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Angular distribution of diffuse radiation: a survey

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ABSTRACT

A survey is made of published information about the angular distribution of diffuse solar radiation, as seen from below and above the atmosphere. The concern is primarily with radiation scattered by the air and by water clouds, rather than with the radiation reflected by the ground.

The survey covers published accounts of (a) programmes of measurements of sky radiance in various directions and irradiance in different planes, taken at ground level, (b) measurements of radiance that has been reflected by clouds, taken from aircraft and spacecraft, (c) simple models of the angular distribution of diffuse radiance as it is observed at ground level.

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The literature of the monitoring and modelling of solar radiation is now expanding at an increasing rate. Any review of it is therefore obsolescent as soon as it has been written. In view of this, it would be desirable to update the present survey each year.

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1. Introduction

1.1 Diffuse form of solar energy

By "solar energy" is meant radiant energy in the short-wave band 0.3 to 3.0 um, originating in the Sun. The rate at which solar energy is incident in a plane of unit area from the whole of a hemisphere of view is the 'global' irradiance. It comprises the 'beam' irradiance from the disc of the Sun, and the 'diffuse' irradiance from the remainder of the seen hemisphere. In some contexts, it would be convenient to regard irradiance that is incident within a few degrees of the solar disc as part of the 'beam', but in the present study it is more appropriate to use the strict definition of the beam, that is, energy received within the 32' arc of the Sun's disc.

The distribution of diffuse light over the sky is hardly ever uniform. In a cloudless sky, there are two regions where diffuse radiance rises above the mean value: the 'circumsolar' region surrounding the Sun and the 'circumhorizontal' region immediately above the horizon. Radiance diminishes gradually away from these two centres of brightness, and neither region has a definite boundary. Some authors refer to a 'background' radiance, but this level is only arbitrary.

Under an overcast layer of cloud of uniform thickness, the sky will appear brightest at the zenith. It is not unusual, however, to find variations in cloud thickness, which will mask the smooth increase in radiance from horizon to zenith. (This is especially noticeable in Stratocumulus, which is the commonest cloud type in the British Isles.)

In a partly clouded sky, the distribution of light is more complex. As seen from the ground, a dense cloud appears bright on the part of its surface facing the Sun and dark on the rest of its surface ("bright" and "dark" being meant relative to the surrounding blue sky). Small clouds, however, are translucent and the surfaces facing away from the Sun may appear brighter than the blue sky. The illuminated surfaces of broken cloud can be up to ten times brighter than the blue sky (Luckiesh 1919).

The distribution of light in a partly clouded sky depends largely on the positions of the clouds relative to the observer and to the Sun. These positions tend to be neither uniform nor purely random, owing to the effects of perspective and the vertical extents of clouds. As a result of perspective, the part of the sky around the zenith is more likely to be filled with a single cloud (and hence be of locally uniform brightness) than is an equal angular area at the periphery of the sky. The vertical extents of clouds, on the other hand, increase the likelihood of full cloud coverage at the periphery.

It seems impossible to predict from back-of-envelope calculations even the qualitative form of the radiance distribution in a partly clouded sky - such as where in the sky the radiance will be greatest. This is because the radiance field is complex and discontinuously varying. No simple, predictable trends can be discerned in it; hence the mean field is not readily computed. Consequently, reasonable predictions can be made only from fairly detailed simulations or long series of measurements.

It is sometimes argued that, since clouds may be assumed to be in random positions distributed uniformly in the sky, any instantaneous non-uniformity in the radiant energy reflected by clouds will be averaged out over periods of a day or more. To see that this is not so, we must digress to consider cloud distributions.

One should beware of confusing the two senses in which a partial cloud field can be uniform: clouds can be distributed uniformly in the horizontal plane, or they can be distributed uniformly in the observer's field of view. The latter case is unlikely to occur as it implies that the horizontal distribution of the clouds is circularly symmetric about the observer. Even Steven (1977a) falls into this confusion: "If cloud is distributed randomly over the sky and the cloud positions of different scans are not correlated, then [the relative frequency with which the Sun was obscured] will ... approximate the fraction of sky covered by cloud as seen from the viewpoint of the instrument". In fact, these two quantities (the complement of the sunshine duration, 1-S, and the apparent cloud amount, C) will be systematically different. (The only two exceptions are the unphysical cases of (i) perfectly flat clouds and (ii) cloud fields that are so arranged that they appear uniform to the ground observer.)

The fractional area of sky covered by cloud at each zenith angle will increase toward the horizon (i.e. as the zenith angle increases), because the vertical extent of a cloud will become more visible the further it is from the zenith. Consequently, the relationship between the relative duration of sunshine, S (or its complement, the relative duration of solar obscuration) and the fractional cloud coverage C will depend on the solar elevation: if the Sun is at the zenith, then S must be greater than C; but if it is near the horizon, then S must be less than C.

1.2 Applications of radiation data

Although reference will be made below to the use of the Sun as an energy source for engineering, it should be noted that information about solar irradiation is used in other applications that might be regarded as more important.

- In meteorology, the solar heating of the ground and the atmosphere is the main source of energy for air movements, and a knowledge of the radiation income is required in the long-term prediction of weather.

- In hydrology, the evaporation of surface water is driven by solar energy, and information about irradiation is required in irrigation management and drought monitoring.

- In agriculture, the receipt of sunlight is one of the meteorological variables required to be known for crop forecasting.

Irradiation modelling should therefore aim to produce general-purpose models that can be used in applications of different types.

2. The need to know the angular distribution

2.1 Irradiation on tilted surfaces

Numerous meteorological services possess extensive records of solar irradiation, but the irradiation is almost always measured in the horizontal plane. There are, however, many applications in which it is desired to know the irradiation on a tilted rather than horizontal surface. In order to be used in those applications, the records must be converted to values for inclined planes.

The conversion of hourly values of beam irradiation from the horizontal plane to a tilted plane can be done with reasonable accuracy by regarding the beam as coming from the point at the centre of the Sun's disc.

The corresponding conversion of values of diffuse irradiation cannot be done accurately unless the distribution of radiance over the sky is known. That distribution is, of course, nearly always unknown. A simplifying assumption must be made, the simplest and commonest assumption being that the distribution is uniform or 'isotropic'. Experimental data from several sources suggest that this assumption leads typically to mean errors in the diffuse irradiation of -5% for an equator-facing plane and +40% for a pole-facing plane; see e.g. Garnier & Ohmura (1970), Stewart et al. (1981), Svendsen (1977a). Here, and below, the errors refer to worst-case slopes, from about 30° to about 60°. It is well-known that irradiance is only weakly sensitive to surface tilt within this angular range, and it is reasonable to assume that the error with which we are concerned has a similarly weak sensitivity. Of course, the errors for individual hours will often be larger than those mean errors, and Garnier & Ohmura (1970) report systematic changes in the magnitude of the range of error with the time of day.

Another simple assumption, which has recently become popular among workers associated with the Commission of the European Communities programme, is that the diffuse irradiance on any surface will lie between values computed for a cloudless sky and an overcast sky, and will be related linearly to the amount of cloud in the sky. This seems originally to have been proposed by Kondratyev & Manalova (1960b). More recently, it has been advocated by researchers at Technisch Physische Dienst, Delft (Slob, Brethouwer, & den Ouden 1980, van den Brink & Verdonschot 1982, van den Brink 1982, 1983), and their formula has been adopted by the CEC European Modelling Group in its detailed modelling of solar-energy systems (Dutre 1983). In fact, the diffuse irradiance on a horizontal plane has a non-linear dependence on the cloud amount, as has been known for some time (Bener 1963; Kasten & Czeplak 1980). Hence the Delft assumption is invalid in the limiting case of zero tilt, and there is no evidence that the relationship becomes linear as the tilt increases from zero. Steven's (1977a) review also found no evidence for a linear relationship between the cloud amount and the diffuse irradiance in a tilted plane.

There is thus a lack of a sound method of making estimates of the radiance distribution to accompany the hourly irradiation values that are routinely archived by the meteorological services. Hence we do not have a satisfactory means of converting those archived data to tilted planes. Of course, ultimately the accuracy with which the archived data can be converted is limited by the amount of information in those data. That is to say, a given value of irradiation in the horizontal plane may have been produced by any one of a range of different radiance distributions. At present, though, there does seem to be some scope for extracting improved estimates of inclined-plane irradiation from archived data.

There is a secondary application that we should note here. The distribution of the diffuse field must be known, or assumed, in order to compute the energy absorbed by a surface, since the absorptance of any real surface depends on the incidence angle of the radiation. The accuracy of the estimated absorptance for diffuse radiation is, of course, less important than the accuracy with which the amount of incident energy is estimated, and we shall not consider the absorptance further.

Although, as we have noted, there is not yet a sound model of solar irradiance in inclined planes, the assumption of isotropy will not lead to very large absolute errors in irradiance estimates. The relative error in the estimated diffuse irradiance in a pole-facing plane (typically 40%) is quite large, but the absolute error is small and comparable to the error associated with an equator-facing plane. This is made clear in Figure 1, which is based on Svendsen's (1978) measurements. It seems that the only applications in which the anisotropy is important are those in which the solar gain occurs mainly through surfaces that face toward the pole. For instance, the heat budget of rooms on the poleward side of a building might be appreciably influenced by the estimated receipt of diffuse solar energy.

The assumption of diffuse isotropy almost always leads to systematic errors for a surface of given orientation and tilt (e.g. of about -5% in diffuse irradiance for equator-facing collectors). Therefore, estimated monthly and yearly irradiations will involve similar relative errors. In some applications, such errors may not be tolerable.

Such errors are probably tolerable in the design of active solar-heating systems, since there will be greater uncertainties in other factors. The design of these systems is currently one of the major uses of hourly values of irradiation. They are used either directly in detailed hour-by-hour simulations or indirectly in simplified methods based on detailed simulations.

Would the errors be tolerable in the design of buildings that use passive solar-heating? Preliminary simulations carried out at SERI (Robbins 1985, personal communication) indicate that they would not.

Exercises in monitoring solar installations are unlikely to need models of the diffuse radiation field. In the monitoring of an existing solar-heating installation, the irradiance should be measured in the plane of the solar collectors, and there will be no need to estimate the irradiation in an inclined planes. Only in a badly instrumented installation will it be necessary to make some assumption about the diffuse radiation field; i.e. if the collectors are tilted but the irradiance is measured in the horizontal plane only.

2.2 Irradiation mapping from satellites

Archives of radiation measurements taken at ground stations serve two purposes. First, they form a reference set of typical values that can be used as a common input to models of energy systems - for example, in comparisons between alternative models of solar-heating installations or comparisons between competing systems. Second, they form a basis on which the geographical distribution of irradiation can be determined.

In the first application, the accuracy of the radiation data is not crucial, since the main concern is with the comparative performance figures of different simulation runs, not the absolute values of the performance figures. For this application, we require only that the statistical properties of the meteorological variables, and the relationships between the variables, should approximate those found in reality.

In the second application, the accuracy of the resulting radiation maps is essential. The maps may be used either to compare different regions in respect of their solar-energy income, or to compare the Sun as an energy resource with other fuels. In both cases, the validity of any conclusions drawn from the maps will depend on the maps' accuracy.

When the irradiation maps are derived from ground stations, the accuracy is limited by the distances between the stations in comparison with the distances over which radiation climate can substantially change. This problem is especially acute over mountainous areas. Since a dense network of stations for measuring radiation is not financially feasible, the only means of obtaining accurate irradiation maps is the use of satellite pictures.

There is, however, a major obstacle to this use of satellite data. A satellite cannot measure the surface irradiance directly, but can measure only the radiant energy that leaves the top of the atmosphere, which comprises energy reflected by the atmosphere and that reflected by the ground and transmitted by the atmosphere. (Recall that we are considering only short-wave radiation here, so we exclude long-wave energy emitted by the ground and atmosphere.) A numerical model must be used to estimate the surface irradiance on the basis of the radiant energy detected by the satellite. Since a satellite views a particular part of the Earth from a specific angle at any instant, the radiance it measures will depend on the angular distribution of the reflected light.

