Mem. Natl Inst. Polar Res., Spec. Issue, **52**, 122–134, 1998

SURFACE UV RADIATION ENVIRONMENT OVER THE ANTARCTIC: ROLE OF SURFACE AND CLOUD PROCESSES

Catherine GAUTIER[1,2], Paul RICCHIAZZI[1] and Shiren YANG[1]

[1] *Institute for Computational Earth System Science, University of California Santa Barbara*
[2] *Geography Department, University of California Santa Barbara,*
6832 Ellison Hall, Santa Barbara, CA 93106, U.S.A.

Abstract: This paper presents a review of a body of research regarding the UV environment over Antarctica. In particular, it explores the role of surface and cloud processes and their coupling on the highly variable UV radiation field.

The main results of this research are that: (1) clouds may play a role on mitigating the effects of ozone decrease on the UV radiation through coupling with surface processes due to multiple reflections between the surface and clouds, (2) mapping of UV from space is still limited by our inability to detect clouds over highly reflective surfaces and (3) cloud-surface reflection interaction can affect both satellite and surface data interpretation in coastal regions due to multiple reflections between clouds and surface processes.

1. Introduction

The atmospheric environment over the Antarctic is not only harsh at the surface but it is also rather difficult to investigate from space due to low solar illumination and low temperatures, that make it challenging to quantitatively monitor the surface and lower atmosphere with the high resolution sensors on operational satellites. With regards to the UV radiation environment, the highly reflective snow and ice surfaces induce an increase in scattering that enhances the influence of surface properties, in both clear and cloudy skies. Coupled with dramatic changes in ozone concentration, these surface effects strongly affect the UV radiation field.

In this paper we review some recent results regarding the variability of surface UV radiation as determined from surface and satellite measurements and the effects of surface and clouds have on this variability. These results are presented in the context of the impact of UV radiation variations on the marine ecosystems.

2. Surface UV Radiation Changes

2.1. Overview

Dramatic changes in the surface UV radiation environment have been observed over the Antarctic, mostly resulting from changes in stratospheric ozone. Radiative transfer computations straightforwardly show that stratospheric ozone concentration decrease induces an increase in surface UV radiation. These results have been confirmed with surface measurements at different stations over the Antarctic (Stamnes *et al.*, 1988; Lubin, 1989; Lubin *et al.*, 1989a, b). Cloud and surface processes, however, can modulate these UV radiation changes dramatically by reflecting the incoming radiation, and also trapping it through multiple reflection processes. So the combined effects of cloud and surface processes are not straightforward and their impacts on the radiation environment that is relevant to the marine ecosystems can be quite complex. Indeed, biological production in the maritime Antarctic is affected by the ratio of irradiance in the UVB band to that in the UVA or PAR radiation bands (Smith and Cullen, 1995). This is because some of the damaging effects of UVB photons can be erased by DNA repair mechanisms which are powered by UVA or PAR photons. Whereas the presence of opaque clouds certainly reduces the UVB, UVA and PAR irradiance, the effect these clouds have on the UVB/UVA or UVB/PAR irradiance ratios depends on the nature of the surface-cloud interaction.

Below, we show that under some circumstances, clouds have the potential to partly mitigate the damaging effects of ozone depletion on the Antarctic marine ecosystems (Gautier, Ricchiazzi and Yang, 1996, later on referred to as GRY).

2.2. *Method*

In order to investigate the role of clouds on the surface UV radiation environment, GRY applied a combined observations and modeling approach. They used observations made by the NSF/UV spectroradiometer (Booth *et al.*, 1995) deployed at Palmer Station, Antarctica (64°46′S, 64°04′W). In addition microwave observations from the SSM/I sensor aboard the DMSP satellite were used to estimate the ice aerial coverage for the south west coast of Anvers Island. To distinguish the cloud effect from the strong modulating effects of the total ozone, a retrieval technique was developed which simultaneously retrieves column ozone and cloud opacity. The retrieval technique is based on the idea that atmospheric transmission for pass-bands in the UVA and UVB differ in their response to overcast and ozone. The UVA irradiance responds to changes in cloud thickness but is relatively insensitive to the ozone column amount, while a UVB band is sensitive to both ozone and clouds. The differing response of these wavelength bands to clouds and ozone provides the leverage required to make the retrievals. A detailed plane-parallel radiative transfer code was used to relate irradiance to cloud optical depth and total ozone amounts (Ricchiazzi *et al.*, 1997). The model calculations were carried out over a wide range of solar zenith angle, surface snow fraction, cloud optical depth, and ozone amount. Setlow's biological action spectra (Setlow *et al.*, 1993) was used to characterize the degree of DNA damage expected from a given UVB spectra. The UVB irradiance convoluted over Setlow's action spectra will be denoted as the "DNA" band. Measurements in a narrow band centered at 345 nm are taken to represent the UVA radiation unaffected by ozone absorption and is used with radiative transfer (RT) model results to get a first guess at the cloud optical depth. The final values of cloud optical depth and ozone amount are a result of a simultaneous retrieval consistent with measurements in the DNA and UVA (345 nm) bands. The ozone retrievals based on this approach agree well with satellite estimates. No direct measurements of total ozone were available for comparison. Total ozone from TOMS (solid line) and the surface retrieval (dotted line) are shown

