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Antarctic Skies
1. Diurnal Variations of the Sky Irradiance, and UV Effects of the Ozone Hole, Spring 1990

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This is the first of two papers reporting measurements made near Scott Base, Antarctica, during the spring of 1990 (October–November). The present paper describes the hourly and daily variations of the light falling on a horizontal surface, with the incident light divided into two components, that from the Sun directly and that from the sky. The light has been separated into four wavelength bands covering the blue to the UVB region of the spectrum. The intensities have been compared with values measured in Wellington, New Zealand. A simple air mass dependence has been found which fits the complete data set once a surface albedo parameter is taken into account, which provides an easy estimate for the daily average illumination throughout the year. The paper also correlates the changes in the UV and UVB with changes in upper atmosphere ozone concentration and compares the total daily UV dose in the Antarctic with that at Wellington, a typical mid-latitude site.

1. INTRODUCTION

There has been much speculation recently on the effects of changes in UV light levels resulting from the ozone hole in the sky above Antarctica on life in that region. For instance, contradictory views have been reported on the influence of enhanced UV radiation on the growth of sea ice algae, see for instance *Roberts* [1989]. Very few studies have been made of the characteristic properties of the radiation falling on Antarctica. *Baker-Blocker et al.* [1984] made the first wide band (300–380 nm) UV measurement at the south pole, while *Lubin and Frederick* [1989*a*, *b*] have pioneered the first studies of the Sun's spectrum measured in the Antarctic, part of the NSF monitoring program with UV spectrometers. These spectrometers monitor the total intensity falling on a horizontal surface and should provide detailed long term spectral data on UV levels. *Frederick and Snell* [1988] and *Lubin et al.* [1989] have made theoretical estimates on the amount of UV at McMurdo Station.

This is the first of two papers reporting measurements made near Scott Base, Antarctica (77.85°S) during the spring of 1990 (October–November). These were aimed at characterizing properties of the light from the Sun and the sky falling onto the Antarctic continent. The second paper [*Beaglehole and Carter*, this issue] describes the intensity and polarization distribution of the skylight and demonstrates the importance of the high snow surface albedo in determining these properties. The present paper describes the hourly and daily variations of the light falling on a horizontal surface, with the incident light divided into two components, that from the Sun directly and that from the sky. The light has been separated into four wavelength bands covering the blue to the UVB region of the spectrum. The intensities have been compared with values measured in Wellington, New Zealand (41.25°S). A simple air mass dependence has been found which fits the complete data set once a surface albedo parameter is taken into account and provides an easy estimate for the daily average illumination throughout the year. The paper also looks at the variation of the UV component through the spring and shows the effects of changes in the ozone hole on the UVB radiation reaching the Antarctic surface.

In our work we have used a three-filter detector monitor, measuring in the blue, the violet, and the ultraviolet. The latter region is subdivided into total UV and UVB using an auxiliary filter. The aim was to have a monitor that would show the presence of cloud cover from irregularity in the blue (B) record and to provide sufficient information in the violet (V) and UV to be able to separate changes due to ozone absorption from any changes due to aerosol scatter and absorption. In the Antarctic it has turned out that the skies are very pure, and this feature has not been used, though the trend through the blue to the ultraviolet provides some broadband spectral information.

2. IRRADIANCE MONITOR

The monitor has three interference filters. The filter characteristics are shown in Figure 1, along with the extraterrestrial solar spectrum. The blue filter is centered at 460 nm with a 10 nm band pass, the violet filter is centered at 370 nm with a 10 nm band pass, and the UV filter is centered at 300 nm with a 40 nm band pass. A narrower UV filter would have been desirable but was not found, so an auxiliary long-pass Schott WG320 filter could be placed in front of the UV filter, eliminating the UVB radiation, the measured residue being then essentially UVA. The response of the filter combination in the UV is quite subtle. Figure 2 shows the spectrum with and without the WG filter and the difference. The UVB and UVA intensities obtained in this way peak at 290 and 320 nm, respectively. However, it is important to take into account the effects of ozone adsorption in the UV region first. We have used the *Arveson et al.* [1969] Table 3 solar spectrum with minor corrections suggested by *Nicolet* [1981]. Figures 2*b* and 2*c* then show that the UVA peaks at around 330 nm, while the difference UVB peaks at around 310 nm.

The three filters were placed behind a 1-mm-thick Teflon diffuser which gave a good cosine response, and UV grade fused silica lenses were set at 1 focal length distance from

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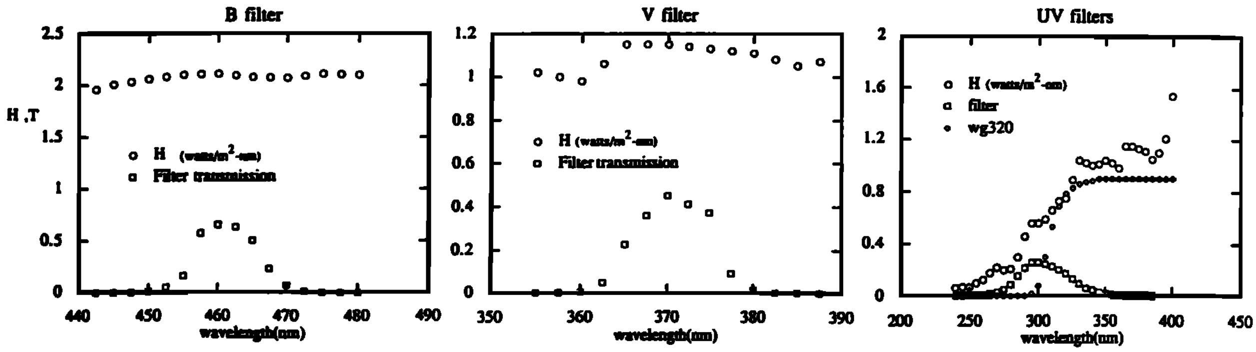