Most of the present models for estimating ground irradiance from satellite imagery involve estimating the cloud cover and then estimating the fraction of the (downward) extraterrestrial irradiation that is transmitted though the cloud field, using an empirical correlation. These methods have an accuracy of about 10% to 15% in daily irradiations (e.g. Moser & Raschke 1983). This is, in fact, about the accuracy that can be obtained with ground observations of sunshine duration. A satellite picture, however, conveys much information about the spatial distribution of cloud in the atmosphere, which the ground observer cannot see. It would be surprising, therefore, if satellites could not be made to yield better estimates. Modelling the transmission of light in the atmosphere, especially in fields of broken cloud, is needed to achieve that objective.

Of course, we cannot rule out the possibility of a purely empirical correlation between the two-dimensional radiance pattern depicted in the satellite imagery and the underlying distribution of irradiance at ground level. Nevertheless, the presence of two dimensions of data in the satellite picture creates a combinatoric increase in the number of possible correlations. In other words, the number of variables involved is prohibitively large for a comprehensive empirical investigation. One would have to pre-select correlation formulae that one would subjectively expect to be successful.

A more plausible approach is to formulate a model that (a) describes the leading physical effects on the transmission of radiation through the atmosphere, but (b) requires for its inputs the information that can be extracted automatically from digitised imagery. Clearly, if it is physically realistic then the same model should predict the angular distributions of both the upwelling radiance leaving the top of the atmosphere and the downwelling radiance reaching the bottom of the atmopshere.

It is therefore recommended that a unified approach should be taken toward the modelling of both upwelling and downwelling radiation fields.

3. Downward diffuse radiation

3.1 Methods of measurement

The main difficulty in experimentally determining the angular distribution of diffuse radiance is the need to measure simultaneous values of fluxes in many directions. This may be done either with many sensors each in a fixed orientation or with a smaller number of sensors attached to a rotating platform, which allows the sensors to scan the sky.

Photovoltaic cells are often used in arrays of sensors, as they are cheaper than thermopile devices. Capital expenditure can also be saved by using a scanning array rather than a stationary one, but the speed of response of the sensors is then crucial. Thermopile radiometers are slow to respond to sudden changes in the irradiance that they receive and it is common to use photovoltaic cells for scanning, as their response times are shorter by several orders of magnitude. Photocells thus have two practical advantages and, as a consequence, several published studies of the distribution of diffuse light have been based on photocell measurements.

Unfortunately, the physical quantity detected by a photocell is not the 'radiance' in the usual sense of that term. A photovoltaic sensor has a highly peaked spectral response with weak sensitivity to infrared light, in contrast with the spectrally flat response of good thermopile or pyroelectric sensors. The spectral sensitivity of the photocell resembles that of the human eye, so the quantity measured with the cell is referred to as the "flux density of luminous radiation", or the "luminance". Its match with the human-eye response is not perfect, and filters are sometimes used to improve the resemblance. Strictly speaking, therefore, the photocell measures 'luminance' only when it is filtered to have a spectral response matching the standard 'photopic' distribution defined by the CIE. In other devices, filters are used to flatten the spectral response in order to increase the resemblance with thermopile sensors, but the filters cannot enhance to a useful extent the photocell's sensitivity to infrared radiation. Some photocells that are used as cheap pyranometers have no filter; these instruments register a quantity intermediate between luminance and irradiance. Measurements of radiant energy taken with different photovolatic sensors are therefore not generally comparable with one another, owing to differences in spectral sensitivity. Moreover, they are not comparable with measurements taken with thermopile sensors because the cells do not respond to infra-red radiation.

Kondratyev (1969) found that zenith-normalised distributions of radiance and luminance may differ by up to a factor of three at some points in the sky. Petheridge noted this difference in the sky near the horizon, where radiation in the red and near-infrared is stronger, and blue radiation is weaker, than over the sky as a whole. Dave (1978) presented theoretical curves for an idealised atmosphere, which illustrated well how different the angular distribution of sky-light is at different wavelengths. One implication is that the angular distribution measured with a photocell (especially one with a non-flattened spectral response) will differ appreciably from the angular distribution of the radiance. Nevertheless, a photocell can still provide some useful information, since the spectral reflectance of cloud masses is almost flat and the measured distribution of luminance in an overcast is a good guide to the distribution of radiance.

The distribution of diffuse light may be determined either with pyranometers, each of which views a full hemisphere, or with pyrheliometers, each of which views a region of sky spanning an angle between 6° and 10°. A pyrheliometer can provide a more precise mapping of spatial details of the distribution, but this improvement matters only in overcast skies and cloudless skies. In partly clouded skies, there are random radiance gradients which are orders of magnitude greater than can be resolved by either pyrheliometers or pyranometers, so the advantage of a narrow aperture is rendered meaningless.

A further advantage of a pyrheliometer is its exclusion of radiation reflected from the neighbouring ground, except when the instrument is set at a low elevation angle. Radiant energy reflected by the ground is specific to a locality and is an obstacle to obtaining a general characterisation of sky radiance. If a pyranometer is used, the energy reflected by the ground can be eliminated only partly, by means of an artificial horizon. For example, Svendsen (1978) surrounded his scanning pyranometers with a (non-black) honeycomb, and Kasten (1980) employed a more elaborate apparatus comprising concentric blackened shields. Of course, neither shield will be perfectly black, and weathering will weaken the actual blackness of the material. Furthermore, the edge of the shield cannot match precisely the horizon, and the pyranometer will therefore still receive light that has been reflected by any nearby walls.

The indirect effect of local terrain cannot be eliminated completely, even when ground-reflected energy is excluded from the radiometer. Sky brightness near the horizon will be enhanced by light that is multiply reflected between the atmosphere and the ground, so changes in the ground albedo are reflected in the sky. In the normal conditions found in Britain, the brightness of the sky is affected only slightly by the albedo of the ground. The effect will be greatest when the sky is very dusty or when snow covers the ground. Coulson (1968) has presented some illustrative results on this subject.

Neither pyrheliometers nor pyranometers offer a spatial resolution sufficient to pick out individual clouds. To record such detail it is necessary to focus an image of the whole sky onto some recording surface. Recording may be done either with a photographic film (see e.g. McArthur & Hay 1978a,b) or with an array of many photocells whose outputs are electronically encoded on videotape (see Robbins & Hunter 1983a,b). The use of photographs brings in an extra stage of processing, as a computer-readable copy of the photograph must be made by densitometry ('digitisation') before automatic data processing can be carried out. Both methods (chemical films and vidicon cameras) involve non-flat spectral responses.

In estimating the irradiance on tilted surfaces, Svendsen (1977b) noted that pyranometric measurements in 25 planes can provide an adequate characterisation of the diffuse field. This is because in almost all applications radiant energy is collected by a plane surface with a hemispheric view, and an angular resolution greater than 25 planes would not add significantly to the determination of the irradiance on the plane in question. (As we shall see later, this is not true in studies of the upwelling radiant energy that is recorded in satellite pictures. There, a higher angular resolution is required.)

3.2 Survey of data sets

This section describes a number of sets of measurements of diffuse radiance that have been reported in the literature. The list is not exhaustive but it is thought that most important data-sets have been included.

O--- The earliest experimental data to which I have found references are measurements of sky luminance reported by Kohler (1908) and Dorno (1919) (both in German).

O--- Kimball, working for the Committee on Sky Brightness of the US Illuminating Engineering Society, made an extensive investigation of the distribution of sky luminance. After a description of some preliminary studies (Kimball & Hand 1921), the results of 825 determinations of the luminance distribution were reported (Kimball & Hand 1922), each determination involving measurements in 31 directions. The measurements were taken in two batches: during ten months at Washington (latitude 39°) and during two months at Chicago (latitude 42°), using a Sharp-Millar photometer.

Kimball & Hand (1922) presented the results as tables giving the mean radiance in 31 directions in one half of the sky (referenced to an imaginary grid of 5 azimuth angles by 6 zenith angles, plus the zenith direction). These tables were given separately for overcast and cloudless skies; and, for cloudless skies, separate tables were given for seven solar elevations. If symmetry is assumed about the plane that passes through the Sun and the zenith, then the 31-point grid for the half-sky implies a 49-point grid for the whole hemisphere. Results were tabulated for two air conditions, clear (Washington) and polluted (Chicago).

The authors compared their results with Dorno's (1919) measurements, taken in the mountain site of Davos, Switzerland. The sky near the horizon at Davos was found to be brighter that at the two USA sites, especially in Winter, and they attributed this to multiple reflections between snow-covered ground and the air. Consistent with that explanation were unpublished measurements by F.W. Little (mentioned by Kimball & Hand 1921). These showed a diminished sky radiance at the horizon over a body of water, the albedo of which may be expected to be about 5%, in contrast with the albedo of 20% normally associated with land.

The effect of turbidity was investigated only by comparing the measurements taken in the clear and polluted areas. The beam illumination in the polluted area (Chicago) was reduced by a factor of 0.80 relative to the beam illumination in Washington. On equator-facing surfaces the global illuminations were approximately the same at both sites, but on pole-facing surfaces the global illuminations were reduced in the polluted area. This suggests that the main effect of the pollutants is to scatter radiation by a few degrees from the beam. That is to say, the pollutants exhibited strong forward scattering.

Kimball & Hand reported that rain or snow falling under an overcast approximately halved the sky luminance, but did not alter its angular distribution. On the 17 occasions on which there was precipitation, however, luminance measurements were taken indoors, the sky being viewed through a window up to an elevation of 60°.

Being aware of the spectral difference between radiance and luminance, Kimball & Hand (1922) gave a conversion table relating their luminance values to associated values of radiance. This table was based on simultaneous readings of a photometer and a pyrheliometer. Strictly speaking, though, it applies only to radiation having the same spectral distribution as beam radiation, and should not be applied to radiance from blue sky. The table might be a valid approximation for radiance from an overcast sky, since scattering by cloud droplets has only a weak spectral dependence.

According to Robbins & Hunter (1983b), the results obtained by Kimball, as presented in the Handbook of the US Illuminating Engineering Society, have been the "most commonly used daylight data".

O--- The first experimental determination of the distribution of radiance, as opposed to luminance, seems to have been that carried out by Kondratyev and his co-workers in the USSR in the 1950s. Yaroslavtzev (1953) and Kondratyev et al. (1955) investigated the distribution of both the diffuse solar radiance and the diffuse luminance. (Kondratyev states that a Yanishevsky pyranometer was used to measure the radiance, but the nature of the data suggests that the instrument was a pyrheliometer. Valko (1980) says that a 'modified pyranometer of 10° full view angle' was used.) The only original presentation of their results in English literature seems to be that given by Kondratyev (1969).

The Russian workers produced diagrams of diffuse radiance in cloudless and overcast skies on particular days. Kondratyev (1969) concludes thus: "These results give ... the main peculiarities in the angular structure of the diffuse radiation field: increase of intensity in the circumsolar zone and toward the horizon, symmetry of angular distribution relative to the solar vertical, and minimum intensity in the Sun's vertical at 90° angular distance from the Sun". They did not, however, give empirical formulae to describe the distributions.

Perhaps the most important finding in their work was the great divergence between the angular distributions of radiance and luminance in a cloudless sky. In contrast, there was a close correlation between the two distributions under an overcast sky.

In a brief review of the subject, Kondratyev (1977) mentions that early measurements of inclined-surface irradiance had been taken by V.A. Smirnov, but he gives no reference to Smirnov's work. According to Kondratyev, Smirnov found a ratio of 113:96 between the diffuse irradiances received by equator-facing and pole-facing surfaces. This indicates only a weak anisotropy. It seems likely, therefore, that those measurements were taken under a very clear atmosphere.

In the same review, Kondratyev mentions measurements taken in the 1950s of the diffuse irradiance on variously oriented surfaces with and without a snow covering on the neighbouring ground. For surfaces tilted more than 30° from the horizontal, the contribution of snow-reflected radiation was appreciable and, for very large tilt angles, it dominated the diffuse irradiance. Kondratyev does not say where these experiments are reported in detail, but his bibliography lists a number of papers in Russian (Kondratyev & Manalova 1953, 1956, 1957, 1958, 1960a; see also Kondratyev & Zavodchikova, 1953).

O--- In the USA, Parmelee (1954) measured global irradiance with a vertical pyranometer oriented at a variable azimuth angle. He recorded the readings under cloudless skies only.

As a simple measure of the atmospheric turbidity, Parmelee introduced a 'clearness ratio', which was the ratio of the observed beam irradiance to that predicted for a standard atmosphere (using Moon's model). This ratio ranged from 0.5 to 1.3.