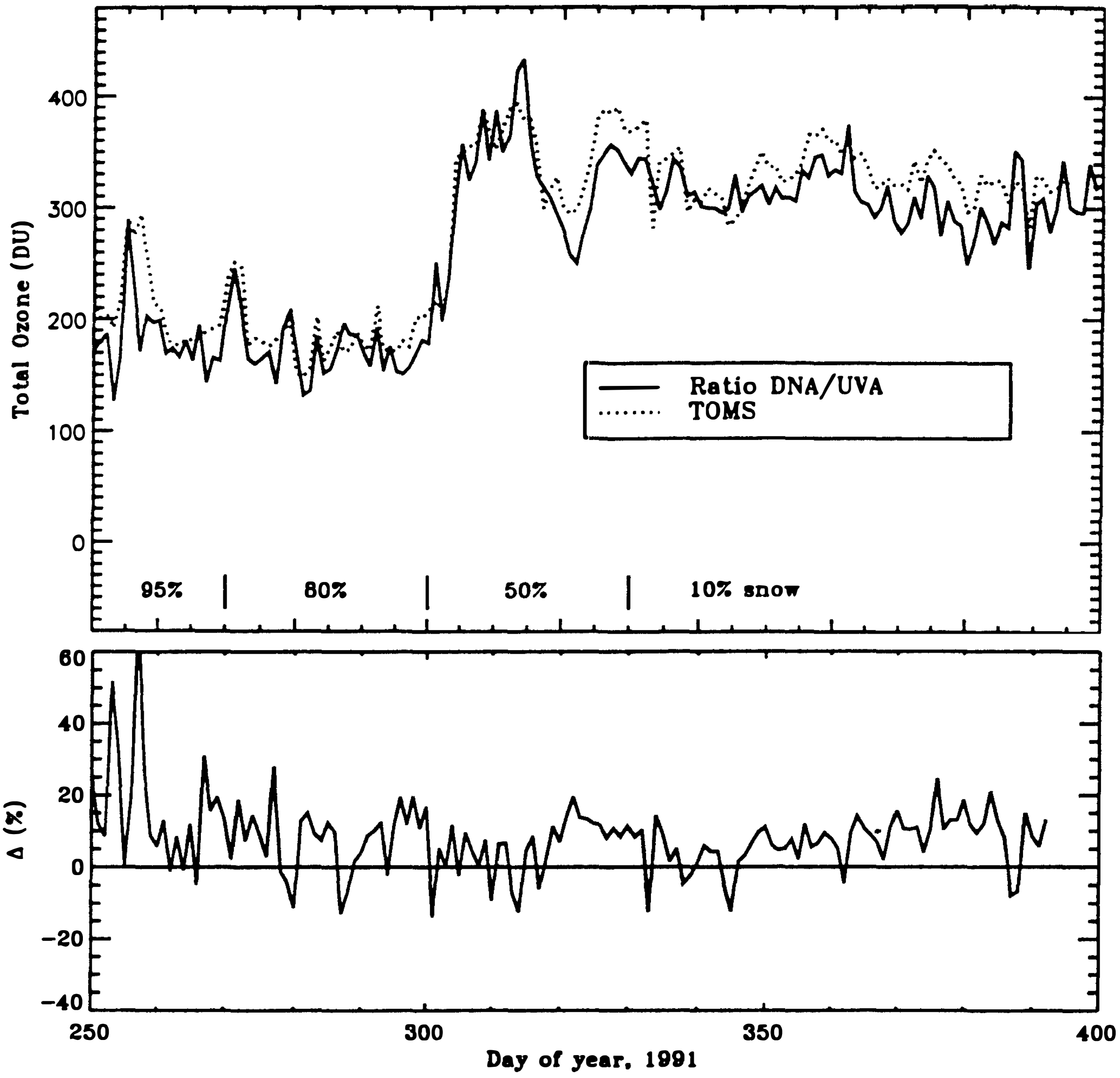

Fig. 1. *The total ozone from TOMS (solid line) and the surface retrieval (dotted line) for the austral spring of 1991.*

in Fig. 1 for the austral spring of 1991. The slightly smaller ozone amounts from TOMS may be explained by: 1) the coarse spatial resolution used in the satellite retrievals, 2) 3-D cloud morphology, or, 3) to an underestimate of the surface albedo due to the coarse spatial resolution of SSM/I.

2.3. *Results*

To evaluate the strength of the cloud effect, GRY considered the ratio of DNA/UVA divided by the same quantity in clear sky conditions (normalized DNA/UVA ratio). Dividing through by the clear sky ratio suppresses sensitivity to changes in stratospheric ozone. Figure 2 shows the normalized DNA/UVA ratio and the cloud transmission for the austral spring of 1991. The surface fraction of snow/ice estimated from SSM/I (at the coarse resolution of about 40 km) is indicated along the x-axis and