Fig. 1. The extraterrestrial solar intensity H and the passband transmission for the B, V, and UV filters.

Hamamatsu siicon photodetectors, so that only on-axis light passing through the filters would reach the detectors. A thin hemispherical shadow band could be placed over the monitor to shadow out the direct light, the fraction of the sky that it obscured being measured during heavy cloud when the radiation reaching the detector was isotropic. A heater was incorporated and the temperature of the inside of the monitor maintained at 25 ± 1°C.

The monitor was mounted with the top Teflon surface horizontal; a fraction of the direct sunlight greater than about 20% was shadowed by the edge of the monitor lid when the Sun's altitude was less than 10°. Note that in the violet and ultraviolet, direct sunlight is only a small proportion of the total irradiance.

The monitor output was stepped under computer control around the three detectors which were recorded and filed by the computer. The shadow band and auxiliary filter in this prototype required manual placement. Subsequent analysis gave the direct and indirect intensities falling onto the horizontal diffuser surface in the four wavelength bands; during the evening when the Sun's altitude was low, the three channels were recorded continuously without using the shadow band or auxiliary filter to give the total radiation in the UV, V, and B bands.

3. Monitor Measurements

A summary of the times of the monitor measurements is given in Table 1. The measurements described here are for clear skies. To illustrate the main features, we first compare the meridian values for both Wellington and Antarctic sites in Figure 3. There is a general trend in the irradiance as the spring develops, due to the increase in the Sun's noon altitude. There is one exception to that increase, which is the Scott Base UV irradiance which shows a decrease on day 314 (November 10), due to the filling in of the ozone hole that occurred at that time (section 6). The levels of irradiance in the Antarctic at solar noon can be seen to be about half of those in Wellington. The most dramatic difference between the Wellington and Antarctic sites is the relative strengths of the direct and indirect radiation, Figure 4, the indirect being much stronger than the direct in the violet and ultraviolet in the Antarctic and much weaker than the direct in Wellington. This change in dominance between the direct and indirect radiation is due partly to the low Sun altitude in the Antarctic, but it is also affected by the high snow surface albedo (see below).

Detailed properties of the illumination are described in the next sections. We show that the average daily illumination is about half of the solar maximum. The direct illumination is shown to vary exponentially with air mass, with an attenuation coefficient which is fairly strongly wavelength dependent but not simply that of a Rayleigh atmosphere. The dominant (at shorter wavelengths) indirect radiation does not follow the same law. Rather, a simple power law is shown to fit the total illumination over a very wide range of air mass.

TABLE 1. Measurements With the Monitor 1990

Date	Day	Location	Time, NZST	Solar Noon, NZST	Ozone Level* Arrival Heights, Near Noon, DU
October 18	291	Wellington	1100–1483	1212	
October 26	299	Scott Base, snowing			
October 27	300	Scott Base	0822–1846	1235	171
October 29	302	Scott Base	meridian	1235	151
October 31	304	Scott Base	meridian	1235	166
November 3	307	Scott Base	0933–3200	1235	176
November 10	314	Tent Island, 25 km north of Scott Base	0833–2650	1235	353
November 26	330	Wellington	1050–1225	1215	
December 4	338	Wellington	0592–1300	1218	

Hours past 24 correspond to the following day.

*I am grateful to Sylvia Nicol of the New Zealand Meterorological Service for these values. DU, Dobson units.

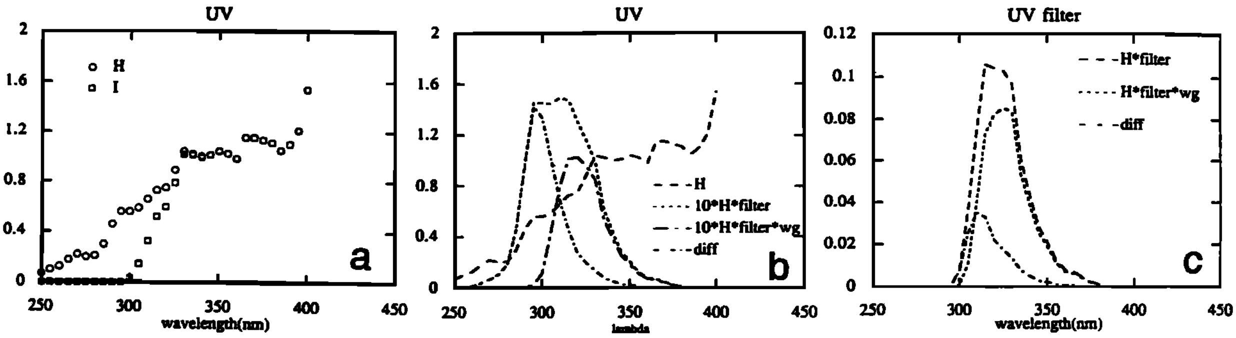

Fig. 2. (*a*) The extraterrestrial UV solar spectrum H and as modified by absorption in passage through 350 DU of ozone I. (*b*) Decomposition of the extraterrestrial spectrum using the auxiliary WG320 filter. (*c*) Decomposition of the ozone-modified spectrum using the auxiliary filter.