When the Sun was fairly low in the sky (20°), the diffuse irradiance in the vertical plane facing the Sun (the sunward direction) was found to be up to twice that in the vertical plane facing away from the Sun (the anti-sunward direction). As the Sun rose to 45°, this ratio increased to a maximum of about 3.5:1, but as the Sun rose further, the ratio diminished toward 1:1. The fact that this variation shows a peak might be explained from a-priori considerations, as follows. When the Sun is low, the circumsolar radiation is partly obscured by the horizon. As the Sun rises, the circumsolar irradiance reaches its full magnitude. Thereafter, the circumsolar light is incident to an increasing extent in the anti-sunward plane. In particular, note that if the Sun is at the zenith, then the irradiance on a vertical surface will be independent of the surface's azimuth; the ratio of sunward:anti-sunward will be 1:1.

When the beam irradiance at normal incidence decreased, owing to greater turbidity, it was found that the diffuse irradiance in the sun-facing plane increased, while that in the plane away from the direction of the Sun remained approximately constant. This was attributed to energy being shifted from the solar beam into the circumsolar region. (Cf. Kimball & Hand (1922), who also found the diffuse irradiance increased in the Sun-facing plane when the air was polluted, although in the anti-sunward direction they found a slight decrease rather than constancy.) Conversely, in the case of very clear skies, with clearness ratios above 1.1, the circumsolar radiation was negligible and the sunward:anti-sunward ratio for diffuse irradiance dropped to 1:1. The sky radiance would in that case have been approximately circularly symmetric about the zenith.

Parmelee assumed that solar energy that had been reflected by the ground was negligible. Bulb-type Eppley pyranometers were used, which were undoubtedly less accurate than modern pyranometers. Parmelee's results illustrated clearly the qualitative form of the diffuse distribution but did not furnish a general quantitative relationship.

O--- Also in the 1950s, measurements of irradiance on tilted surfaces were taken in Germany by Ambrosetti & Thams (1953), Grafe (1956), and Volz (1958). Volz included an investigation of the effect of turbidity on the diffuse irradiances.

O--- Continuing their programme in the USSR, Kondratyev & Manalova (1960a) measured the diffuse radiance in 37 directions under cloudless and overcast skies, using the Yanishevsky device. Their radiance values were integrated numerically and presented in the form of computed irradiances in various planes. They concluded that the isotropic assumption was valid for overcast skies, but they regarded anisotropy as significant in cloudless skies. When the Sun was at 48°, they found a ratio between diffuse irradiances in the sunward and anti-sunward vertical planes of only 1.5:1, which indicates a weaker anisotropy than that observed by Parmelee (who observed a corresponding ratio of 3.5:1).

Kondratyev & Manalova went beyond Parmelee's study insofar as they considered planes of different tilts (again for a solar elevation of 48° in a cloudless sky) as well as different azimuths; Parmelee's pyranometer was fixed in a vertical mount. The irradiances in sunward and anti-sunward planes exhibited opposite variations with respect to tilt (as one would expect). As the tilt of the Sun-facing surface was increased, the diffuse irradiance on the surface went through a maximum (of 140% of the horizontal value) at a tilt of 75°; as the tilt increased to 90°, the irradiance diminished to 120% of the horizontal value. In contrast, as the tilt of the surface facing away from the Sun was increased, the irradiance went through a minimum (of 60% of the horizontal value) at 45°; as the tilt increased to 90°, the irradiance increased to 80% of the horizontal value. The authors noted that these variations were quite different from those predicted from an assumption of isotropy. It might also be noted that they invalidate the assumption (used by e.g. Slob et al. 1980) that the irradiance on a tilted surface should be interpolated linearly between the horizontal and vertical values.

Kondratyev & Manalova did not investigate the effect of variations in turbidity. Differences in atmospheric dust load may have caused the disagreement between the Russians' results and Parmelee's.

O--- Van Deventer & Dold (1963) and Van Deventer & Joubert (1963) measured the distribution of sky radiance with a Moll-type thermopile having a 10°12' full aperture. (Note that this description fits a Linke-Feussner pyrheliometer.) They did not investigate the effect of variations in turbidity.

o--- Threlkeld (1963) in the USA, and Funk (1965) in Australia, took measurements of irradiance on vertical planes, but made only cursory analyses of the data.

o--- Dehne (1974) reported measurements of the angular distribution of spectral sky radiance under cloudless and cloudy conditions at wavelengths of 409, 561, and 720 nm with a 'high speed rotating spectrophotometer', which was probably a photocell with the appropriate filters. These data do not readily yield the angular distribution of the spectrally integrated irradiance.

o--- Coulson's (1975) review of the angular distribution of diffuse radiance included, as an illustration, measurements taken under a cloudless sky in Los Angeles (Coulson 1969). The data show the difference between clear air and smog, the main feature being the pronounced enhancement of circumsolar radiance when the air is polluted.

o--- The first experimental study of sky radiance using thermopile pyrheliometers (as opposed to photocells or Kondratyev's modified pyranometer) seems to have been that carried out by Prof. J.L. Monteith's researchers at the University of Nottingham. Steven (1977a) monitored the diffuse radiance in nine directions under all sky conditions for a year, using a custom-made pyrheliometer. In addition, he made several determinations of the radiance in a denser grid of 34 directions in cloudless skies, using a Linke-Feussner pyrheliometer. The Linke-Feussner offers a high precision of measurement but is not waterproof, hence its use must be limited to dry weather and is normally limited to occasions of cloudless skies. Steven's analysis of cloudless-sky radiance is most widely known (Steven 1977b, Steven & Unsworth 1979a), but he has also published results on overcast skies (Steven & Unsworth 1977b).

Results were expressed in terms of the 'relative radiance', defined as

$$N(Z,A) \,/\, G_d$$

in which

$N(Z,A)$ = radiance at specified zenith and azimuth angles, Z and A, in Wm^{-2}/(steradian/pi)

G_d = diffuse irradiance in horizontal plane from whole sky, expressed in Wm^{-2}

Note that the unit of the radiance is contrived so that in an isotropic sky the radiance is numerically equal to the horizontal diffuse irradiance.

Steven concluded that the atmospheric turbidity had a "significant but small" effect on the distribution of radiance in a cloudless sky, and that this could be ignored for the range of turbidities normally found in Britain.

This runs contrary to the advice offered by other researchers. For example, it is inconsistent with Parmelee's (1954) observation that, for diffuse irradiances on vertical surfaces, the equator-facing : pole-facing ratio varied between 3.5:1 and 1:1 according to the turbidity.

It seems likely that the major cause of the discrepancy is that the range of turbidities represented by Steven's data might not have been wide enough to bring out the influence of turbidity. Unfortunately, Steven used a 'turbidity coefficient' that was quite different from Parmelee's 'clearness ratio'. Hence we cannot directly compare the range of atmospheric conditions encountered by Parmelee and Steven.

A further, but minor, contribution to the disagreement may be the coarse angular resolution of Steven's measurements, for he took no measurements closer than 10° to the Sun's disc (with a sensor aperture of 5.1°), and therefore omitted the most intense circumsolar radiation. In contrast, Parmelee used a narrow-aperture occulting disc. We know that a rise in turbidity will cause more energy to be scattered out of the solar beam and into the circumsolar region. Since the diffuse radiance tends to be larger nearer the Sun, we may assume the increase in radiance due to turbidity will be greater nearer to the Sun. Hence Steven's use of measurements centred on points 10° from the Sun will miss the largest radiance gains produced by the rise in turbidity. A consequence of this will be some under-estimation of the effect of turbidity on radiance, although we do not know its magnitude. Steven (1977b) wrote, "... a possible error of 25% in the estimation of [the circumsolar radiance] could result in a 3% error in [the horizontal diffuse irradiance]". It may be expected to yield a larger relative error in the irradiance in the vertical plane facing the Sun than in the horizontal plane, but even so it will be small in relation to the discrepancy between Steven's results and Parmelee's.

Although Steven concluded that turbidity would have a negligible effect in normal weather in Britain, he nonetheless evaluated this effect by means of a linear regression, or radiance against the Unsworth-Monteith turbidity coefficient. Data were included from a few days with unusually high turbidity, in order to get a more reliable fit. As turbidity increased, he found that diffuse radiance increased throughout the sky, although it increased at a greater rate in some regions of the sky than in others, as one would expect. Steven's analysis of the effect of turbidity is limited by his division of the sky into only a few zones:

circumsolar	(about 10° from Sun)
perpendicular	(azimuthal distance 90° from Sun)
anti-solar	(azimuthal distance more 90° from Sun)
lower	(zenith angle more than 30°)
upper	(zenith angle not more than 30°)

For each of these zones, the mean relative radiance was regressed on the turbidity. It was found that the upper zone of the sky exhibited a more rapid increase in radiance than other zones and its relative radiance therefore increased while the relative radiance of other zones decreased. The fact that Steven divided up the sky into so few zones, however, makes it very difficult to discern the physical reasons for the observable effect produced by the rise in turbidity. For instance, although Steven found that the relative radiance increased in the upper zone, he did not ascertain whether it increased in the sunward or the anti-sunward halves of that zone (or both). Nor do we learn whether the radiance decreases in any of the individual anti-sunward directions, as Kimball & Hand (1922) had found.

In his study of partly-clouded skies, Steven investigated the dependence on various sky parameters of the relative radiance. He found that the relative radiance was linearly related to the diffuse fraction of the global irradiation:

$$D^{dy} = H_d^{dy} / H^{dy}$$

and with the relative sunshine duration:

$$S^{dy} / S_o^{dy}$$

Some seasonal variation was found in these relationships, but Steven regarded it as negligible. He did not examine the effect on the relationship of cloud type or solar elevation (in which case he would have needed to consider the correlation of hourly, rather than daily, data). Note that, although the relative radiance has a linear dependence on the two sky parameters (S^{dy}/S_o^{dy} and H_d^{dy}/H^{dy}), the absolute value of the radiance does not.

O--- Temps & Coulson (1977) measured global and diffuse irradiances in 49 directions in one half of a cloudless sky. Only two days' data were analysed in their paper, however, and the effect of turbidity was completely ignored. The results were presented in graphical form and resembled those presented by earlier authors. (According to Svendsen, this density of measurements (i.e. 49 directions) is unnecessary, because of the poor spatial resolution of the pyranometer. Svendsen himself measured the irradiance in only 25 planes.)

O--- McArthur & Hay (1978a,b) made extensive determinations of the angular distribution of diffuse light, using both a Linke-Feussner pyrheliometer and an all-sky camera. The photographs were digitised using 32 levels of brightness, but the spatial resolution was not specified.

McArthur & Hay (1978a) only outlined their programme. Valko refers to a 1220-page document (McArthur & Hay 1978b). A copy of this has been requested but not yet been obtained.

It may be noted that McArthur & Hay (1978a) appear to be unique in using the word "eolotropic" as a synonym of "isotropic".

O--- After a visit to the Swiss Meteorological Institute (Svendsen 1977a) (see below), Svendsen developed an instrument that allowed the continuous scanning of the global irradiance in 24 planes, using three pyranometers. The pyranometers were oriented at three tilt angles and were stepped through eight azimuth positions, with a complete scan being completed every minute. At the same time, stationary pyranometers recorded the global and diffuse irradiances in the horizontal plane and the global irradiance in a plane tilted 45^{o} toward the equator. (Thus the global irradiance was monitored in a total of 25 planes.) The scanning instrument came into use in April 1978 and was operated, with some breaks, for three years. The project was funded initially by the DTI's Building Research Establishment (BRE) and later by the DEn's Energy Technology Support Unit (ETSU).

A prototype, comprising a single pyranometer, and the full instrument, comprising three pyranometers, have been described by Svendsen (1978a and 1979 respectively). Svendsen (1979) also describes results up to his departure from the SEU in September 1978. McGregor took over the project in July 1979, and the apparatus was finally dismounted at the end of July 1981. Svendsen's apparatus and the measured data are described briefly by McGregor (1979,1980c,e,f,g). The data were converted into a form designed for improved data processing (McGregor 1980a) and ten months of hourly averages of the data were tabulated (McGregor 1980b).