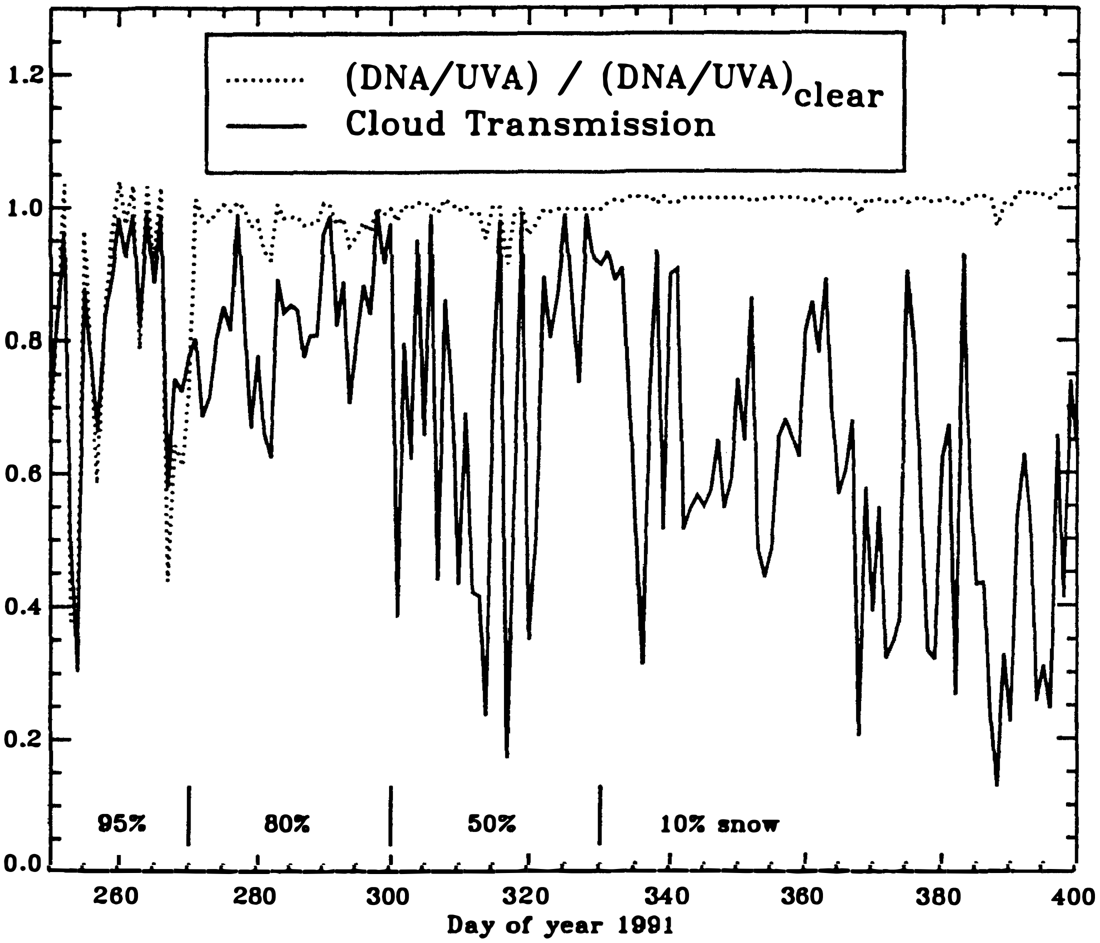

Fig. 2. Normalized DNA/UVA ratio and the cloud transmission for the austral spring of 1991.

varies from 95% around day 270 to less than 10% after day 330. The correlation between the normalized ratio and cloud transmission is seen to be strong only for the time interval for which the surface fraction of snow/ice is above 95%. Figure 3 shows the normalized DNA/UVA ratio versus cloud transmission selected according to surface condition. The sensitivity of the normalized DNA/UVA ratio to the cloud transmission drops significantly for snow/ice fractions less than 60%. Radiative transfer model calculations were also performed to investigate how the normalized DNA/UVA ratio depends on cloud optical depth for a range of hypothetical surface and atmospheric conditions. The results are shown in Fig. 4. The cloud effect virtually disappears when the snow fraction or the amount of tropospheric ozone is set to zero (in all cases the amount of stratospheric ozone is held fixed at 310 DU; the nominal tropospheric ozone amount was that of the McClatchy, 1972 subarctic summer atmosphere). The normalized DNA/UVA ratio decreases with increasing cloud optical depth most strongly for high clouds over a 100% snow surface. The strength of the effect does not depend on the spectral variation of the snow albedo. When the snow albedo is fixed at 0.97—a value midway between the pure snow albedos at 300 nm and 350 nm that are obtained by Wiscombe and Warren (1980) in their model computations

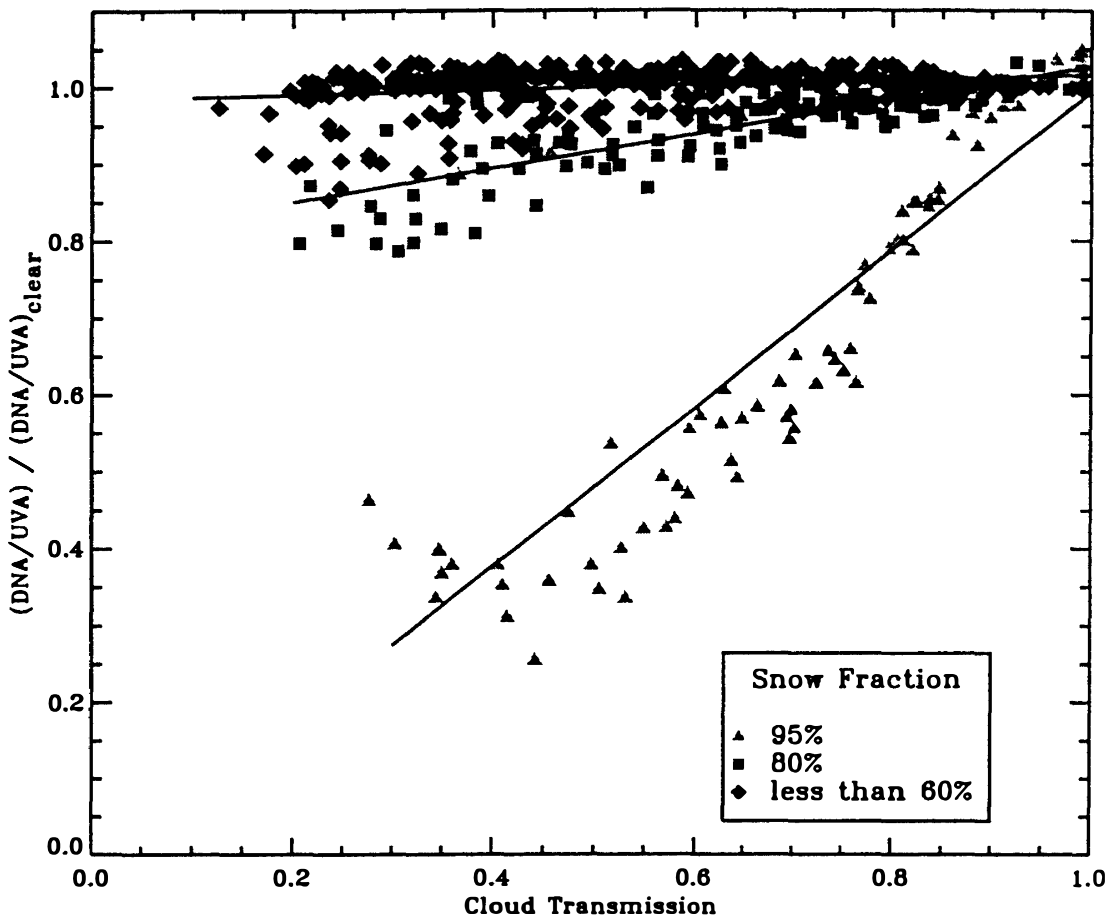

Fig. 3. Normalized DNA/UVA ratio versus cloud transmission selected according to surface condition.

