission of the Director.

REFERENCES

1. V H C Crisp and J W Ure. 'The energy implications of flexible lighting controls'. Proc IEEE Conf on Effective Use of Electricity in Buildings, 1980 (BRE Reprint R6/81).

2. V H C Crisp 'BRE research report: Lighting - the energy key?', Building Services (J CIBS) 6 (5) 67, 1984.

3. G Kasabov (ed.) 'Buildings the key to energy conservation', RIBA Energy Group, London, 1979.

4. V H C Crisp and G Henderson, 'The energy management of artificial lighting use' Ltg Res & Technol 14 (4) 193-206, 1982.

5. 'Automatic lighting control' Expanded project profile 27, Energy Efficiency Demonstration Scheme (ETSU, Harwell, 1984).

6. S M Secker and P J Littlefair, 'Geographical variations in daylight availability and lighting use' Proc CIBSE Nat Ltg Conf, Nottingham, 1986 (Ltg Res & Technol 19 (2) 25-34, 1987).

7. P J Littlefair, 'Daylight availability for lighting controls' Proc CIBS Nat Ltg Conf, Cambridge, 1984 (BRE Reprint R3/84).

8. D R G Hunt 'The use of artificial lighting in relation to daylight levels and occupancy', Building & Environment 14 (1) 21-33, 1979.

9. D R G Hunt 'Predicting lighting use - a method based upon observed patterns of behaviour', Ltg Res & Technol 12 (1) 7-14, 1980.

10. 'Lighting controls and daylight use' Digest 272, BRE, Garston, 1983.

11. P J Littlefair, 'Predicting lighting use in daylit buildings' Proc Lux Europa, Lausanne, 1985.

12. R G Hopkinson, P Petherbridge and J Longmore 'Daylighting' Heinemann, London, 1966.

13. 'Estimating daylight in buildings' Digests 309 and 310, BRE, Garston, 1986.

14. L H McDermott and G W Gordon-Smith 'Daylight illumination recorded at Teddington'. Proc Building Res Congress, Div III, p 156, Garston, 1951.

15. D R G Hunt 'Availability of daylight', BRE, Garston 1979.

16. Proceedings of CIE Conference, Paris, 1948.

17. W R G Atkins and P G Jenkins, 'Photometric measurements of the seasonal variations in daylight at Plymouth from 1947 to 1949' J Roy Met Soc 78 (335) 70-75, 1952.

18. P R Tregenza, 'The daylight factor and actual illuminance ratios' Ltg Res & Technol 12 (2) 64-68, 1980.

19. P R Tregenza, 'A simple mathematical model of illumination from a cloudy sky' Ltg Res & Technol 12 (3) 121-128, 1980.

20. P R Tregenza, 'Measured and calculated frequency distributions of daylight illuminance' Ltg Res & Technol 18 (2) 71-74, 1986.

21. P J Littlefair, 'Daylighting design and energy conservation' PhD thesis (BRE/CNAA, Garston, 1984).

22. W Chroscicki, 'Calculation methods of determining the value of daylight's intensity on the ground of photometrical and actinometrical measurements' Proc CIE, Barcelona, 1971.

23. R Kittler, 'Definitions of characteristic daylight climates in various climate zones' Proc Conf 'Daylighting and energy conservation', Univ. New South Wales, Kensington, Australia, 1982.

24. P J Littlefair, 'The luminance distribution of an average sky' Ltg Res & Technol 13 (4) 192-198, 1981.

25. P J Littlefair, 'Designing for daylight availability using the BRE Average Sky' Proc CIBS Nat Ltg Conf, Warwick, 1982 (BRE Reprint R2/82).

26. P J Littlefair, 'Modelling real sky daylight availability with the BRE Average Sky' Proc CIE, Amsterdam, 1983.

27. R H Collingbourne, 'The United Kingdom solar radiation network and the availability of solar radiation data from the Meteorological Office for energy calculations' Proc Int Solar Energy Soc Conf on UK Meteorological Data and Solar Energy Applications, London, 1975, pp 1-20.

28. Solar radiation data for the United Kingdom, 1951-75' Meteorological Office Met O 912, Bracknell, 1980.

29. J McGregor, 'Daily tabulations of meteorological and tilted surface irradiance data at Cardiff for the period July 1978 - April 1979' Solar Energy Unit Report 181, University College, Cardiff, 1980.