Svendsen's programme of measurements seems to be unique in its rapid sampling rate, involving a complete scan of the sky every minute. The brief duration for which each pyranometer was stationary (only 5 seconds) presented a major problem. Two novel methods were used to remove the distorting effect of the thermopiles' slow responses. In the prototype apparatus, Svendsen used a filtering circuit designed by Brinkworth & Hughes (1975,1976) to accelerate the effective sensor response. After further investigations, Svendsen decided to employ numerical filtering, rather than electronic filtering, in the final system that started running in April 1978. This system logged the signals directly, and the filtering was done in off-line computer pre-processing.

O--- As part of Project F (Solar Radiation Data) of the Solar Energy R&D Programme sponsored by the Commission of the European Communities (CEC), a programme of measurements of irradiance in inclined planes was started by the Royal Netherlands Meteorological Institute (RNMI) in collaboration with the Technisch Physische Dienst (TPD) (Institute of Applied Physics).

Slob, Brethouwer, & den Ouden (1980) described the monitoring apparatus and the results obtained in the first eight months (during 1979). Van den Brink & Verdonschot (1982) described a further four months of data (the Winter of 1979/1980) and van den Brink (1982) examined empirical models of the data; further analyses have been presented by Slob (1982). Van den Brink (1983) has given a brief summary.

The apparatus comprises pyranometers registering global irradiance in thirteen fixed directions:

(a) horizontal down and horizontal up;
(b) vertical (North, South, East, West);
(c) 45° tilt (East, South, West, South-East, South-West);
(d) 22.5° and 67.5° tilts (South only);

also, near-infrared hemispheric irradiance (500 nm to 3000 nm band) in three directions:

(e) two fixed directions, horizontal and 45° tilt South;
(f) normal to the solar beam.

One further pyranometer, equipped with a shading ring, recorded the horizontal diffuse irradiance. A pair of pyrheliometers measured the normal-incidence beam irradiance over the whole spectrum and in the infrared (500 to 3000 nm). The instruments were situated in open grassland at Cabauw (latitude 52°N, almost the same as Kew Observatory).

This programme has resulted in a high-quality set of measurements of a comprehensive range of quantities. It is therefore disappointing that only very simple analyses have been made of the data. The results, which have been summarised by van den Brink (1983), involved the simple correlation of vertical irradiations with horizontal irradiations, and this for only four conditions (defined by the elevation of the Sun and its position relative to the plane of measurement). Clearly, there is a great deal more information to be extracted from the data. It is not known whether the Dutch will proceed with this work.

o--- Also within CEC Project F, a small programme of irradiance measurements in inclined planes was undertaken by the German Weather Service (Deutscher Wetterdienst) in Hamburg. The apparatus and some initial results are described by Kasten (1980) and the results of two years' monitoring are reported by Kasten, Dehne, & Brettscheider (1982).

The global irradiance in only four planes was measured: the horizontal, and the equator-facing planes tilted at 30°, 53.6°, and 90° from the horizontal. The results, which are presented in a variety of graphical forms, may be of some use in some design applications, but they seem unlikely to provide much information for the theoretical study of the diffuse radiation field, because they span only a small portion of the sky.

O--- A team led by Valko at the Swiss Meteorological Institute is engaged in a continuing programme of radiation measurements, which includes an extensive investigation of the angular distribution of sky radiance. This project was preceded by a ten-year programme of measurements of irradiance in vertical planes facing the four cardinal directions, North, South, West, and East (Valko 1970,1972). The apparatus that has been used in the later project was developed in the early 1970s (Bener et al. 1973). Results for this later work have not yet appeared in widely available journals, but have been outlined in conference proceedings (Heimo & Valko 1977, Valko 1983), reports to the CEC (Valko 1979, 1981, 1982a,b,c,d), and reports to the IEA (Valko 1980, Valko & Heimo 1980).

The monitoring equipment is housed in a mobile caravan, including a range of sensors, mountings, and a minicomputer. Recordings of several types are made:

O Global irradiance measured in 77 upward-facing planes and 77 downward-facing planes. Upward-facing measurements are taken with four pyranometers that complete a scan of the sky every six minutes. Downward-facing measurements are taken less frequently - with one pyranometer that completes a scan of the ground every 26 minutes. The thinking behind this difference in frequency of measurement is that the radiation field in the sky fluctuates rapidly with changes in the cloud canopy, whereas the radiation field presented by the ground fluctuates only slowly. Of course, the distribution of light reflected by the ground will, to some extent, be influenced by the distribution in the sky. In particular, if small clouds are blown rapidly between the observer and the Sun, then intermittent cloud shadows on the ground will create appreciable fluctuations in the ground-reflected radiation field. Most ground surfaces, however, are highly non-specular, and their field of reflected radiance will inevitably have less sharp contrasts than the field of sky radiance. Therefore, apart from the occasional instance of scudding cloud in a clear sky, the provision of a low sampling rate in the instruments facing downwards is appropriate.

O Global irradiance measured in the plane normal to the Sun's beam. The device used to take this measurement is made to track the Sun by a micro-computer aboard the caravan.

O Global irradiance, measured in the horizontal plane.

O Diffuse radiance measured in 121 upward-facing directions and 77 downward-facing directions. Upward-facing measurements are taken with four photovoltaic pyrheliometers (having a 5° full-view angle) that complete a scan of the sky every 2 minutes. Downward-facing measurements are taken with one other 5° photovoltaic pyrheliometer that completes a scan of the ground every 26 minutes.

Again, we see that a less frequent sampling is employed with downward-facing sensors. In this case, however, the angular resolution is also reduced in the downward direction. This is because the fine structure of the field of ground-reflected radiance is highly specific to the site.

- Beam irradiance, measured in the normal plane - (a) with an absolute pyrheliometer over the whole spectrum, and over three spectral intervals; and (b) with a 'spectro-radiometer' at 16 'discrete wavelengths'. (In a report on Valko's experiment, Svendsen (1977a) mentions only 12 wavelengths, which are selected to lie outside the spectral regions of water-vapour absorption.)
- All-sky photographs, which are digitised in two ways: manually, by recording on pre-printed forms the cloud type in 12 sectors and the cloud amount in 24 sectors; and electronically, using a densitometer scanning in a 500x500 grid with 255 levels of brightness.

The spectral response of the photovoltaic pyrheliometers is 'rectified' with a blue filter, but it is not known how flat the resulting sensitivity distribution is. According to Valko et al. (1981), the sensor's spectral range spans 300 to 1100 nm and would be inadequate for the measurement of beam radiation, but it covers almost all of the radiation received from a cloudless sky, which is predominantly blue. The light reflected from the sunlit side of a cloud, though, will have roughly the same spectral intensity as the beam radiation, and the photocell will not register its full magnitude.

Strictly speaking, Valko is incorrect in referring to the data as measurements of 'radiance', since the non-ideal spectral sensitivity of his photovoltaic sensors makes the measured quantity intermediate between luminance and radiance. Nonetheless, we shall follow his terminology for the sake of simplicity.

Valko's reports contain contour graphs on polar axes of two kinds. First, those showing the angular variation of irradiance: in these, the angular coordinate represents the azimuth, and the radial coordinate represents the tilt. The value assigned to each point is the global (or diffuse) irradiance incident in a plane of the indicated orientation. Second, those showing the angular distribution of radiance: in these, the angular coordinate is again the azimuth, but the radial coordinate is the zenith angle (i.e. angular distance from the zenith) - or the nadir angle for downward-facing planes. The value assigned to each point in a graph of this kind is the radiance in the indicated direction.

Graphs of the angular variation of irradiance are less useful, for our purposes, than those of the distribution of radiance. In the former, the details of the radiation field have been blurred through integration over a hemisphere of view; this can be seen clearly when graphs of the two types of distribution are seen side-by-side (Valko 1980) - the radiance plot has much sharper gradients than the irradiance plot. Moreover, all irradiances on slopes will be affected by reflections from the neighbouring ground. The latter problem is especially acute for slopes greater than about 30°.

Valko's measurements of the circumsolar radiance are unsatisfactory. "Since the circumsolar radiance may drop by 10^{-3} - 10^{-4} at an angular distance of 1 - 2° from the edge of the solar disc, the variations of sky radiance as measured by instruments having a full view angle of 5° are only meaningful if the immediate vicinity of the Sun is excluded" (Valko 1980). Owing to the strong gradient of its distribution, the radiance near the Sun requires a variable-aperture pyrheliometer for its measurement.

The problem of how to present the wealth of data generated by so extensive a programme as Valko's is at once apparent when one reads his reports. A contour plot of the sky radiance has the distinguishing feature that it completely defines the field of diffuse radiation. Unfortunately, it is very difficult to grasp the relative values of irradiances in different planes simply by looking at a contour plot of sky radiance. Valko therefore presents a plethora of graphs that depict the dependence of global and diffuse irradiances on the major parameters, such as tilt and azimuth of the surface, the turbidity of the air, the amount of cloud in the sky, and the elevation of the Sun.

So far, Valko's analyses of his data seem to have produced rather limited results, beyond the summary presentation of measurements. One of Valko's general conclusions is that the angular distribution of diffuse radiance in a cloudless sky depends strongly on turbidity. (This agrees with other workers, with the exception of Steven (1977b).) Valko's specific conclusions about the diffuse radiation field are mostly the same as those reported by Kimball & Hand (1922) and Kondratyev (1969).

Valko provides a fuller account of some features that have previously been observed in less detail. For instance, Valko (1982d) shows not merely that turbidity reduces the radiance falling on an anti-sunward surface under a cloudless sky (an effect observed by Kimball & Hand 1921), but also shows that this reduction is more rapid with lower turbidities. In Valko's reports the diffuse fraction of the global irradiance,

$$D = G_d / G$$

is employed as a measure of the degree of turbidity. As the turbidity increases, a greater proportion of the global irradiance becomes diffuse, hence D increases. Valko found that doubling the value of D from 0.1 to 0.2 approximately halved the radiance falling in the anti-sunward plane, but an equal increase in D from 0.2 to 0.3 reduced it by only a quarter. So, after the initial impact made by the presence of a small amount of dust in the air, the effect of further augmenting the dust load is diminishingly small.

One of the few new qualitative features that Valko noted is that Cirrus cloud has a more isotropic effect in the scattering of light than dust has.

It seems that there is little more to be discovered in respect of the qualitative features of the diffuse field, and that what is required now is to ascertain what functional forms are suitable for describing the angular structure of the field. Valko claims, at several points, to have established empirical relationships that enable the diffuse field in a cloudless sky to be predicted. These relationships, however, seem to be purely graphical and that the important step of fitting mathematical functions has not yet been accomplished.

O--- At the Solar Energy Research Institute (SERI) in America, an 'all-sky flux mapper' has been developed to assist in modelling the day-light available in buildings (Robbins & Hunter 1983a,c).

The instrument is a videotape recorder comprising a standard vidicon sensor fitted with a fish-eye lens and a 'photopic' filter. This filter is designed to produce a spectral sensitivity matching that of the human eye. Electrical signals output by the sensor are fed into a PDP-11 micro-computer. The computer can display contour lines of luminance over the field of view, together with a grey-scale image of the light distribution. The data can be stored on tape or sent to a mainframe computer for further processing.

The vidicon sensor is made up of an array of photocells facing the same direction. Robbins & Hunter give few details about the sensor. (In one paper (1983c), the authors refer to "approximately 100 Licor photometric sensors ... with another 100 being added", but it is not clear whether this refers to the 'flux mapper' or to some other instrumentation.)

Measurements taken with the 'flux mapper' are accompanied by hourly photographs of the sky, taken through another fish-eye lens. The authors do not say whether the photographs are subsequently digitised.

The authors regarded their device as a prototype, and intended to use an improved apparatus (then being planned) to "define daylight and sunlight availability for over 200 US cities" (Robbins & Hunter 1983c). (Presumably, by "define" they mean measure.) At that time, their research programme had produced hourly estimates of illumination on horizontal and vertical surfaces in 80 US cities. Those estimates were computed, not with the measured distributions of luminance, but with the assumed isotropic distribution (Robbins & Hunter 1983b).

This 'flux mapper' may be expected to facilitate the rapid acquisition of a data-set comparable to that established under Valko at the Swiss Meteorological Institute. The utility of such a data set for our purposes, however, would be limited by the sensor's non-flat spectral response. It might be possible to use it for validating detailed models of radiative transport in the atmosphere, provided that such a model predicted the spectral dependence of the angular distribution of radiance. It would, nevertheless, be difficult to use the data directly to fit simple mathematical functions to the diffuse radiation field. The latter would require the use of a conversion formula for relating values of luminance to values of radiance. It is possible that an empirical function may be found in the course of the SERI programme, since simultaneous measurements of irradiance and illuminance will be taken. A conversion formula fitted to such data alone, though, would be unable to allow for the spectral difference between blue sky-light and grey cloud-light, because irradiance measurements by themselves carry no spectral information.