with snow effective radius of 125 μm—the reduction is very close to that obtained using the observed spectral albedo of snow. Evidently, clouds over a highly reflective surface amplify the absorption of UV by tropospheric ozone. Because snow reflectivity is very large for these UV wavelengths, the photons which do manage to penetrate the cloud layer will undergo multiple reflections between cloud and surface. Assuming a simple two stream radiation model, the net transmission to the surface is given by:

$$T=\frac{T_{\mathrm{clr}}(1-A_{\mathrm{c}})}{1-T_{\mathrm{bc}}^{2}A_{\mathrm{s}}A_{\mathrm{c}}}, \qquad (1)$$

where A_{c} is cloud albedo, A_{s} is the surface albedo, T_{bc} is the transmission (excluding multiple scattering effects) below the cloud layer, T_{ac} is the transmission above the cloud layer, and T_{clr} is the clear sky transmission ($T_{\mathrm{clr}}=T_{\mathrm{ac}}\,T_{\mathrm{bc}}$). The ratio of transmission in the DNA and UVA band, normalized by the clear sky transmission ratio, is then given by,

$$\left[\frac{T_{\mathrm{DNA}}}{T_{\mathrm{UVA}}}\right]\left[\frac{T_{\mathrm{UVA}}}{T_{\mathrm{DNA}}}\right]_{\mathrm{clear}}=\frac{1-A_{\mathrm{s}}A_{\mathrm{c}}}{1-A_{\mathrm{s}}A_{\mathrm{c}}T_{\mathrm{bc}}^{2}}. \qquad (2)$$

In this equation T_{bc} is taken to be the below cloud transmission in the DNA band (T_{bc}

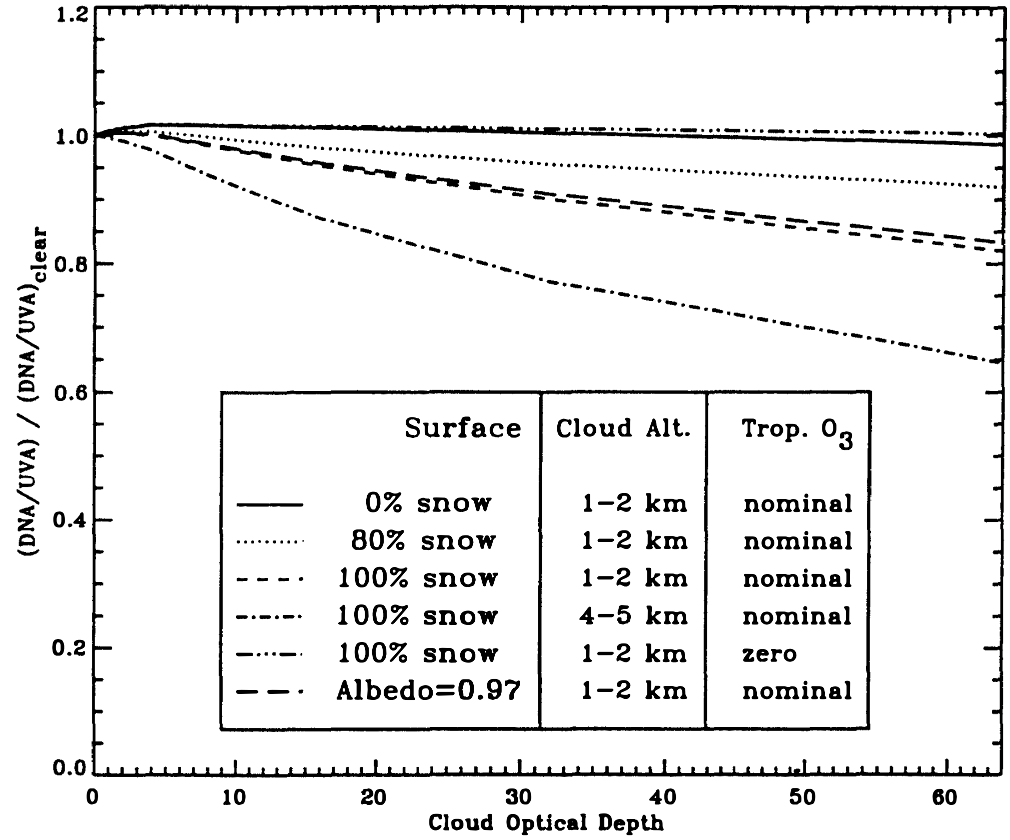

Fig. 4. Theoretical dependence of the DNA/UVA ratio on cloud optical depth for different cloud heights and tropospheric ozone amount.

(UVA) is assumed to be very close to one). It is also assumed that the cloud and surface albedo do not vary over the DNA and UVA regions. This formula indicates why the cloud effect is only important over a highly reflective surface. Only when the product of the surface albedo and the cloud albedo is close to 1 does the value of T_{bc} (DNA) becomes important.

2.4. Implications

The reduction of the normalized DNA/UVA ratio under clouds also has implications for surface retrievals of total ozone and for the impact of ozone depletion on surface UV radiation. For surface retrievals at Palmer Station, the current practice (Lubin and Frederick, 1990; Booth *et al.*, 1995) is to assume the aerial coverage of snow/ice is less than 50% and to use the ratio of narrow lines at 300 and 313.5 nm to obtain the ozone amount. However, when snow covered sea ice surrounds the station the effective surface albedo can be well above 90% (Ricchiazzi *et al.*, 1995). In this case, clouds can greatly amplify absorption by tropospheric ozone, causing the surface retrievals to overestimate the ozone amount. Figure 5 shows the amount of overestimate for actual ozone amounts of 150, 250 and 350 DU, and for 100% snow surface fraction. The overestimate becomes more serious for high clouds because of the additional ozone below the cloud. This analysis indicates that the current procedures