3.1. *Hourly Variation and the Average Day Illumination*

A typical monitor recording of direct, indirect, and evening total is shown in Figure 5. This example was recorded at Scott Base on November 3, 1990, for 24 hours. (We use New Zealand standard time, which is 12 hours ahead of GMT.) This day is well into spring time, and the Sun does not sink below the horizon. Some light clouds affected the intensities near the end of the recording period (hours past 24 correspond to November 4). The total intensity follows approximately a sine function, so that a 24-hour average intensity is approximately half the maximum intensity when the Sun is at meridian. The total intensities were also measured on a thick cloud and falling snow day October 26 and the following day which was clear. The recorded intensities at the meridian during snow were about 80% of total clear sky intensities for all three channels.

3.2. *Altitude Variation of the Direct Intensity*

The illumination of the horizontal monitor by light falling directly from the Sun must vary in the first instance as sin α, where α is the Sun's altitude. It must also vary as $\exp(-Kz)$ where z is the path length through the atmosphere and K is a wavelength dependent extinction coefficient. For a planar atmosphere $z = z_0/\sin \alpha$, z_0 being the zenith thickness. It is customary to write the air mass m as $m = z/z_0$ in units of the zenith thickness, so that the extinction varies as $\exp(-\kappa m)$, with $\kappa = Kz_0$. Refraction and the curved atmosphere give corrections to the path length. These are summarized by *Paltridge and Platt* [1976], and we have used the *Kasten* [1966] and *Kasten and Young* [1989] approximation for an improved air mass m_K. Together we might expect the direct intensity to vary as

$$mI_d = I_{d0} \exp(-\kappa_d m_K).$$

This function fits well not only the daily variations at Wellington (mid-October and early December 1990) and Scott Base separately but also the combined data, Figure 6. Table 2 lists the exponents κ and the scaling intensities I_{d0}: these signal levels are specific to the monitor (the calibration will be described below). The UVB data are clearly more scattered than the other, partly because the signals are small but mainly due to changes in the UV spectrum, see below, and have not been fit.

The wavelength variation of these extinction coefficients $\kappa_d \propto \lambda^{-\alpha}$ has $\alpha \sim 2.5$. Pure Rayleigh scattering would give $\alpha = 4$, while most measurements [*Paltridge and Platt*, 1976] find α in the range 1–2. The larger value is an indication of the atmosphere purity.

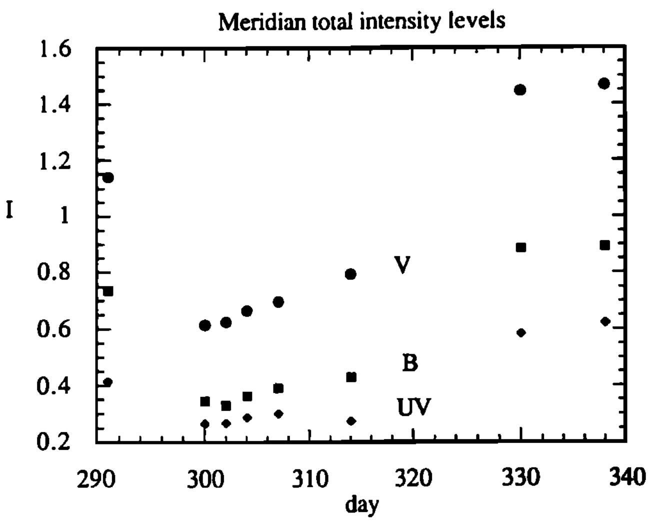

Fig. 3. The meridian (solar noon) total intensity levels at Wellington and Scott Base (days 300–314).

3.3. *Altitude Variation of the Indirect and Total Intensity*

The indirect intensities vary strongly with latitude and wavelength, in Wellington the ultraviolet being about 10% and in the Antarctic about 500%, of the meridian direct intensities, the air masses being around 1.2 and 2.5, respectively. During the day at each site the indirect intensity also varies with air mass. If we plot ln (I_i) versus m_K, it is seen that the Wellington and Scott Base data cluster separately, so that no simple function of m_K will give a unifying plot. An

TABLE 2. Least Squares Fitting of Direct and Indirect Intensities to the Functions given in the Text

	$I_{d0}(v)$	κ_d	$I_{i0}(v)$	κ_i	β	I_{d0}/I_{i0}
UVA	1.0	1.0	0.42	0.40	1.6	2.4
UV	1.04	0.91	0.51	0.41	1.5	2.0
V	2.39	0.67	0.88	0.37	1.6	2.7
B	1.23	0.37	0.21	0.19	1.53	5.8