4. Upward radiation above clouds

4.1 Methods of measurement

Until the advent of remote sensing by satellite, measurements of upwelling radiation above clouds or fog were taken only occasionally. In the earliest experiments, an inverted pyranometer would be suspended below a balloon to measure the up-welling global irradiance above a cloud or fog mass, and measurements of the down-welling irradiance would be taken on a cloudless day, thereby enabling an estimate to be made of the albedo of the cloud or fog. After the First World War, experiments were conducted in aeroplanes: two pyranometers, one facing up and the other inverted, would be exposed on an aeroplane's wing, enabling a more direct determination of the albedo.

There is an obvious difficulty in keeping radiometers in stable orientations when they are borne on an aircraft, owing to pitching, rolling, and yawing of the vehicle.

This must limit the accuracy with which the angular distribution of up-welling radiance can be measured with a narrow-aperture instrument, although Brennan (see below) did not regard this as a major problem. Most experiments employed a single inverted pyranometer facing the nadir, but some involved a few pyranometers oriented in different directions. Since the early 1960's, however, orbital satellites have been used as platforms having stable orientations for a variety of radiometers. These have provided important new data-sets, but they have two major drawbacks: (a) they allow the determination of only the combined reflectance of the Earth and the whole depth of atmosphere; (b) so far, the spatial resolution of satellite data has been too coarse to allow the detection of mesoscale clouds. The French SPOT satellite, which recently came into operation, will allow the resolution of cloud structure at the sub-kilometre level, but it is not known how widely available (or expensive) its data will be.

4.2 Survey of data-sets

This section describes some experimental determinations of cloud albedo.

O--- The earliest measurements of above-cloud irradiance seem to be those of Aldrich (1919) in the USA, taken with a pyranometer suspended below a balloon. Measurements were taken over a thick fog that had formed in a valley during a clear night. At dawn, the fog or low-lying cloud lay between the heights 320 and 800 m. In the course of the day, the lower surface rose to 620 m, while the upper surface remained at a constant height, although it became more ragged.

A cable was used to transmit the signal from the pyranometer to the ground. Over the day, the temperature difference between the upper and lower surfaces of the cloud increased, and Aldrich assumed that the afternoon recordings lost accuracy owing to a thermoelectric EMF in the cable. During the morning, it was found that the albedo varied negligibly for solar elevations from 31° to 57°, and the average albedo was 0.78.

Robinson (1958) notes that Aldrich's value of 0.78 was widely accepted in subsequent years, even for appreciably thinner cloud masses.

O--- Luckiesh (1919), a contemporary of Aldrich in the USA, carried out a larger series of measurements of the zenith brightness of the sky and the nadir brightness of the ground, from an aeroplane. The apparatus was not described, but Luckiesh referred to it as registering 'brightness', so we may presume that his data are values of what is now called "luminance". It should be noted that clouds generally have a spectrally flat reflectance, so Luckiesh's values of albedo for brightness will not differ much from the albedo for radiance.

A large number of measurements were taken of the vertical reflectance of thick cloud. The values varied from 0.7 to 0.8, with a mean of 0.78; this agrees with Aldrich's albedo for thick cloud. Fewer measurements were taken of thin clouds, and the albedoes of these varied from 0.36 to 0.62.

Luckiesh obtained some interesting comparative values that do not seem to have been recorded elsewhere. For example, the sunlit part of the surface of a dense cloud was found to be up to six times brighter than the shadowed part of the cloud, and sunlit cloud surfaces were found to be five to ten times brighter than adjacent patches of blue sky. Note that the latter figure is almost certainly an under-estimate. This is because the grey, or white, light reflected by the cloud will contain a higher proportion of infra-red than the surrounding blue sky-light, but the sensor is unlikely to have registered it.

O--- Robinson (1958) took a series of measurements with a normal and an inverted pyranometer on an aeroplane. Data were recorded above and below areally extensive layers of cloud. (The air above the cloud layer was horizontally uniform - either cloudless, or else overcast or nearly overcast.)

Most of the values of albedo obtained by Robinson were lower than Aldrich's (1919) value of 0.78. The values of albedo that were not less than Aldrich's were

0.78 - Stratocumulus 1000 ft thick, Sun at 18°
0.78 - Stratocumulus 1800 ft thick, Sun at 26°
0.79 - Stratocumulus 5000 ft thick, Sun at 22°
0.80 - Stratocumulus 2700 ft thick, Sun at 20°
0.82 - Stratocumulus 4000 ft thick, Sun obscured
0.82 - Stratocumulus 5000 ft thick, Sun obscured
0.87 - Cumulus and Sc 3500 ft thick, Sun obscured

Only one value (0.87) substantially exceeded Aldrich's (0.78), and that was obtained with a mixture of Stratocumulus and Cumulus below the aeroplane. We should expect the castellated surface presented by the Cumuli to enhance or diminish the effective albedo according to the relative positions of the Sun, the aeroplane, and the Cumuli.

It seems reasonable, then, to regard 0.8 as an upper bound for the albedo of a thick cloud having a fairly flat upper surface, provided that neither the viewing angle nor the solar angle take extreme values. Robinson's main concern was with the 'mean' albedo of cloud (to which he assigned the value 0.6), but this is of limited use owing to the variable constitution and form of clouds. Moreover, for thin clouds the apparent albedo of cloud would have been affected appreciably by the albedo of the underlying ground.

Almost all of the measurements were taken with the Sun in the limited range of elevations from 20° to 35°, and the data could therefore not indicate whether the cloud albedo varied significantly with the solar elevation.

O--- Conover (1965) seems to be the earliest author to have determined cloud albedos using imagery from the early American satellites of the TIROS series.

O--- Ruff et al. (1966,1968) examined measurements of radiance in a visible band, 550-750 nm, taken with a scanning radiometer mounted on the satellite TIROS IV. This instrument had an aperture of 10°, but was deployed in a fixed orientation on the spacecraft.

Data were recorded on numerous occasions when the field of view of the sensor was filled by cloud. The field of view was assumed to be cloudy when the temperature of the observed surface was less than 255 K, as determined with a far-infrared radiometer mounted on the satellite. Cloud tops are nearly always much colder than the ground, especially within the latitudes that the satellite viewed.

Since the satellite can observe any patch of cloud from one direction only, only one reflectance measurement can be taken from each cloud mass. Hence Ruff et al.'s study of the angular distribution of reflected light was concerned with the median conditions for all clouds, rather than with any individual cloud mass.

It was found that the reflectance exhibited two maxima with respect to the direction of reflection. First, there was a weak maximum in the direction of the Sun, due to back-scattered radiation. The magnitude of this peak diminished as the Sun rose. (Note that the sensor points away from the Sun when measuring reflectance in the direction of the Sun.) Second, there was a stronger maximum near the horizon at an azimuth of 180° away from the Sun, due largely to foward-scattered radiation. As the Sun sank, this peak became more pronounced. Radiation scattered in this direction could not be measured when the Sun was near to the horizon, as part of the solar beam would be included in the radiance detected from the satellite. Nonetheless, the authors noted that the data indicated a rapid decrease in the reflectance peak in the direction away from the Sun when the Sun was very low. A possible cause of that decrease is the raggedness of the upper surface of the cloud field.

The main part of this angular dependence of the reflectance is qualitatively similar to the probability distribution (or 'phase function') for the direction of scattering relative to the incident direction after a single scattering event. This would appear to be physically reasonable, if we suppose that most of the light 'reflected' by the cloud has suffered only single scattering. (The objective meanings of the terms "reflected" and "back-scattered" are the same when the terms are applied to radiation that leaves the cloud in directions more than 90° from the incident beam. Their subjective connotations are different, however: the use of "reflected" suggests that we are thinking of the cloud as a closed body rather than as an ensemble of droplets.)

O--- Griggs & Marggraf (1967; also Griggs 1968) determined the albedo of Stratus cloud with upright and inverted pyranometers on an aeroplane. The flights were made above sea water, which has a low and fairly constant reflectance, so that the data were little affected by the surface beneath the cloud. Measurements were taken both with a cloudless sky above the Stratus and with a partial cover of higher clouds; no differences in the albedo of the Stratus were observed.

Griggs (1968) plotted the clouds' albedos against their thicknesses. The data were highly scattered, and no relationship could be discerned between the two variables. The author noted that this contradicted Neiburger's (1949) observation of a close relationship between the albedo and thickness of clouds. It was suggested by Griggs that the lack of correlation in his own data might be due to a wider range of water densities in the clouds. He showed that there was a (weak) correlation between the albedo of the cloud and its water density.

There was evidence that the albedo of the Stratus diminished as the Sun rose in the sky, which would be consistent with the results of earlier workers. Although the Sun was generally between 35° and 55°, on at least one occasion it was as low as 20°. This low elevation might have increased the albedo of the Stratus appreciably.

On several occasions, the albedo was as high as 0.8. Only once was it found to take a significantly higher value (about 0.9). This confirms the hypothesis that there is usually an upper bound of about 0.8 for the albedo of a smooth-topped cloud. Unfortunately, Griggs gives few details about the conditions under which the measurements were taken, so we cannot evaluate in detail the effect of solar elevation on the albedo.

O--- Brennan and his co-workers at NASA determined the angular distribution of up-welling diffuse radiance using an aeroplane-borne radiometer (Brennan, Halev, & Strange 1968; Brennan & Bandeen 1970). Brennan & Bandeen (1970) claim that errors due to variations in aircraft attitude were smaller than those introduced in the reading of the strip chart. The radiometer had an aperture of about 3°, and the data from different scans were averaged in intervals of 1°; the radiometer scanned only in the vertical plane containing the aircraft's trajectory.

Brennan & Bandeen's results agree with those of Ruff et al. (1968). The former found that the angular reflectance of stratiform cloud had a weak maximum in the direction of the Sun, and a strong maximum near the horizon in the direction away from the Sun, the latter being stronger with lower solar elevations. These two peaks are attributed to the known propensity of cloud droplets to scatter light in the backward and especially the forward directions, rather than at a right angle to the incident ray. Measurements were recorded with solar elevations from 10° up to 37.3°. Over that range, the reflectance peak due to forward scattering (i.e. in the direction away from the Sun) decreased from about 16 to about 4 times the zenith reflectance.

Some of Brennan & Bandeen's data showed the reflectance diminishing slightly for extremely low solar elevations, below about 3°. There is difficulty in obtaining accurate measurements with such a low Sun. We therefore cannot put very much reliance on this result, although we can note that it agrees with Ruff et al.'s result.

Radiance measurements were taken in two spectral bands, at the two ends of the visible range: 200-400 nm, covering ultraviolet and blue light, and 550-850, covering red and near-infrared. There were relatively small differences between the angular reflectances of stratiform cloud in the two bands - the shorter-wavelength radiation exhibited slightly greater anisotropy. The small magnitude of the difference agrees both with everyday experience, insofar as clouds have the same grey appearance from all directions, and with Kondratyev's (1969) comparison of the angular distributions of luminance and radiance under an overcast.

5. Radiation reflected from the ground

There have been numerous studies of ground albedo in which an inverted pyranometer has been suspended a few metres above the ground. Some of these experiments have been continued on a routine basis over several years. Inevitably, they provide information about only a specific type of surface, and it would seem that aerial measurements are more useful for our purposes.

The albedo of the ground varies greatly with the type of the surface, and the details of these variations would take us outside the scope of this review, which is concerned primarily with the atmosphere. Nevertheless, a brief outline will help to put the more relevant information into context. A substantial review is given by Kondratyev (1969; chapter 7); further results are given on the anisotropy of ground reflectance by Brennan & Bandeen (1970) and on the solar-elevation dependence and spectral selectivity of ground reflectance by Coulson & Reynolds (1971).