30. H Al-Ayfari, 'Correlation analysis of Birmingham meteorological data' Proc Solar Energy and Building Design workshop, Univ Birmingham, 1985 (UK-ISES, London, 1985).

31. S M Secker, 'External natural illumination' MSc thesis, Liverpool University, 1979.

32. P J Littlefair, 'The luminous efficacy of daylight - a review' Ltg Res & Technol 17 (4) 162-182, 1985.

33. S M Secker, 'Regional variations of daylight availability - a review of measured data and estimating methods' Ltg Res & Technol 15 (3) 151-156, 1983.

34. S M Taylor and L P Smith, 'Estimation of averages of radiation and illumination' Meteorol Mag 90 289-294, 1961.

35. L P Smith. 'The agricultural climate of England and Wales. Areal averages 1941-70' Techn. Bull. No 35 (Min Ag Fish Food, London, 1976).

36. S Aydinli, 'The calculation of the available solar radiation and daylight' Proc CIE Symposium on Daylight, Berlin, 1980.

37. S Aydinli and J Krochmann, 'Data on daylight and solar radiation' Draft for CIE TC 4.2, August 1983.

38. J K Page and J L Thompson, 'Modelling daylight availability,' Proc CIBS Nat Ltg Conf, Warwick, 1982.

39. J K Page, J L Thompson and J Simmie, 'Algorithms for building climatology applications' (Univ of Sheffield/ERSU, Didcot, 1984).