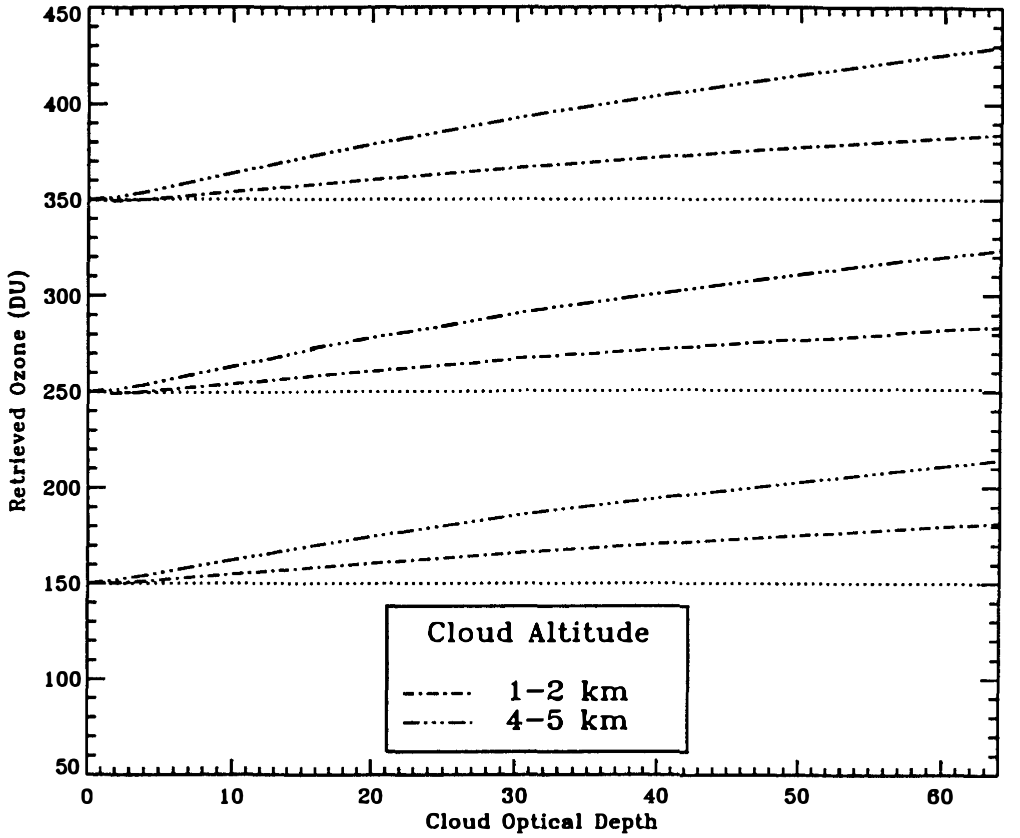

Fig. 5. Retrieved ozone amount over 100% snow covered surface as a function of optical depth. These results are for actual ozone amounts of 150, 250, and 350 Dobson units, and for low (1–2 km) and high (4–5 km) clouds. The discrepancy between the retrieved and actual ozone amounts is greater for higher clouds due to the enhanced tropospheric ozone absorption between the surface and cloud.

used for surface ozone retrieval are only appropriate under clear skies or when the snow fraction is below about 70%. Since cloud cover is a ubiquitous feature of the maritime Antarctic, this limitation implies that current procedures cannot be used during the early parts of the austral spring when the snow/ice cover is widespread. It is during this time that biological production is most vulnerable to damage caused by stratospheric ozone depletion. For this period, it is crucial to develop techniques to predict how UV-B dose to UV-A ratio responds to the combined effects of clouds, surface conditions and tropospheric ozone.

3. Mapping UV from Space

3.1. Overview

Changes in the Antarctic surface UV and PAR radiation environment cannot be investigated from surface measurements solely because of their lack of spatial coverage. Only space observations can provide the coverage necessary to address continent wide issues. Lubin, Ricchiazzi and Gautier (later referred to as LRG, 1993) have produced preliminary maps of surface UV radiation for the Antarctic continent and