Inevitably, the ground is not a perfect Lambertian surface. It has been found that naturally occurring ground surfaces are as anisotropic as clouds, and the qualitative form of their directional reflectances are similar. Sandy desert soil seems to have the least anisotropic reflectance, and forests the most anisotropic. (Experimental data on the reflectance of vegetative covers have a consistency that is remarkable in view of the structural complexity of the plants.) The height of the Sun affects the reflectance of the Earth's surface in the same way that it affects that of clouds. On most types of Earth surface, though, this effect ia small. Reflectance is greatest at a low solar elevation, about 10°, although the maximum is usually weak. There is a sharp drop in reflectance at solar elevations lower than about 10°. Open water is an exception: the maximum there does not seem to be a reduction when the Sun becoms very low. The reflectance of open water varies systematically with the wind speed, owing to changes in the roughness of the water surface.

Reflectances of ground surfaces are usually spectrally flat, with the exception of vegetative covers. The reflectance of green vegetation is very low up to about 700 nm, beyond which it increases rapidly to a moderately high value of about 0.6; there is a slight maximum at about 530 nm.

6. Simple models of the diffuse field

6.1 General remarks

Simple models of the diffuse field may be either idealisations derived from the leading features of the atmosphere, or they may be purely empirical regressions. An idealised model has the advantage that it is physically meaningful, and this often makes it more general. An empirical regression, on the other hand, is established by fitting an arbitrary or subjectively chosen mathematical function to measured data. It has the disadvantage that the constants occurring in the fitted function are specific to the particular data-set used.

It may be helpful to introduce a simple scheme for classifying the various models that have been put forward. Most of the simple models that have been proposed consist of two functions that represent the following two components.

(a) The circumsolar radiation, which is represented by a function of the angular distance from the Sun, and may be

PC: a single point identified with the centre of the Sun (the 'point circumsolar' model);

DC: a circular region having a discrete boundary and centred on the Sun (the 'discrete circumsolar' model);

CC: a circularly symmetric field centred on the Sun and diminishing continuously away from the Sun (the 'continuous circumsolar' model).

(b) The hemispherical radiation, which is represented by a function of the zenith angle, and is usually one of the following.

IH: a uniform field covering the whole sky (the 'isotropic hemispherical' model);

AH: a single function with maximum magnitude near the horizon (the 'anisotropic hemispherical' model);

CH: a linear combination of two components, one being a uniform field and the other being a field with maximum magnitude near the horizon (forming the 'combined hemispherical' model); the two components are respectively the 'background' radiation and the 'circumhorizontal'.

Of course, only the hemispherical component will be present in the case of an overcast sky.

The circumsolar and hemispherical components may be either added or multiplied together to form the model. If we include the possibilities of an absence of circumsolar radiation (a '0C' model) and of an absence of hemispherical radiation (a '0H' model), this scheme allows 24 types of model:

	Additive models				Multiplicative models		
	(..+0H)	(..+IH)	(..+AH)	(..+CH)	(..*IH)	(..*AH)	(..*CH)
(0C...)	-	0C+IH	0C+AH	0C+CH	-	-	-
(PC...)	PC+0H	PC+IH	PC+AH	PC+CH	PC*IH	PC*AH	PC*CH
(DC...)	DC+0H	DC+IH	DC+AH	DC+CH	DC*IH	DC*AH	DC*CH
(CC...)	CC+0H	CC+IH	CC+AH	CC+CH	CC*IH	CC*AH	CC*CH

In reality, there is no such thing as the 'background' radiation, nor is there any discernable boundary between the circumsolar and circumhorizontal radiance fields. On that consideration, the types CC+AH and CC*AH might be regarded as the most reasonable, as these comprise continuous functions for the circumsolar and circumhorizontal radiation components. Nonetheless the other models may be useful approximations.

If we consider the physics of radiative scattering by the atmosphere, a multiplicative model seems more reasonable than an additive one. An informal argument for this premiss can be given as follows.

The enhanced brightness of the sky near the horizon is due primarily to the greater mass of air lying in directions of low elevation, whereas the enhanced brightness around the Sun is due to the propensity of dust particles to scatter light through small angles. If the atmosphere were so thin that each ray of light would be scattered no more than once, it is evident that the sky radiance received from any direction will be proportional to the mass of air lying in that direction. In any particular direction, the contribution of radiance from each species of particle would be proportional to that species' directional reflectance into that direction. If the particles' directional reflectance is anisotropic then the resulting diffuse field will be the product of (a) a function of the zenith angle, representing the dependence on the mass of air lying in any direction, and (b) a function of the angular distance from the Sun, representing the dependence on the anisotropic single-scattering phase-function.

In a more realistic model atmosphere, the multiple scattering would not be negligible, and so this simple argument would begin to break down. The multiple scattering will not, howvever, be the dominant process, unless the sky is cloudy or the local atmosphere possesses a degree of turbidity like that normally associated with sandy deserts. Therefore, we should expect a multiplicative model to be appropriate for cloudless skies in Britain.

The presence of clouds might, of course, change the type of model that should be required. That is to say, a multiplicative model might not be the most suitable for a partially clouded sky.

It is important to note, though, that whatever model is used for partly clouded skies must reduce to the multiplicative model in the limiting case of no cloud.

6.2 Survey of models

This section describes a number of simple models of the diffuse field that have been put forward in the literature. Valko (1980) mentions four unpublished surveys of such models (May 1978, de Brichambaut 1978, Krochmann 1978, and Bener 1980), and it is hoped to obtain copies of these later. From the following list are excluded models that are not applicable to irradiances in all planes (such as those of Parmelee (1954) and Puskas (1972,1973), which apply only to irradiances in vertical planes).

The radiance N(Z,E), at a zenith angle Z and an angular distance E from the centre of the Sun, will be expressed as a function normalised with respect to the zenith:

$$N(Z,E) = N(0).n(Z,E)$$

in which N(0) is the radiance in the zenith of the sky and n is the normalised radiance.

0--- In Moscow, Pokrowski considered a cloudless atmosphere that was thin enough for the multiple scattering of solar radiation to be ignored (Pokrowski 1924, 1925a-c, 1926, 1929a,b). The formula he derived for the normalised sky radiance was

$$n(Z,E) = \frac{1+\cos^2 E}{1-\cos E}(1 - \exp(-d_1 \sec Z))$$

in which d_1 is a constant. This formula disagreed slightly with measurements of radiance in cloudless skies at Moscow and Davos. Pokrowski attributed the discrepancy to multiple scattering, and introduced an empirical term, d_2, to allow for it. The modified formula was

$$n(Z,E) = (\frac{1+\cos^2 E}{1-\cos E} + d_2)\ (1 - \exp(-d_1 \sec Z))$$

$$d_1 = 0.32 \quad \text{and} \quad d_2 = 5$$

At least two other authors have used Pokrowski's formula: Hopkinson (1954) fitted it to measurements of sky luminance taken with a Schuil telephotometer in Stockholm, and Steven (1977a,b) fitted it to measurements of sky radiance taken with a Linke-Feussner pyrheliometer in England. The constants were

$d_1 = 0.32$ and $d_2 = 0$ (Hopkinson)
$d_1 = 0.92$ and $d_2 = 11.7$ (Steven)

Differences in the spectral sensitivity of the radiometers will, of course, have affected the values of these constants.

Since the parameter d_2 is intended to allow for multiple scattering, we should expect its value to represent the degree of turbidity, and the other parameter, d_1, to represent the type of aerosol.

O--- Moon & Spencer (1942) fitted a simple curve to published measurements of luminance in overcast skies. These measurements had been taken by Kimball & Hand (1921,1922) in Washington and Chicago, and by Kohler (1908) in Kiel. The formula was

$$n(Z) = \frac{1 + 2\cos(Z)}{3}$$

Since luminance and radiance have approximately the same angular distribution in an overcast sky, we may apply Moon & Spencer's curve to the radiance as well as to the luminance. It will not be applicable to thin cloud layers, for these will permit the the radiance distribution of the overlying cloudless air to be appreciably visible.

A number of authors have found that Moon & Spencer's function fits measurements of luminance and radiance in overcasts (e.g. Hopkinson 1954, using measurements taken at Stockholm). Middleton (1952), however, generalised the function to

$$n(Z) = \frac{1 + d\cos(Z)}{1 + d}$$

in which d is an empirical constant, taking the value $d = 2$ in Moon & Spencer's original function.

Petherbridge (1955) measured the luminance in a thick overcast above an even blanket of snow, and found that Middleton's function fitted the data with $d = 1$. Steven (1977a) and Steven & Unsworth (1979b) fitted the Middleton function to diffuse radiances measured in overcast skies on 99 occasions. They found almost all the values of d to lie in a range of about 0.5 to 2.0, although values up to 5.0 were recorded. The mean value was 1.4. This agreed with a value of $d = 1.5$ found by Walsh (1961) for overcast luminance distributions.

Steven (1977a) mentions that Goudriaan (1977) gave a theoretical basis for Middleton's function, but I have not been able to obtain a copy of Goudriaan's report.

O--- In the CSIRO in Australia, Morse & Czarnecki (1958) proposed a very simple model, in which all the diffuse radiation was supposed to be incident in the same direction as the solar beam (a PC+0H model). This seems to be an unnecessary over-simplification. Nonetheless, Norris (1966) found this model to be only marginally worse than the isotropic model. Morse & Czarnecki's model was found to give errors in G_t of up to 30%, with a mean of 8%; the corresponding figures for the isotropic model were 22% and 7%.

O--- At what is now the Building Research Establishment (BRE) in England, Loudon & Petherbridge (1965) and Loudon (1967) proposed a model comprising a point-like circumsolar component and an isotropic background component (the model thus being of type PC+IH). Two tables were presented, for cloudless and overcast skies, that specified the circumsolar and background proportions of the horizontal irradiance, G. Given any recorded value of G, it was then possible to convert it to a value for a tilted surface.

The authors did not assess the validity of this table for other sites. It is apparent from recent papers on the problem of estimating the diffuse fraction of global irradiation, that the circumsolar and background components of G will vary significantly with meteorological conditions and with the location. It is therefore very likely that the table given by the BRE workers is specific to the set of data from which it was derived.

O--- In the ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) in the USA, Morris & Lawrence (1971) fitted a mathematical function to measurements of sky radiance that they had taken with an Eppley pyrheliometer (which had been adapted to enhance its sensitivity). The model comprised two components, representing the circumsolar and hemispherical radiance fields. The circumsolar component was limited to a disc of angular radius 52° concentric with the Sun. Within that disc, the circumsolar radiance was represented by

$$n_c(E) = d_1 \exp(d_2\ E)$$

in which

$$d_1 = 5.70303221$$
$$d_2 = -0.04435017 \quad \text{radian}^{-1}$$

The authors note that when the Sun is low in the sky, the contribution of the circumsolar radiation must be reduced in proportion to the fraction of the 52° disc that is below the horizon. The hemispherical radiance was represented by

$$n_h(Z) = d_3 + d_4\ (Z-pi) + d_5\ (Z-pi)^2$$

in which

$$d_3 = 2.840503$$
$$d_4 = -0.06643253$$
$$d_5 = 0.0004686631$$

Inside the 52° disc centred on the Sun, the radiance was taken to be the sum of the hemispherical and circumsolar components, so that the model was of type DC+AH. Note that their constants are almost certainly quoted to too many decimal places.

Morris and Lawrence used values of the radiance averaged over time, and thereby ignored the effects of variations in turbidity.

O--- In California, Temps & Coulson (1977) fitted a function of a multiplicative type, CC*CH, to measurements of global irradiance taken in variously tilted planes. They also fitted a function to the ground-reflected irradiance.

Temps & Coulson's data are not ideal. As mentioned above, Temps & Coulson (1977) analysed data from only two cloudless days (in January and April), so that it was not possible for them to investigate the effect of turbidity. Moreover, the irradiances they measured with their pyranometer included radiation reflected from the adjacent ground, which was an open field of short grass. Their data were consequently affected by the local terrain.

Unlike most other authors, Temps & Coulson did propose a function that represented the anisotropy of the ground-reflected radiation. The use of this factor may have removed some of the effect of the local terrain from their data, but it will by no means have eliminated it.