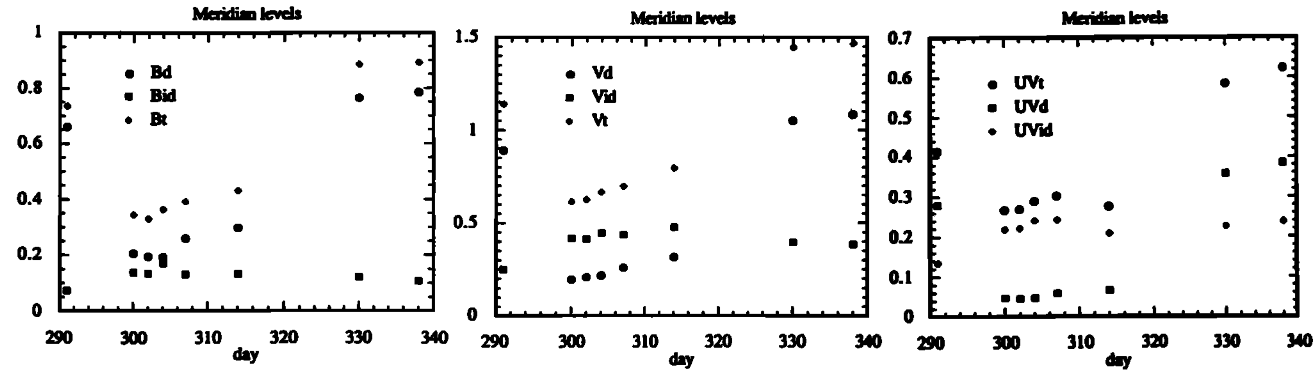

Fig. 4. The meridian levels separated into solar direct, sky indirect, and total intensities.

example is shown in Figure 7. It can be seen that a scaling factor β (which we will interpret later as an albedo factor) equal to about 1.5 for the Wellington data (taken as 1.0 for Antarctic data) brings the data into uniformity. The fitting constants for the function

$$\beta I_{id} = I_{i0} \exp\,(-\kappa_i m_K)$$

as listed in Table 2, but the quality of the log linear fit is not good at larger values of air mass.

The direct Sun was low and weak during the evening, so only total intensities were recorded between 2000 and 0800 LT. These match smoothly on to the daytime indirect measurements but follow a slower variation with air mass, see for instance Figure 8, with the variation apparently the same for all wavelengths.

It is clear that a simple log linear fit does not represent the data over the range of air masses encountered in the Antarctic. It seemed desirable to check other functional variations for the total and indirect radiation, to attempt to unify the evening with the daytime variations. A power law variation of βI_t versus m_K was found to fit all the combined day and evening data over the complete range of air mass, with a slope of between -1.5 and -1.6 for all wavelengths. The data are shown in Figure 9, and the fitting constants I_0 and ε in the expressions $\beta I_t = I_0 m_K^{\varepsilon}$ are given in Table 3. The separate UVA and UVB totals do not have the extended

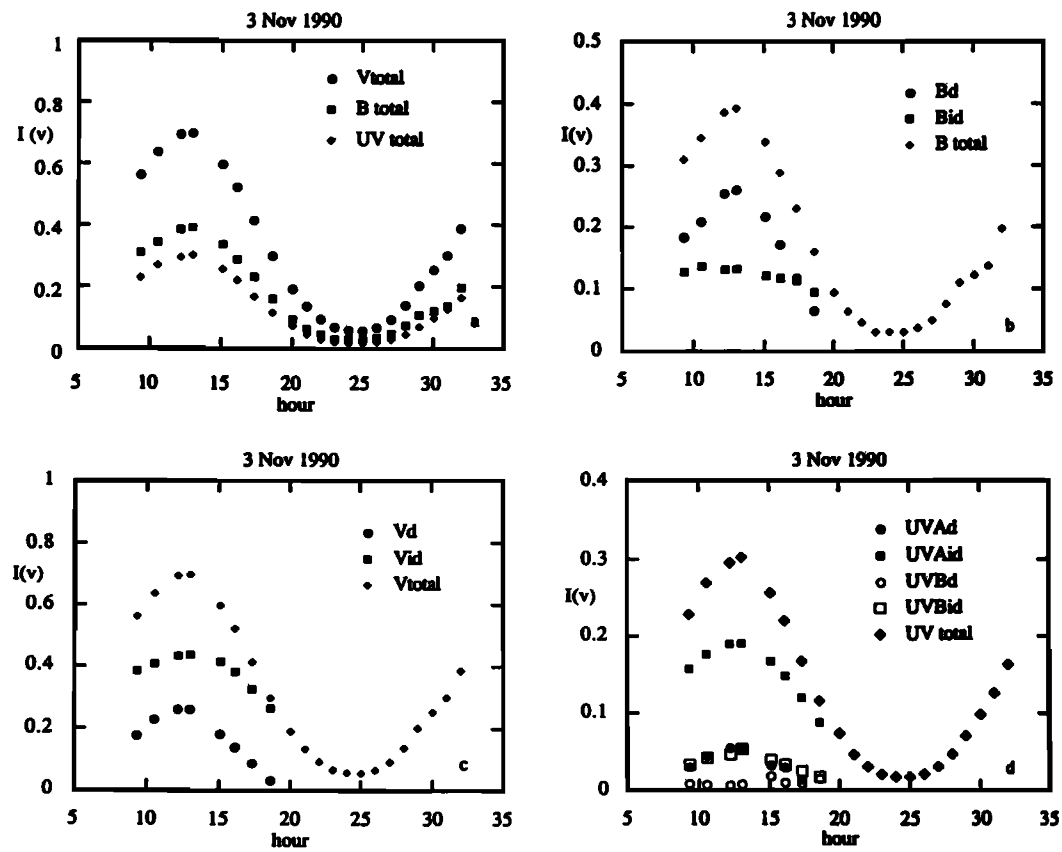

Fig. 5. A typical daily variation (cloudless skies) of the irradiance at Scott Base divided into direct and indirect intensities.