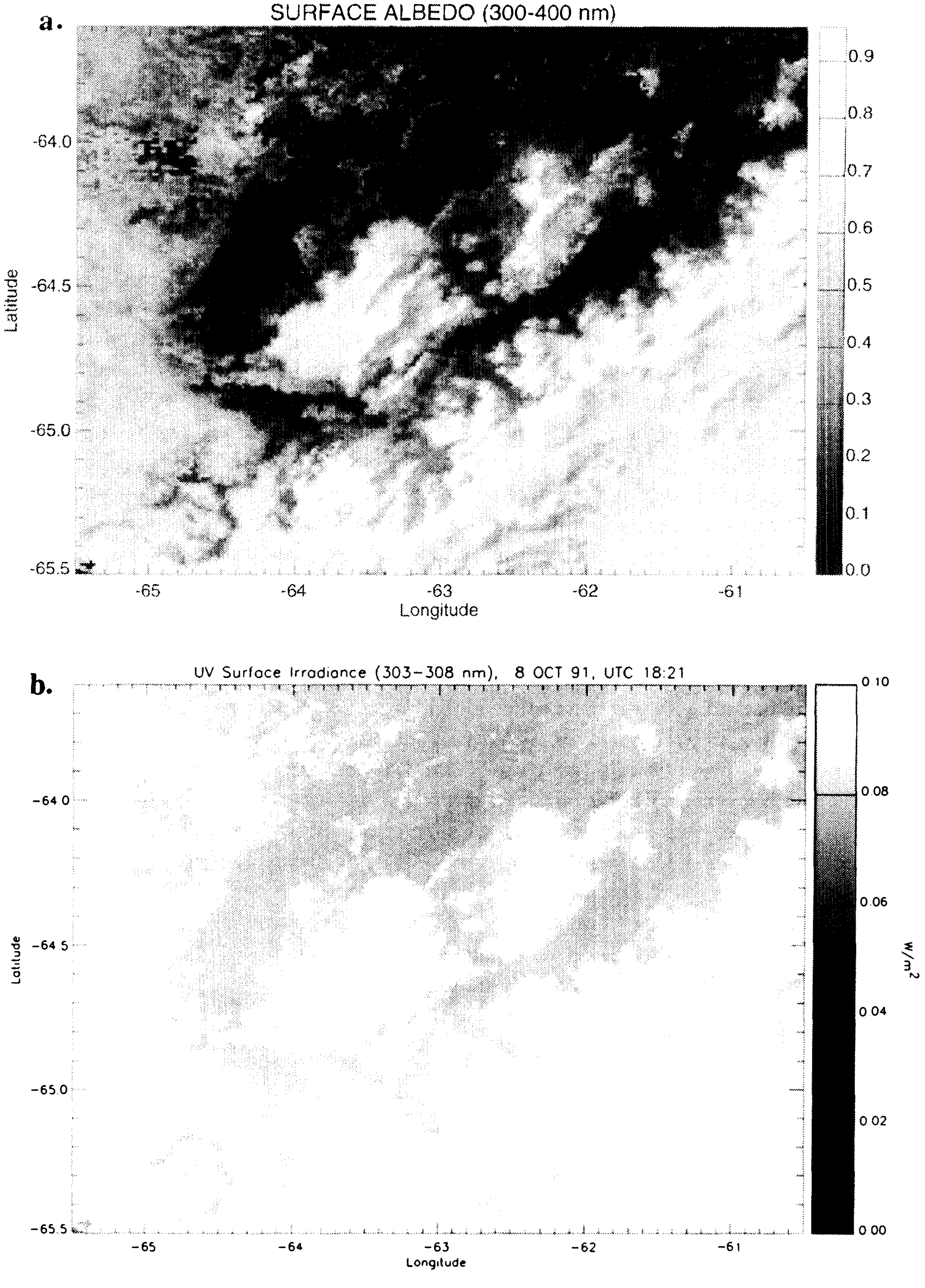

Fig. 6. Radiation conditions for the area around Anvers Island, Antarctica.
a) Surface Albedo for the 300–400 nm band.
b) Surface UV irradiance for the 303–308 nm band.

surrounding environment. These are based on visible satellite observations from the Advanced Very High Resolution Radiometer (AVHRR).

3.2. Method

The algorithm depends on the fact that the ozone depletion occurs mainly in the stratosphere. Hence, the total ozone measurements can be converted directly to maps of UV-B irradiance at the top of the troposphere. The remaining task of computing the transmission through the troposphere is accomplished in two steps. First, a plane-parallel radiative transfer model is run in inverse mode to obtain cloud optical depth from AVHRR channel 1 measurements. This procedure is similar to the cloud optical depth retrievals carried out by the International Satellite Cloud Climatology experiment. Second, the RT model is used again in forward mode to obtain the transmission to the surface at various UV and visible wavelengths. Both of these steps depend on good estimates of the surface albedo at each pixel. Construction of the surface albedo map is accomplished by searching many satellite scans for clear sky areas and running the RT model to compute the inherent reflectance of each pixel. The surface albedo map is complete when the entire surface area can be pieced together from a composite of these cloud free areas obtained from different satellite scans. Due to the persistent cloudiness over the Southern Ocean, the time interval required to complete this surface albedo composite may extend to months. Over this length of time the surface condition may evolve to a state much different from the current surface albedo estimate.

3.3. Results

Figure 6a and b shows the surface albedo map and one of the UVB maps from the LRG study for an area centered on Anvers Island, Antarctica. LRG's UV mapping algorithm uses observations from the Total Ozone Mapping Spectrometer (TOMS) together with several AVHRR channels to predict total atmospheric transmission. The difficulty in generating good estimates of surface albedo is probably one of the largest sources of error in the surface UV estimates. The accuracy of these UV predictions is also limited by: 1) the neglect of horizontal transport in the surface-cloud radiative interaction (RICCHIAZZI an GAUTIER, 1996, 1997), 2) the difficulty of detecting clouds over the highly reflective and cold surface background, and 3) the bi-directional reflectance (BDRF) properties of the snow surface.

4. Surface Effects

4.1. Overview

The importance of the surface reflection on the radiation environment cannot be overemphasized. It affects both surface and space observations and thus needs to be better modeled if we are to properly interpret surface and space observations in terms of changes in atmospheric and cloud properties. Surface albedo and cloud effects are strongly coupled over highly reflecting surfaces due to multiple reflections. This induces uncertainties in the estimation of surface albedo and cloud optical thickness from surface observations (RICCHIAZZI *et al.*, 1995). Also, the representativity of surface radiation observations in coastal regions may be limited due to multiple reflections that increase the influence of distant surface elements on the local downwelling irradiance. The non-Lambertian nature of snow reflection makes the retrieval of surface or cloud properties difficult. We have tried to address each of these issues using 1-D and 3-D radiative transfer models applied to observations obtained from Palmer Station, Antarctica.

4.2. *Surface radiation in coastal areas*

An analysis of results based on a newly developed 3-D radiative transfer model applied to the coastal area around Palmer Station model suggests a number of new effects that bear on both satellite and surface remote sensing (RICCHIAZZI and GAUTIER, 1996). This new model explicitly includes radiative interactions between plane-parallel clouds and heterogeneous surface topography and also includes the effects of gas absorption and Rayleigh scattering (RICCHIAZZI and GAUTIER, 1997).

First, we find that bright surface features affect the planetary albedo beyond the coastal margins delineated by a typical albedo map (Fig. 7). The width of the affected region is about twice the cloud altitude, which implies significant degradation of spatial resolution in cases of high clouds over high contrast surfaces. This is a significant effect for satellite remote sensing of cloud optical depth which requires registration of satellite