Their regression formula for sky radiance is the product of two components, which represent the circumsolar and circumhorizontal fields; and to this added their term for the ground-reflected irradiance:

$$G_{dt} = G_d \cdot R_d \cdot g_c \cdot g_h + r \cdot G \cdot R_g \cdot g_g$$

in which the 'tilt conversion' factors are

$$R_d = \frac{1+\cos(\text{tilt})}{2}$$

$$R_g = \frac{1-\cos(\text{tilt})}{2}$$

and the basic terms are

G_{dt} = diffuse irradiance in tilted plane, Wm^{-2}
G_d = diffuse irradiance in horizontal plane, Wm^{-2}
G = global irradiance in horizontal plane, Wm^{-2}
r = albedo of ground
g_c = normalised circumsolar irradiance
g_h = normalised hemispherical irradiance
g_g = normalised ground-reflected irradiance

In the specific model proposed by the authors, the anisotropic fields are represented thus:

$$g_c = 1 + \cos^2(E)\ \sin^3(Z^o)$$
$$g_h = 1 + \sin^3(\text{tilt}/2)$$
$$g_g = (1 + \sin^2(Z/2))\ \text{abs}(\cos(A-A_o))$$

in which A and A_o are azimuth angles of the surface and the Sun, respectively.

Digression:-

There is some confusion about the form of g_c. Temps & Coulson (1977) give two expressions for it:

$$g_c = [(1 + \cos^2E\ (\sin^3Z))]$$

in which there are two redundant pairs of parentheses, and

$$g_c = [(1 + \cos^2 a)(\sin^3 Z)]$$

in which 'a' is an undefined term, although we may assume that it is a misprint for 'E'. The second of these two expressions is clearly wrong, since it implies that the diffuse irradiance is zero whenever the Sun is at the zenith. The first of these two expressions receives support from Smietana et al. (1984), who looked it up in Temps' MSc thesis (Temps 1977) and found the expression

$$g_c = 1 + \cos^2 E \sin^3 Z$$

This expression is also used by Klucher (1978, 1979) and Stewart et al. (1981), and we shall take it as the correct version here. In this connection, though, we might note that Valko (1980) used the second version given by Temps & Coulson, which predicts zero diffuse irradiance when Z_o=0. Valko found that this formula was much less accurate than other published formulae in predicting G_{dt}, and it is surprising that he did not spot the misprint. Another problem arises in the expression for g_g, for Smietana et al. give

$$g_g = 1 + \sin^2 Z \text{ abs}(\cos(A_o))$$

instead of Temps & Coulson's

$$g_g = (1 + \sin^2(Z/2)) \text{ abs}(\cos(A-A_o))$$

We shall take Temps & Coulson's as the correct expression.

Temps & Coulson claimed that their model gave an estimate of G_{dt} that was appreciably better than that given by the isotropic model, but only for equator-facing planes. For planes in other orientations, the improvement was small. This is unfortunate, for most workers have found that the isotropic model substantially over-predicts the diffuse irradiance in planes facing away from the equator, and we might therefore have hoped that Temps & Coulson's model would have some impact on errors in those directions. A possible explanation is that Temps & Coulson apparently took their measurements on an unusually clear day and that the circumsolar radiance was unusually weak. (The ratio of irradiance in the equator-facing vertical plane to that in the pole-facing plane was only about 3:4 when the Sun was at 34°, in contrast with a roughly corresponding ratio of 3:1 found by Parmelee (1954).)

It seems likely, therefore, that Temps & Coulson's results are biassed toward conditions of low turbidity. They quote a 'turbidity coefficient' of 0.04, but neglect to say which definition of turbidity coefficient they are using (Angstrom's, Linke's, or Unsworth & Monteith's).

The factors for anisotropy, g_c, g_h, and g_g, were intended as correction factors for irradiance estimates based on the isotropic model. They would be used as follows. One would measure the horizontal irradiances, G and G_d, then estimate G_{dt} and G_{gt} using the assumption of isotropy, and then apply the correction factors. Unfortunately, the values of horizontal irradiance that Temps & Coulson used were not measured. (One has the impression that the authors possessed only one pyranometer with which to carry out their work.)

The horizontal irradiances were in fact estimated with a simple model of beam attenuation, which will inevitably have introduced an error into the values G_d and G. When the authors compared the model predictions of G_t with measured values of it, the discrepancies that they found found were due not entirely to the model of the diffuse field but also to the inevitable inaccuracy of the model of the beam attenuation. Consequently their correction factors will have been affected by the errors introduced by the model of beam attenuation.

O--- Shortly after Temps & Coulson's paper, Klucher (1978,1979) compared their model with his own measurements of diffuse irradiance in two planes tilted toward the equator, taken over six months.

Although Klucher referred to his data as 'measurements' of the diffuse irradiance in an inclined plane, this is not strictly correct. As in other studies, the diffuse irradiance in the inclined plane, G_{dt}, was found by subtracting the computed beam irradiance, G_{bt}, from the actually measured global irradiance, G_t, in the inclined plane.

The best way of determining the beam irradiance would have been to measure the normal-incidence beam G_{bn} with a pyrheliometer. A minor geometric conversion would then have yielded G_{bt}. Unfortunately, Klucher did not have a pyrheliometer, and was obliged to compute G_{bn} by an indirect means. Global and diffuse irradiances in the horizontal plane were measured with pyranometers, and G_b was computed to be the difference, $G-G_d$. The value of G_{bt} was computed from G_b using a geometric factor, which would almost always have been greater than 1.0 (so that errors in G_b would be magnified).

The diffuse irradiance in the horizontal plane, G_d, was determined with a shading ring. The correction factor for readings taken with shading rings are by no means accurate. In fact, Klucher ironically used a correction factor that was derived from the assumption of an isotropic diffuse field.

The error in G_d due to the shading ring would have been carried through into the experimental value of G_{dt}. It is quite possible that the resulting error in G_{dt} was of the same magnitude as the errors in the model estimates of that quantity. Therefore, where Klucher found errors in the estimates of G_{dt}, he is unjustified in attributing those errors entirely to the model of the diffuse radiance. The errors will be due partly (probably appreciably) to inaccuracy in the correction factor for the shading ring.

Experimental errors notwithstanding, Klucher's results are consistent with those of other workers. The isotropic assumption was found to work well with overcast skies, but with cloudless skies it was associated with an error of about -5% in the global irradiance in an inclined plane facing the equator. Temps & Coulson's model was found to work well with cloudless skies. Their model, however, does not apply to cloudy skies. Klucher therefore devised a hybrid model, which smoothly turned into Temps & Coulson's model as the cloud cover tended to zero and smoothly turned into the isotropic model as the cloud cover approached an overcast:

$$g_c = 1 + (1-D)\ \cos^2 E\ \sin^3 Z$$
$$g_h = 1 + (1-D)\ \sin^3(\text{tilt}/2)$$

in which

$$D = G_d / G$$

The hybrid model was found to work well with all conditions of the sky.

There is no allowance in Temps & Coulson's function for variations in the the turbidity regime. Klucher obtained his data over a period of six months, and must therefore have encountered a range of turbidity conditions. Nevertheless, differences between localities (especially between inland and coastal sites) may reveal inadequacies in the model, because geographical differences in turbidity can exceed the temporal changes in turbidity at a site.

Another doubt about Klucher's regression is whether it applies to planes facing away from the equator. Temps & Coulson fitted their model to data from planes of all orientations, but they used only two days' data. On the other hand, Klucher used six months' data but only equator-facing planes.

Stewart et al. (1981) compared the three models discussed above (the isotropic model, the Temps-Coulson model, and the Temps-Coulson-Klucher model) with measurements of diffuse irradiance in inclined planes, taken in New York over six months. It was found that the Temps-Coulson-Klucher model provided predictions only marginally better than those of the isotropic model. The authors gave no indication of how well the Temps-Coulson function performed on cloudless days. (It performed badly in the data set as a whole, but that is not surprising as the function had originally been fitted to cloudless-sky data, whereas Stewart et al.'s measurements covered arbitrary sky conditions. The authors seemed unaware of this point.)

O--- In Britain, Steven (1977a) fitted two mathematical functions to the mean radiance distribution of cloudless skies at Sutton Bonington. These should be regarded more as interpolation formulae than as models.

The first function was fitted fairly precisely, using spherical harmonics. Its formula (referred to as the 'long formula') is published in the Quarterly Journal of the Royal Meteorological Society (Steven & Unsworth 1979a) but with four misprints (two of which were later reported by Steven & Unsworth, 1980); it is also published in a conference paper by Steven & Unsworth (1979b), but without its table of coefficients. The following formula is that given in the thesis.

$$
\begin{aligned}
N(Z,azi) = {} & D1 + \\
& D2 \ast \sin Z \ast \cos(azi) + \\
& D3 \ast \cos Z + \\
& D4 \ast \sin^2 Z \ast \cos(2 \ast azi) + \\
& D5 \ast \sin Z \ast \cos Z \ast \cos(azi) + \\
& D6 \ast (3 \ast \cos^2(Z)-1)/2 + \\
& D7 \ast \sin^3 Z \ast \cos(3 \ast azi) + \\
& D8 \ast \sin^2 Z \ast \cos Z \ast \cos(2 \ast azi) + \\
& D9 \ast \sin Z \ast \cos(azi) \ast (5 \ast \cos^2(Z)-1) + \\
& D10 \ast (5 \ast \cos^3(Z)-3 \ast \cos(Z))/2 + \\
& D11 \ast \exp(\ -D12 \ast \sin(E(Z,azi))\ )
\end{aligned}
$$

in which it assumed (see below) that the azimuth angle is

$$azi = abs(A - A_o)$$

The basic terms are

N = radiance, Wm^{-2}/steradian
Z = zenith angle of point
A = azimuth angle of point
A_o = azimuth angle of Sun
E = angular distance of point from Sun

and the constants D1 to D12 depend on the solar zenith angle, Z_o, as follows.

	$Z_o=35^o$	$Z_o=45^o$	$Z_o=55^o$	$Z_o=65^o$
D1	1.1	1.0	0.40	1.6
D2	0.12	0.7	0.9	1.5
D3	-2.6	-0.7	0.7	-1.6
D4	0.04	0.26	0.38	0.42
D5	-0.04	-0.5	-0.7	-2.0
D6	1.4	-0.04	-1.3	0.2
D7	0.01	0.04	0.09	0.12
D8	-0.1	-0.3	-0.3	-0.32
D9	-0.16	0.01	0.006	0.19
D10	-0.6	0.06	0.6	0.1
D11	5.6	5.8	7.0	9.8
D12	2.3	3.9	4.4	5.2

No definition is given of the azimuth angle, which is denoted by 'azi' here. The only definition that is physically plausible is that 'azi' is the azimuthal distance from Sun's meridian.

The circumsolar component is the eleventh term, as can be recognised by its dependence on the angular distance, E, from the Sun. The remainder of the function must be regarded as the hemispherical component. It can be seen that the hemispherical component has the peculiar property of having an azimuthal dependence as well as a zenithal dependence. (It is therefore outside the classification scheme defined above in sub-section 6.1.) It is difficult to see any physical basis for this azimuthal dependence, and Steven and Unsworth do not mention it.

The second formula has a slightly less precise fit, but is much shorter; hence it is referred to as the 'short formula'. This function was originally proposed by Dogniaux, but has been modified by Steven. Being shorter, it is less prone to being misprinted, and is published correctly by Steven & Unsworth (1979a,b), 'correct' here meaning simply that it is in agreement with Steven's thesis. It is as follows.

$$N(Z,E) = (C1 + C2 * \exp(C3*E) + C4 * \cos^2 E) * (1 - \exp(C5*\sec(Z)))$$

in which the constants C1 to C5 depend on the solar zenith angle, Z_o, as follows.

	Z_o=35°	Z_o=45°	Z_o=55°	Z_o=65°
C1	0.61	0.65	0.73	0.76
C2	11.90	10.70	11.10	13.00
C3	-2.97	-2.82	-2.97	-3.09
C4	-0.12	-0.02	-0.07	0.17
C5	-0.45	-0.48	-0.48	-0.42

In this formula, it matters whether the angle E is in degrees or radians: Steven & Unsworth do not say, but an assumption that E is in radians is found to give the correct values of N.

This short formula consists of a hemispherical component multiplied by a circumsolar component, and is of type CC*CH in our classification scheme.

I have not seen either the long or the short formula quoted outside the papers that have emanated from the research group at Nottingham University. This may be because, in order to compute the diffuse irradiance on an arbitrary surface, Steven's formulae must be integrated over the sector of sky that is seen by the surface. This is not a trivial computation, and its cost might be regarded as prohibitive, especially if the integration is to be done repeatedly for successive time steps.