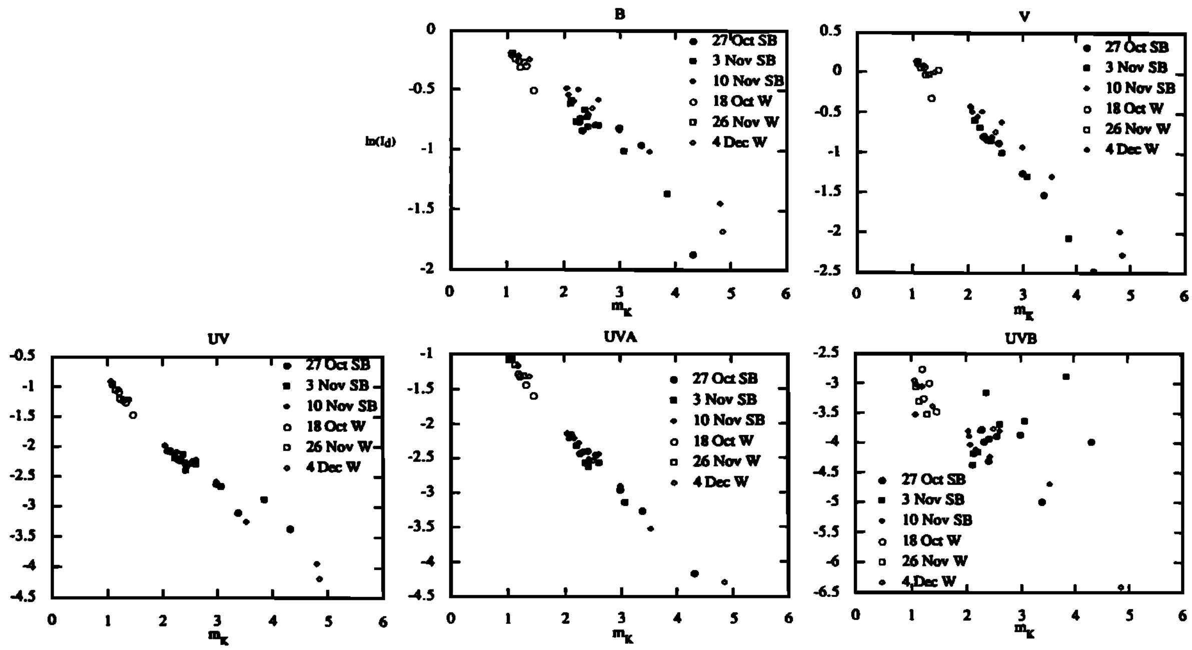

Fig. 6. The ln (I_d) versus m_K, open symbols Wellington, solid symbols Scott Base.

evening range and are also more scattered and have not been fit separately.

This empirical rule for the variation of the total irradiance makes it very easy to calculate the variation of the daily averages of the total irradiance throughout the year, which are needed to determine the growth rates for algae and other photosensitive biological organisms. (The total intensity can then be divided into its two components: the exponential variation for mI_d provides the component coming directly from the Sun, and the difference between this and I_t gives I_{id}.) In Figure 10 we show the daily average for the total intensity calculated for Scott Base and for Wellington throughout the year; this of course is symmetric around day 355, and only the spring variation is shown. The calculation has assumed that the Sun's spectrum remain constant, taking into account only the air mass variation of the intensity. The Sun's altitude has been calculated throughout the day, the corresponding air mass attenuation estimated, and the average performed over a 24-hour period. The average has been normalized by $I_{\max} \times 1$ day, where $I_{\max}$ is