40. W Palz (ed.), 'European solar radiation atlas' Verlag TUV Rheinland, Cologne, 1984.

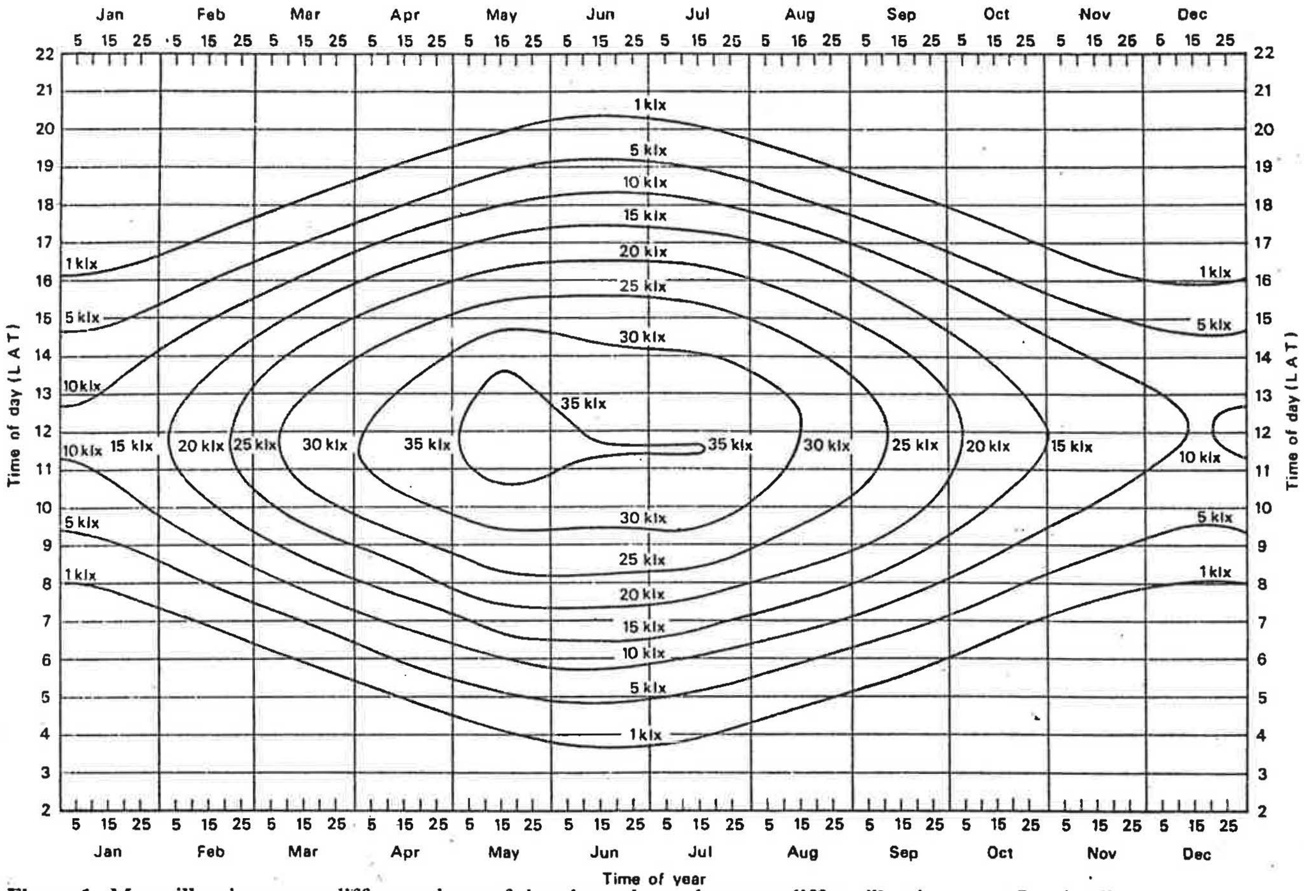

Figure 1 Mean illuminance at different times of day throughout the year: diffuse illuminance at Bracknell