In Canada, Hooper & Brunger (1980) fitted an elaborate CC+CH model to Steven's (1977b) measurements of sky radiance, which had been taken with a Linke-Feussner pyrheliometer, and to their own measurements of sky radiance, which had been taken with a Kipp CA1 pyrheliometer. The latter instrument is similar to the Kipp Linke-Feussner pyrheliometer). The distribution was represented as

$$n(Z,E) = n_c(E) + n_h(Z)$$

in which the normalised circumsolar and hemispherical radiances are, respectively,

$$n_c(E) = d'_1 \exp(-d_1 E \exp(d_2 Z_o))$$

$$n_h(Z) = d'_2 + d'_3 Z^2$$

The authors distinguished between the constants d'_1, d'_2, d'_3, and the constants d_1, d_2. The d' constants served to scale the three components of the distribution, and varied with the solar elevation; the d constants, on the other hand, served to define the shape of the circumsolar distribution of radiance and were supposed to take fixed values.

The values of the constants were first computed by the least-squares method with a combined set of Steven's (1977b) averaged values of radiance in a clear sky and Tonne & Normann's (1960) measurements of luminance under overcasts. (Apparently, Hooper and Brunger were unaware of Steven's measurements of overcast radiance, perhaps because these have been reported only in his thesis (Steven 1977a) and in a UK-ISES conference (Steven & Unsworth 1979b), not in the international journals.)

Steven (1977b) tabulated cloudless-sky radiance at 22 points in the sky for each of four 10°-intervals of the solar elevation (these intervals starting at 30°, 40°, 50°, and 60°). The data points were evenly spaced over the hemisphere, but were rather sparse in the circumsolar region. Hooper & Brunger evaluated the constants d'_1, d'_2, and d'_3 separately for each interval of solar elevations, but evaluated the constants d_1, d_2 for the data set as a whole. The use of such a large number of parameters, five in all, would have greatly eased the fitting of the function. Therefore, unless those constants apply to other localities, the exercise is rather futile.

Hooper & Brunger's distribution fits Steven's figures very well for a solar elevation of 35° (which is the only value of Z_o for which they plot the results), but the RMS error of the fit rises to 17.7% for Z_o in the range 50-55°; the error would presumably be greater for solar zenith angles beyond 55°. The overall accuracy of the model would therefore be poor in the latitudes in which the British Isles lie. For Steven's data,

$d_1 = 0.0145423$
$d_2 = 0.0231798 \quad \text{radian}^{-1}$

The weather-dependent parameters d'_1, d'_2, d'_3 were not given for Steven's data, but only for Hooper & Brunger's own measurements taken in Canada. This may have been because Steven used 10°-intervals of solar elevation whereas Hooper & Brunger's data allowed the use of 5°-intervals, and because the range of solar zenith angles was different (30-70° in Britain, 25-55° in Canada). The values of the constants were as follows.

Z_o	d'_1	d'_2	d'_3
20-25°	-0.17186	0.56024	0.91803
25-30°	-0.14985	0.54548	0.99835
30-35°	-0.09676	0.50144	1.00449
35-40°	-0.06816	0.47481	1.10678
40-45°	-0.05377	0.48940	1.21526
45-50°	-0.01954	0.46846	1.30219
50-55°	-0.01699	0.44391	1.31890

The number of decimal places used should be taken with a pinch of salt.

The authors say their use of the Toronto data is a 'validation' of the model, but they do not compare the values of d'_1, d'_2, d'_3 obtained from Steven's data with those obtained from the Toronto data, so it is difficult to see how the results can be regarded as a validation. The omission of that comparison is unfortunate, as site-independence of the constants is a crucial point.

7. Summary

7.1 Nature and magnitude of the problem

(a) At the bottom of the atmosphere.

The diffuse solar energy received at the Earth's surface is not incident uniformly from all directions in the sky. In a cloudless sky, the radiance is greatest around the Sun's disc and near the horizon. Under an overcast of uniform thickness, the radiance is heightened at the zenith and diminishes toward the horizon. In broken cloud, the radiance varies irregularly and unpredictably over the sky.

When it is desired to convert known values of irradiance in the horizontal plane to corresponding values of irradiance in other planes, the natural and usual method is to assume an isotropic field of diffuse radiation.

In practical terms, therefore, the basic problem of anisotropy lies in the errors introduced into estimates of tilted-plane irradiances by the assumption of a uniform diffuse field. (Here, 'tilted' includes 'vertical'.)

Under a cloudless sky, the assumption of isotropy leads to mean errors of up to about -5% in estimates of diffuse irradiance on a surface tilted toward the Sun, and mean errors of up to about +40% when the surface is tilted away from the Sun. The absolute magnitude of the error, though, is roughly the same whatever the azimuth of the surface; the difference in the relative error is due mostly to the difference in irradiance level. Under an overcast sky, the errors are smaller. When the sky is occupied by broken cloud, we may expect larger instantaneous errors, although positive and negative errors will cancel to some extent when the irradiance is averaged over many days. Note, however, that the integrated irradiance above a threshold is required in the study of both active and passive solar-energy systems, and instantaneous errors in this quantity will cancel to a much lesser extent.

Although the errors are small, they tend to be systematic, so that the same percentage errors will be carried into estimates of long-term irradiations on tilted surfaces.

In all active, and some passive, systems for collecting solar heat, the solar energy is absorbed by a specialised surface which is either fixed in a roughly equator-facing direction, or is made to track the Sun. As we have noted, the percentage error in estimates of the diffuse irradiance on surfaces of these orientations is small. Furthermore, the diffuse irradiance is unlikely to amount to more than half, and usually much less than half, of the global irradiance. For these applications, therefore, the assumption of diffuse isotropy is a minor source of inaccuracy.

In other buildings, however, solar energy is passively collected by all external surfaces. Rooms with external walls on the pole-facing sides of a building will receive solar energy in a predominantly, or exclusively, diffuse form. And, as we have noted, the percentage errors are greatest in estimates of diffuse irradiance in pole-facing tilted planes. Another type of building in which the diffuse anisotropy can be important is that in which rooms have over-hangs to shield windows from strong midday sunlight. Such a window will 'see' a region of sky in which the radiance will be higher than the mean over the sky.

In summary, predictions of the energy gain through passively collecting systems, and of direct energy gain through windows, can be seriously inaccurate if an isotropic diffuse field is assumed.

Diffuse anisotropy also influences the artificial lighting required in rooms which rely partly on natural daylight. Since artificial illumination is a major form of energy consumption in many buildings, the assumption of diffuse isotropy can reduce the accuracy of predictions of the overall heat budget.

A further problem that is caused by diffuse anisotropy is that of correcting measurements of diffuse irradiance which have been made with shade rings and to which have been applied the standard isotropic correction. The values of diffuse irradiance, G_d, that result from the isotropic correction are under-estimates, and they give rise to over-estimates of the beam irradiance, G_b. The error is carried into over-estimates of the global irradiance in tilted planes.

With some planes, the over-estimates due to this source of error can be substantially greater in magnitude than the under-estimates due to the basic problem that has been described above. Nevertheless, the literature on this problem is relatively small.

(b) At the top of the atmosphere.

The solar energy that is reflected out of the atmosphere by the tops of clouds is not distributed uniformly in all directions. The reflected radiation is heightened in the direction of the Sun, and even more so in the direction of low elevation opposite the Sun.

In order to estimate the amount of solar radiation transmitted through atmospheric clouds using satellite pictures, some assumption must be made about the angular distribution of the radiation reflected by the clouds. The simplest assumption is that the cloud reflectance is isotropic. For regions near the periphery of the satellite's field of view, this assumption can lead to systematic errors of more than 10% in the irradiance passing through the cloud. Again, this error is systematic, and will be carried into long-term averages.

7.2 Existing solutions

The radiance distributions observed in cloudless and overcast skies are adequately represented by functional forms given by Pokrowski (1929b) and Middleton (1952), respectively. There is very little scope for improvement in these functional forms, although it should be emphasised that their parameters vary with changes in the cloud canopy and the ground surface. Some benefit might arise from relating the parameters to observed features of the climate and the terrain. Nevertheless, for the purposes envisaged here, the stable conditions of cloudless and overcast skies might be regarded as having been characterised.

Radiance distributions in partly clouded skies, on the other hand, have not been satisfactorily characterised. The prime reason for this deficiency has been the absence of large, computer-readable sets of measurements of the radiation field in arbitrary weather. Partly clouded skies can rapidly and substantially change the radiance field, and a long series of measurements is needed to allow the regular features of these changes to be extracted by statistical analysis.

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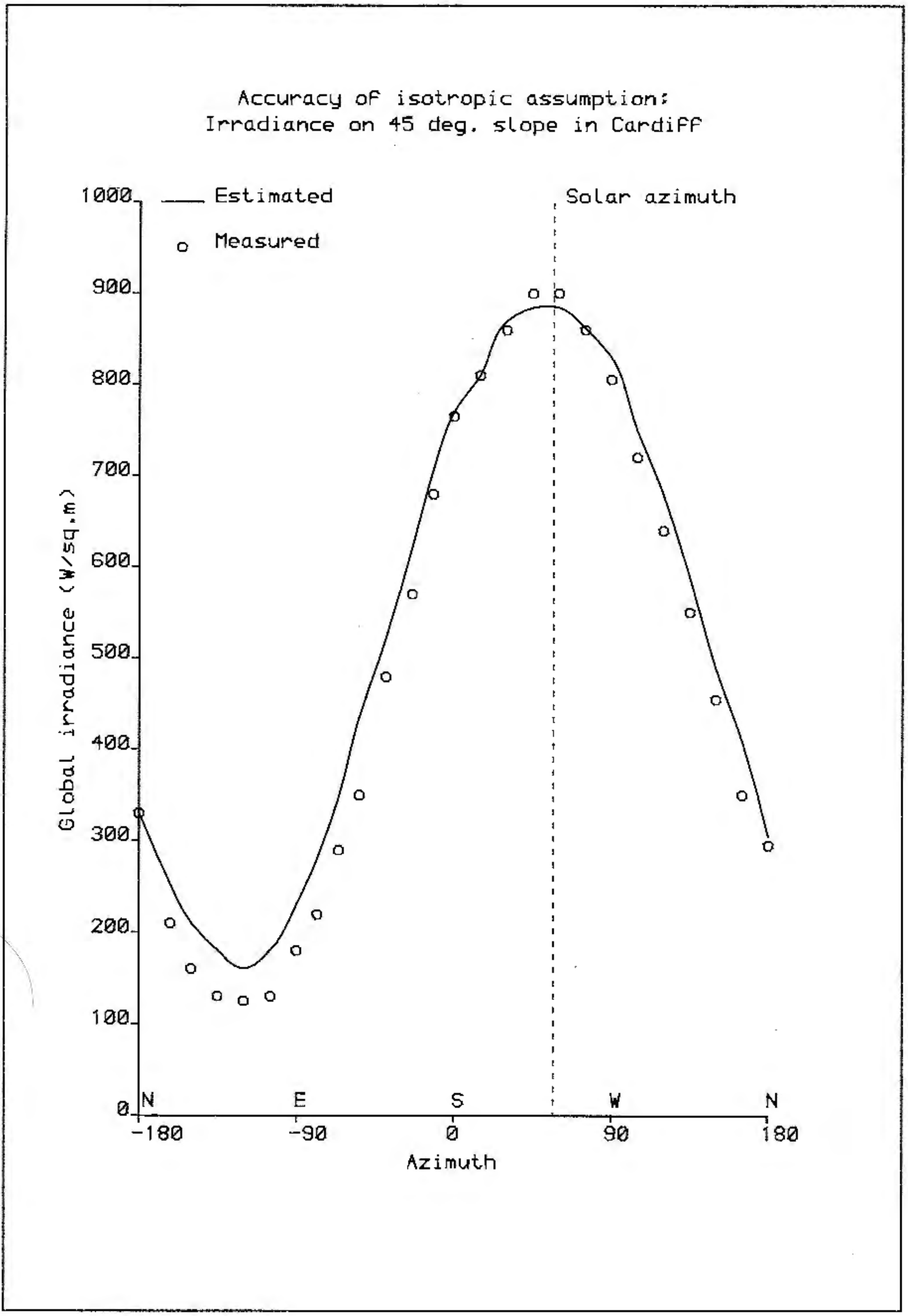

- Figure 1 -

(From: D.A. Svendsen, "The measurement of solar radiation", proc. UNESCO-NELP conf., 'Solar Building Technology', London, July 1977, pp 716-724, publ. RIBA Press, 1978.)