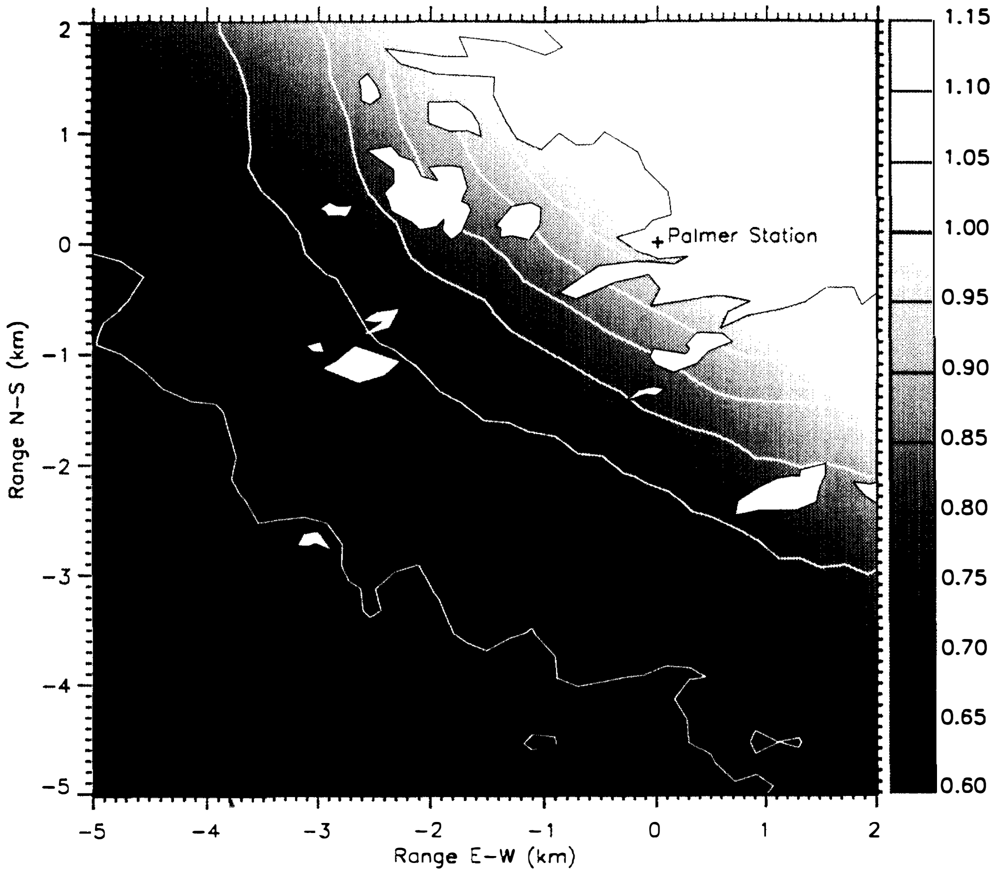

Fig. 7. UV surface irradiance enhancement (300 nm) in the vicinity of Anvers Island. The irradiance enhancement is normalized to one at Palmer Station.

images with a surface albedo map.

Second, we find that the downwelling irradiance below a cloud is affected by the reflectance of distant surface elements. The radius of influence of this surface effect is greater near the center of a large high-albedo surface than over an extensive dark region . This is shown on Fig. 8 which presents, for both AVHRR-1 spectral (left) and 300 nm (right), the variations of the computed irradiance along a SW-NE transect for 3-D computations (top panels) and the difference (expressed in percentage of the 1-D values) between 3-D and 1-D computations (bottom panels) in the case of low cloud conditions (1 km altitude). This figure indicates that a dark surface within a 7 km radius of a snow-covered region can lower the irradiance below the value expected for a uniform snow covered region. In contrast, irradiance values close to that expected for a uniform ocean surface are only obtained at off-shore locations more than about 2 km from the coast. The difference between 3-D and 1-D can reach minus 28% of the 1-D values over a snow region for the AVHRR-1 channel and minus 18% for the 300 nm channel. The non-zero values in the 300 nm channel corresponding to clear conditions (cloud optical depth equals zero) show that similar effects exist when Rayleigh scattering is the dominant scattering mechanism.

The range of the non-local effect increases with the altitude of the scattering layer.

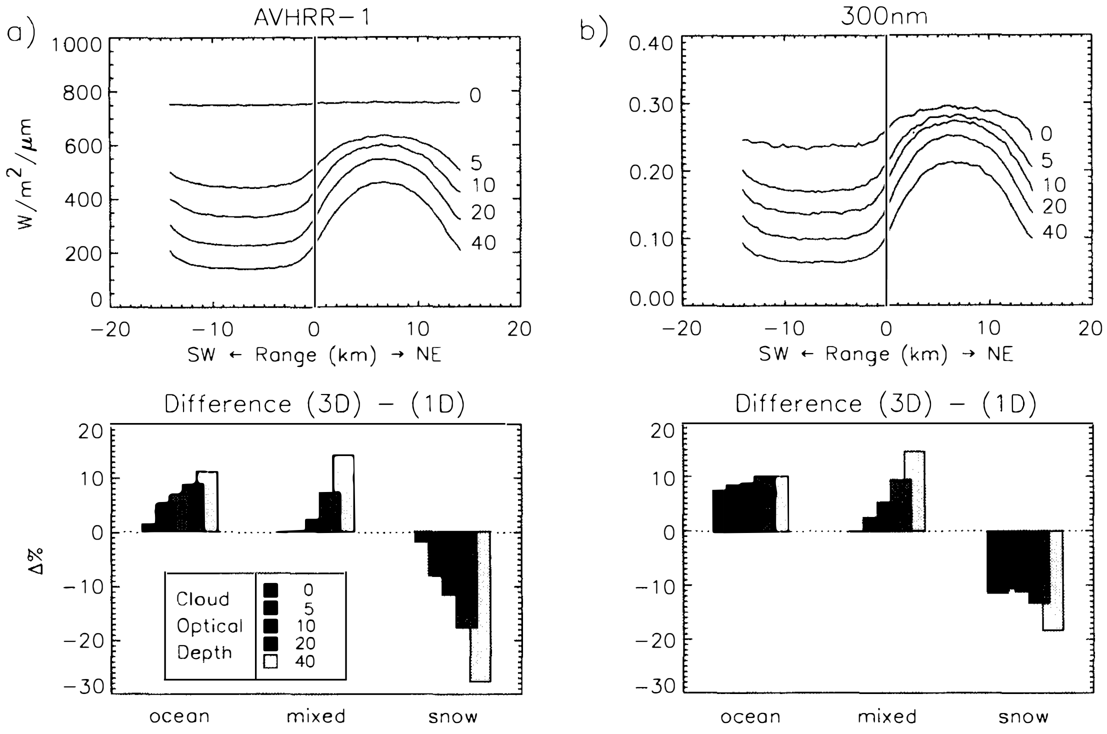

Fig. 8. Transect of surface irradiance for visible (a) and UV (b) wavelengths. The solid lines indicate results for cloud optical depths of 0, 5, 10, 20, and 40. The surface transect runs perpendicular to the coast and passes through Palmer Station at range = 0. The lower panels show the difference between the 3-D and 1-D predictions (as a percentage of the 1-D values) for the areas near −7, 0, and +7 km range. The results for these points were compared to 1-D calculations that assumed a uniform surface composed of 100% ocean, an equal mix of ocean and snow, 100% snow, respectively.

In clear skies and at shorter wavelengths, Rayleigh scattering of reflected radiation can significantly increase the surface irradiance. When clouds are absent, the effective scattering altitude of reflected radiation between 300 nm and 400 nm is greater than 4 km. Hence, an increase in the optical depth of low clouds may actually decrease the irradiance contribution from surface elements more than 5 km away. This effect is important to consider when using single point measurements of UV radiation at a coastal region to represent a larger area over land or open ocean.