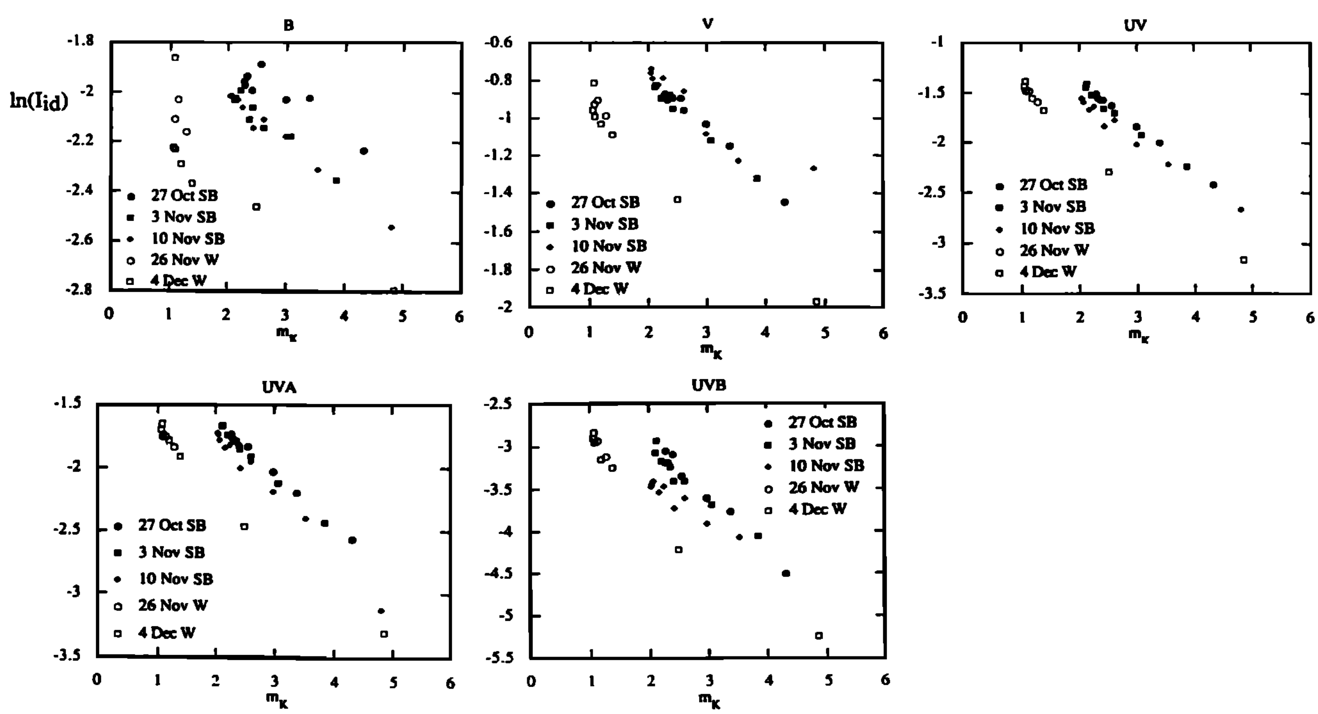

Fig. 7. The ln (I_{id}) versus m_K. Note that the Wellington and Scott Base data cluster separately.

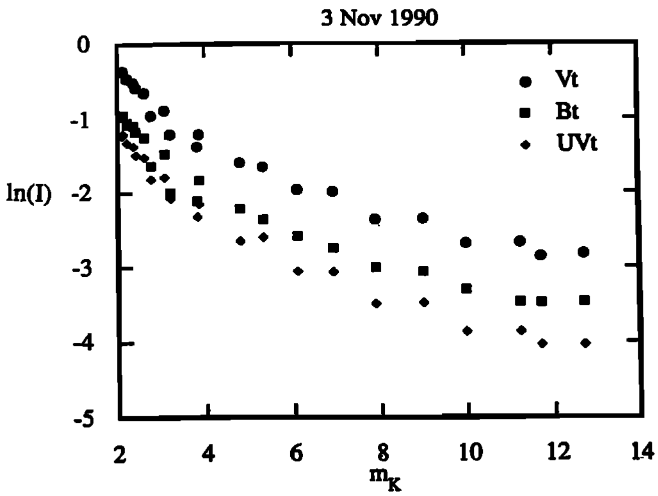

Fig. 8. The ln (I_t) versus m_K including the evening skies. An exponential dependence of I_t on air mass is not observed.

the intensity if the Sun were on the zenith, so that for instance on day 355 the average intensity throughout the day is about 1/4 of the maximum intensity. Around the end of October ($N \sim 300$) the daily average in Scott Base has reached about half the maximum value found at the end of the year.

4. The Surface Albedo

In order to assess the surface albedo at Tent Island (a few inches of snow covering sea ice) the monitor was inverted and the ratio of the upward to downward total flux recorded. This ratio was about 83% in the UV, 88% in the V, and 91% in the B, with a consistency of a few percent over several measurements on several days. A very large fraction of the downward flux is thus reflected from the surface. These values agree reasonably well with the value of 80% (wavelength independent) quoted by Paltridge and Platt (p. 129), for fresh snow surface.

TABLE 3. Fitting $\beta I_t = I_0 m_K^{\varepsilon}$ for All Data, With $\beta = 1.5$ for Wellington, 1.0 for the Antarctic

	$I_0(v)$	ε
UV	1.0	1.50
V	2.46	1.6
B	1.49	1.50

5. Calibration

The detector constant I_0 obtained by extrapolating the air mass intensity variations to zero air mass gives the signal that would be recorded if there were no air in the light path, i.e., the extraterrestrial sunlight. This spectrum is relatively well known and provides an easy method to calibrate the detectors in the V and B. We have used the Arveson et al. Table 3 solar spectrum with minor corrections suggested by Nicolet to obtain the extraterrestrial spectra shown in Figure 1 and have calculated the energy lying within the filter pass bands ($\int H(\lambda)T(\lambda)\, d\lambda$, with filter transmission response $T(\lambda)$ normalized to unity at peak transmission), as listed in Table 4. This procedure is unreliable for the UV region due to the strong ozone absorption which alters the solar spectral shape as a function of air mass. The calibration would be accurate in the limit of small air mass, but the I_0 values obtained by extrapolation from larger air masses are generally low. A better procedure would simulate the actual spectrum using the ozone extinction coefficients over the range of air masses found in the field, in this way finding an