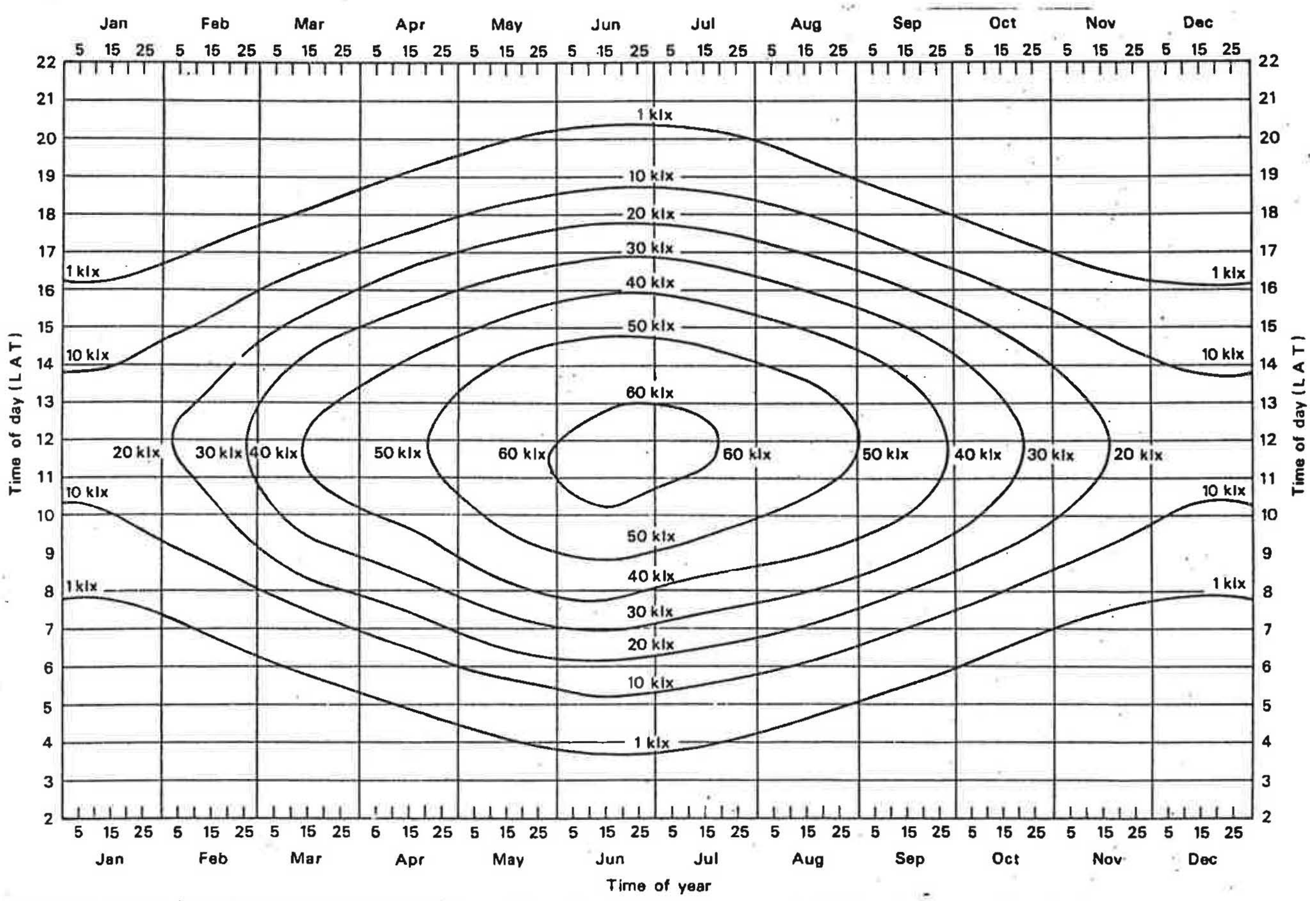

Figure 2 Mean illuminance at different times of day throughout the year: total illuminance at Bracknell