Third, the radius of influence of the non-local effect is smaller for wavelengths with significant atmospheric absorption or reduced snow reflectivity. This brings into question a wide range of spectral diagnostic procedures that have been developed and applied to data from coastal radiation monitoring facilities. For example, total ozone amount above Palmer Station is obtained by the ratio of two narrow UVB bands (LUBIN and FREDERICK, 1991). We have noted in another study that surface ozone retrievals based on spectral ratios are sensitive to cloud amount and surface albedo. Since the two channels have different ozone absorption cross-sections, their response to distant surface features will be different. This introduces a dependence on the snow and ice distribution around the station that will distort the ozone retrievals.

4.3. Snow BRDF at the surface and TOA

We used a detailed 1-D radiative transfer code to model the angular distribution of radiation reflected from a snow surface. The snow surface is included as a scattering layer at the bottom of the radiative transfer computational grid. In this way we are able to accurately model how the anisotropy of the reflected radiation is modified by transmission through the atmosphere. For ultraviolet wavelengths, we find that Rayleigh scattering strongly diminishes the anisotropy at the top of the atmosphere compared to that at the surface. At visible and infrared wavelengths aerosols tend to be more important in isotropizing the upwelling radiance. As the aerosol scattering strength declines toward the infrared, the degree of anisotropy in the TOA radiance becomes much more similar to that at the surface.

5. Conclusions

The importance of surface characteristics on the surface UV radiation environment cannot be overemphasized. In particular, the surface effects are coupled with cloud effects due to multiple reflections between the two in such a way that the presence of clouds modify the spectral composition of the radiation reaching the surface. This has particular implications for the UV radiation environment which is therefore strongly influenced by surface characteristics.

In order to map UV radiation from space, the only way to obtain a representative coverage of the UV environment over the entire Antarctic region, both improved cloud detection and surface characterization must be developed. Some modeling progress have and will be made towards these improvements, but significant improvements are still required. They will likely come from: 1) new data sets such as those to be available from new instruments on the upcoming Earth Observing platforms (EOS-AM and PM), and 2) new algorithm developments which will capitalize on these new instruments.

These will be important in the detection of long-term climate changes and the assessment of the impact of atmospheric changes on marine ecosystems.

References

BOOTH, C.R., LUCAS, T.B., MESTECHKINA, T., TUSSON, J.R., NEUSCHULER, D.A. and MORROW, J.H. (1995): NSF Polar Program UV Spectroradiometer Network 1993-1994 Operational Report. Biospherical Instruments Inc.

GAUTIER, C., RICCHIAZZI, P. and YANG, S. (1996): Could clouds partly mitigate the biological effects of ozone depletion in the Antarctic. International Radiation Symposium Alaska Proceedings.

LUBIN, D. (1989): The Ultraviolet Radiation Environment of the Antarctic Peninsula. Ph.D. Thesis, University of Chicago, Chicago Illinois, 134 p.

LUBIN, D. and FREDERICK, J.E. (1990): Column ozone measurements from Palmer Station, Antarctica—Variations during the austral springs of 1988 and 1989. J. Geophys. Res., **95**, 13883-13889.

LUBIN, D. and FREDERICK, J.E. (1991): The ultraviolet radiation environment of the Antarctic Peninsula—The roles of ozone and cloud cover. J. Appl. Meteorol., **30**, 478-493.

LUBIN, D., FREDERICK, J.E., BOOTH, C.R., LUCAS, T. and NEUSCHULER, D. (1989a): Measurements of enhanced springtime ultraviolet radiation at Palmer Station, Antarctica. Geophys. Res. Lett., **16**, 783-785.

LUBIN, D., FREDERICK, J.E. and KRUEGER, A.J. (1989b): The ultraviolet radiation environment of Antarctica: McMurdo Station during September-October 1987. J. Geophys. Res., **94**, 8491-8496.

LUBIN, D., RICCHIAZZI, P. and GAUTIER, C. (1993): Mapping of surface UV over Antarctica using satellite observations. Norway Proceedings on Atmospheric Radiation, 30 June-1 July, 1993, 199-214 (SPIE Vol. 2049).

McCLATCHY, R.A., FENN, R.W., SELBY, J.E.A., VOLZ, F.E. and GARING, J.S. (1972): Optical Properties of the Atmosphere, 3rd ed. Air Force Cambridge Research Laboratories, Report AFCRL-72-0497.

RICCHIAZZI, P. and GAUTIER, C. (1996): The effect of surface topography on the radiation environment of Palmer Station, Antarctica. International Radiation Symposium Proceedings, Fairbanks, Alaska.

RICCHIAZZI, P. and GAUTIER C. (1997): Investigation of the effect of surface heterogeneity and topography on the radiation environment of Palmer Station, Antarctica with a Hybrid 3-D Radiative Transfer Model. to be published in J. Atmos. Sci.

RICCHIAZZI, P. J., GAUTIER, C. and LUBIN, D. (1995): Cloud scattering optical depth and local surface albedo in the Antarctic: Simultaneous retrieval using ground-based radiometry. J. Geophys. Res., **100**, 21091-21104.

RICCHIAZZI, P, YANG, S., GAUTIER, C. and SOWLE, D. (1997): SBDART: A research and teaching software tool for plane-parallel radiative transfer in the Earth's atmosphere. to be published in Bull. Am. Meteorol. Soc.

SETLOW, R.B., GRIST, E., THOMPSON, K. and WOODHEAD, A.D. (1993): Wavelengths effective in induction of malignant melanoma. Proc. Natl Acad. Sci. U.S. Am., **90**, 6666-6670.

SMITH, R.C. and CULLEN, J.J. (1995): Effects of UV radiation on phytoplankton. Rev. Geophys., Suppl., 1211-1223.

STAMNES, K., HENRIKSEN, K. and OSTENSEN, P. (1988): Simultaneous measurement of UV radiation received by the biosphere and the total zone amount. Appl. Opt., **27**, 2502-2509.

WISCOMBE, W. J. and WARREN, S.G. (1980): A model for the spectral albedo of snow. I: pure snow. J. Atmos. Sci., **37**, 2712-2733.

(Received August 25, 1997; Revised manuscript accepted September 22, 1997)