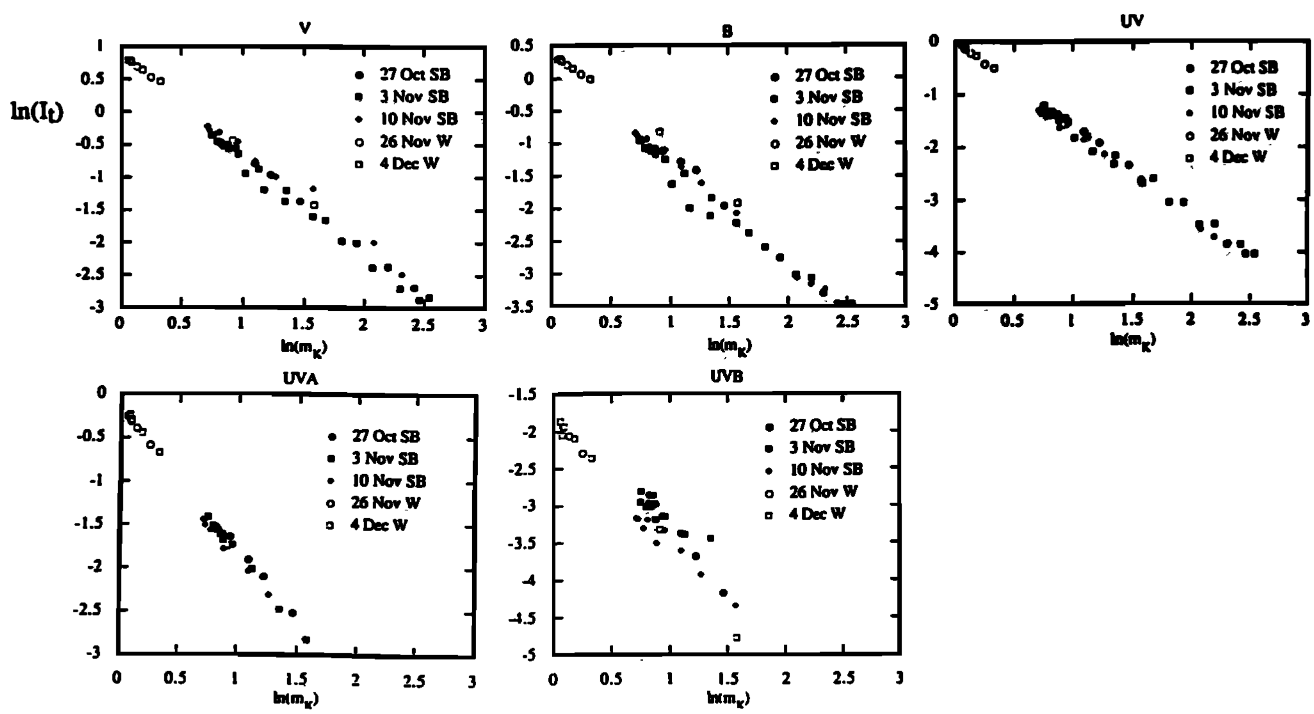

Fig. 9. The ln (βI_t) versus ln (m_K). The linear variation indicates the empirical power law relation between total intensity and air mass. $\beta = 1.5$ for Wellington and 1 for Scott Base.

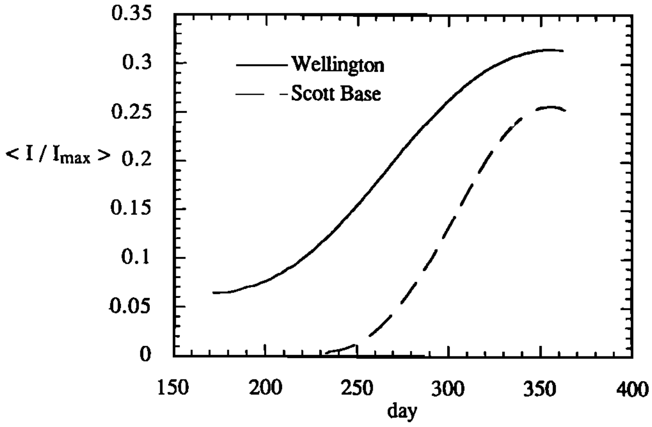

Fig. 10. The daily average of total irradiance, normalized by the intensity if the Sun were on the zenith, through the year for Wellington and Scott Base. Calculated from the empirical air mass dependence of the total irradiance.

effective solar radiation constant. For the present work an absolute calibration has not been needed, so this procedure has not been carried out. The ozone-modified spectrum was shown in Figure 2 calculated for transmission through 300 DU = 0.3 cm at NTP ozone concentration.