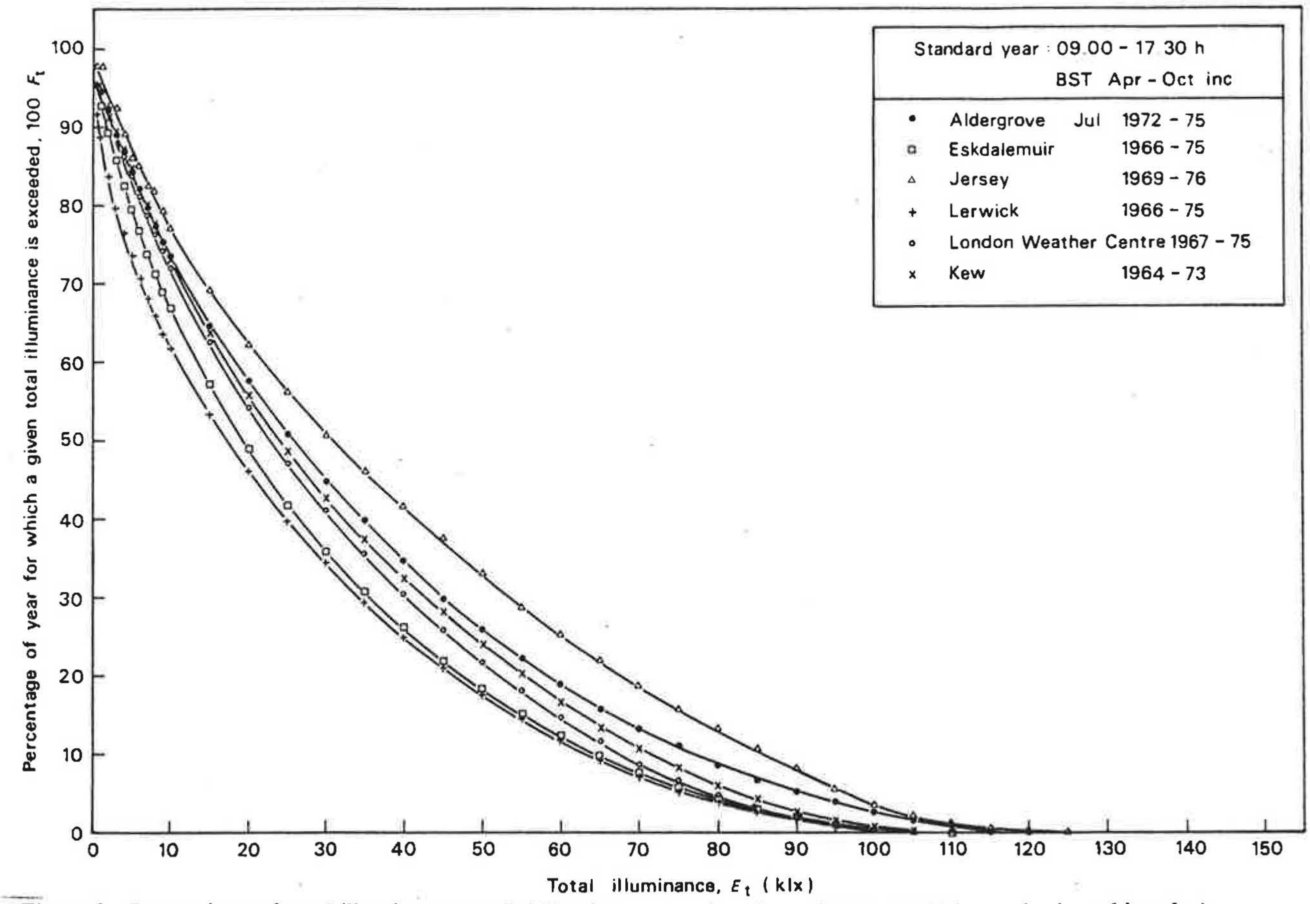

Figure 3 Comparison of total illuminance availability for various locations (09.00 - 17.30 h standard working day)

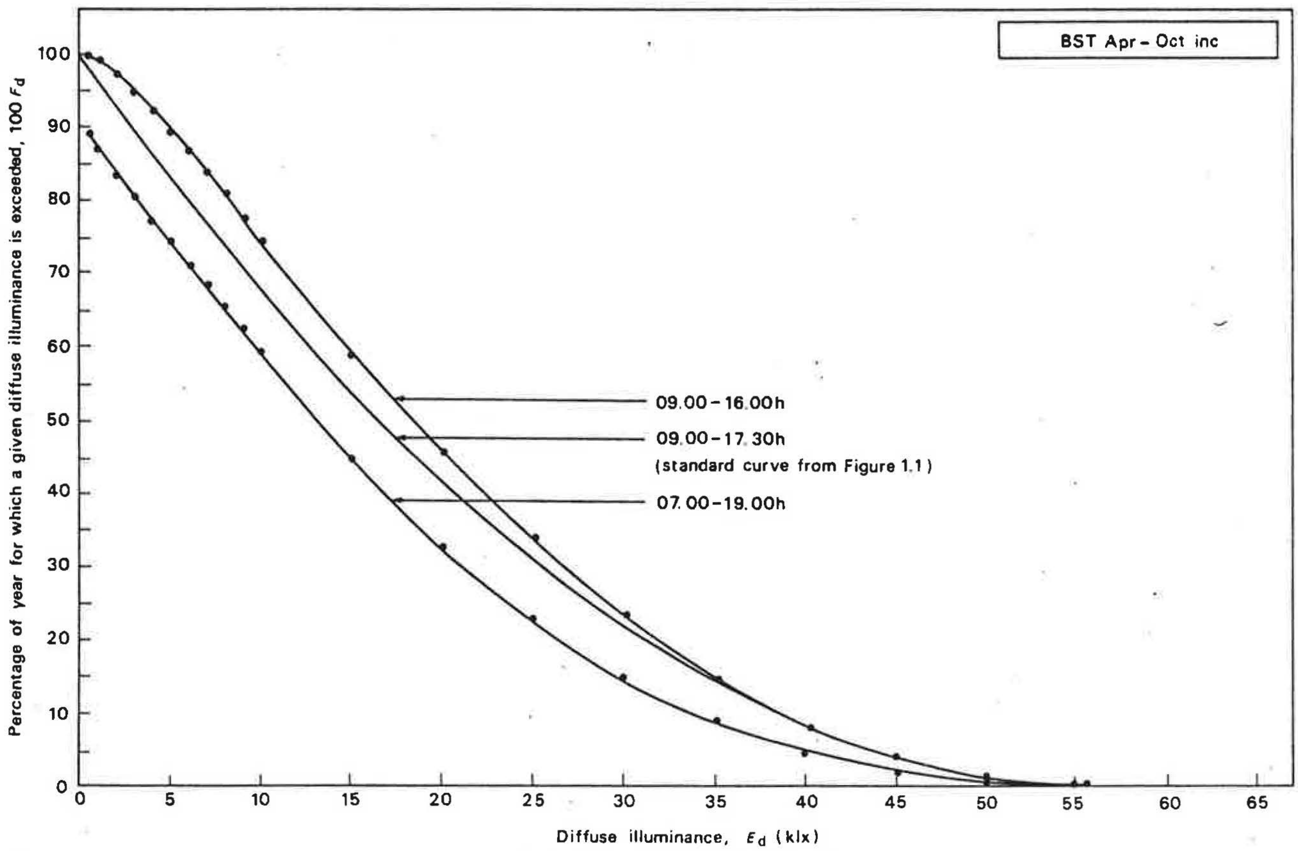

Figure 4 Variations in length of working day: diffuse illuminance availability for Kew

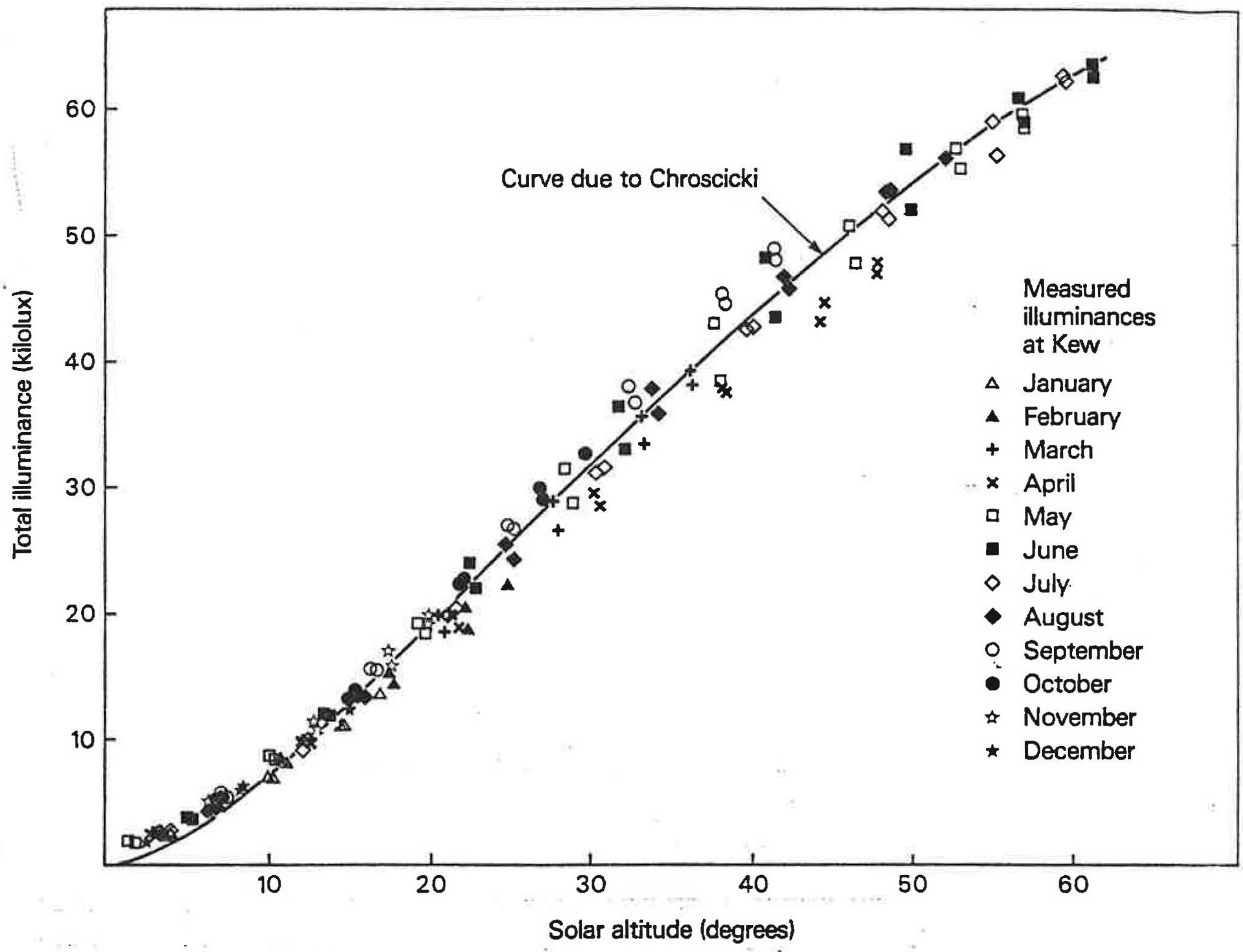

Figure 5 Comparison of month/hour average total horizontal illuminances measured at Kew with values predicted by Chroscicki (22)