6. EFFECTS OF THE OZONE HOLE IN THE UV

Figure 11 shows the variations of the total irradiance (sun plus sky) measured at the solar noon through the spring period. Days with no data suffered cloud cover. We have plotted also the ozone concentration in Dobson units measured at Arrival Heights, Antarctica, near Scott Base; we are grateful to Sylvia Nicol of the New Zealand Meteorological Service for these data. It can be seen that there is a steady increase in all bands as the spring progresses as the Sun gains a higher altitude at noon. There is only one exception to this trend, which occurred on November 12, which is directly correlated with the dramatic increase in ozone on that day. The total UVB level at noon that day was about half that estimated from the trend, the total UVA about 0.8 of the value estimated from the trend. Since the ozone level on previous days was typical of the ozone hole and on November 12 typical of a normal level, we see that the hole increases the UVB by approximately a factor of 2.

In section 3 we showed that daily averaged illumination on day 300 was approximately half the maximum reached at midsummer (December 26) provided the Sun's spectrum remained unchanged. Following the filling in of the ozone hole, the UV level should roughly double to midsummer and thus reach a level then equal to that just prior to the filling in of the hole. This conclusion substantiates the measurements by *Lubin and Frederick* [1989*b*] who reported UV intensities at Palmer Station having values in October equal to those in December.

It should be noted, see Figure 12, that in Antarctica following the spring solstice around day 300 the daily averaged UV intensity level is about half that at noon, while in Wellington the daily averaged intensity is about one third the noon level. From Figure 11 we see that the ratio of total UV in Wellington to that in Scott Base (enhanced by the ozone hole) is a factor of 1.5, the ratio of total (enhanced) UVB a factor of 1. Therefore during 1 day the accumulated UV dose experienced on the surface near Scott Base during the spring ozone hole is about equal to the 1-day dose on the surface at Wellington, the UVB dose about 1.5 times the dose at Wellington.

TABLE 4. Calibration of Filters

Filter	Center Wavelength, nm	Band Pass, FWHM nm	I_0, volts	H, watts/m^2
B	460	10	1.23	23.4
V	370	12	2.39	12.5
UV	310	43	1.04	28.0
UVA	320	36	1.0	14.7
UVB	295	18		13.3
	Ozone-Modified Spectrum			
UVA	325	30		
UVB	310	20		

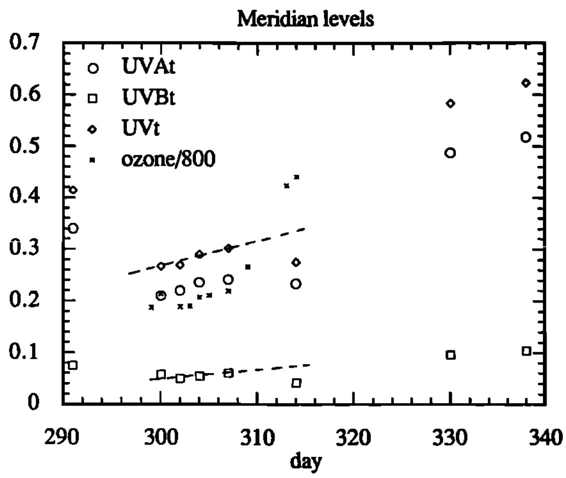

Fig. 11. The figure shows the total UV, UVA, and UVB signals at solar noon near Scott Base, Antarctica, during the spring, as well as the ozone concentration in Dobson units (DU) (scaled by a factor 800). Note the trend to increasing intensity as the spring progresses. Antarctic measurements between days 300 and 314.

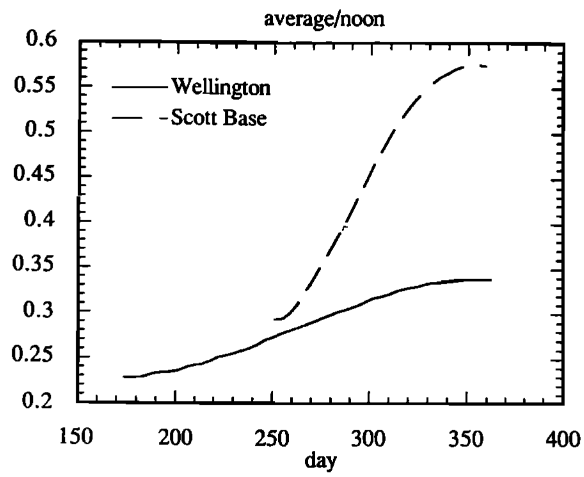

Fig. 12. The ratio of the day-averaged total intensity to the noon intensity, calculated from air masses using the empirical power law variation.

7. SUMMARY

The main results of these measurements are summarized as follows:

(1) The Sun noon intensities in the Antarctica are about half those of a mid-latitude site, Wellington. The daily average in the Antarctic is therefore about equal to that in Wellington as the summer develops later than the spring solstice.

(2) In Antarctica the total irradiance in the violet and ultraviolet is dominated by light from the sky rather than directly from the Sun.

(3) The air mass variation of the total irradiance follows a simple power law variation. When a suitable albedo factor is also taken into account, this variation predicts irradiance levels for both Wellington and Antarctica. This has been used to calculate the daily mean irradiance throughout the year at the latitude of Scott Base.

(4) The ozone hole in early spring caused an increase in the UVB irradiance of about a factor of 2, and in the Antarctic the daily dosage was about a factor of $1\frac{1}{2}$ that received at Wellington.

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