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The ''Radiation Paradox'' on the Slopes of the Antarctic Continent

A contribution to I. A. G. O.*

By Gerd Wendler**

Summary: Detailed radiative measurements were carried out during the austral summer of 1985/86 in Adelie Land, Eastern Antarctica. Our station was located some 100 km from the coast at an altitude of 1560 m on the slope of the Antarctic Ice Sheet. It was found that with increasing global radiation the all wave radiation budget decreased. AMBACH (1974) found similar results in Greenland and called the phenomenon the ''radiation paradox''. Prerequisite for this occurance is a high surface reflectivity. A mean albedo of 82% was observed at our site. Under these circumstances, the increase in the short wave radiation with decreasing cloudiness is over-compensated by the increased long wave radiative losses. A simple model was developed which showed that under our conditions, an albedo above 60.1% had to be present to observe this phenomenon.

Zusammenfassung: Im Sommer 1985/86 wurden in Adelieland, Ostantarktis, in einer Höhe von 1560 m detaillierte Strahlungsmessungen durchgeführt. Mit zunehmender Globalstrahlung wurde eine abnehmede Gesamtstrahlungsbilanz gefunden. AMBACH (1974) bezeichnete dieses Phänomen als ein ,,Strahlungsparadox''. Voraussetzung hierfür sind hohe Albedowerte; wir fanden einen Mittelwert von 82%. Unter diesen Umständen wird die wachsende kurzweilige Strahlungsbilanz bei abnehmender Bewölkung durch die Zunahme der langwelligen Ausstrahlungsverluste mit abnehmender Bewölkung überkompensiert. Ein einfaches Modell wurde entwickelt, welches zeigte, daß für unsere Bedingungen eine Albedo von mehr als 60.1% nötig ist, um dieses Phänomen zu beobachten.

INTRODUCTION

During the austral summer 1985/86, a large U.S.-French experiment was carried out in Adelie Land, Eastern Antarctica which had been planned for several years (WENDLER & POGGI, 1980; POGGI et al., 1982). A major goal of the study was the better understanding of the katabatic wind, a very widespread phenomenon which dominates the boundary layer processes in Antarctica (ANDRÉ, 1986).

For the duration of the study, three slope stations some 5, 105, and 210 km from the coast were occupied — one by us, two by the French — and data were simultaneously collected for a period of about one month. Boundary layer measurements were made using balloons, air foils, and drones. Meteorological data were then transmitted to ground stations via radio, where they were recorded on magnetic tape.

Further, climatological data for the last six years along the slope from Dumont d'Urville to Dome C, some 1180 km inland at an altitude of 3280 m (WENDLER & KODAMA, 1985) were obtained from Automatic Weather Stations (AWS) (RENARD & SALINAS, 1977; STEARNS & SAVAGE, 1981). Dumont d'Urville was used as a long term climatological station — surface as well as upper air. Also, two instrumented aircraft missions were flown, which covered the entire area from Dumont d'Urville to Dome C. Detailed radiative fluxes were obtained at one station as part of this large study. In addition to their intrinsic interest, these observations are also of importance for the better understanding of the energetics of the katabatic wind.

SITE AND CLIMATOLOGY OF THE STUDY AREA

Our station was located at D-47 (67°23'S, 138°43'E) about 105 km from the ocean at an altitude of 1560 m (Fig. 1). The slope angle is $6.5x10^{-3}$, steep for the intermediate plateau of Antarctica, and the slope di-

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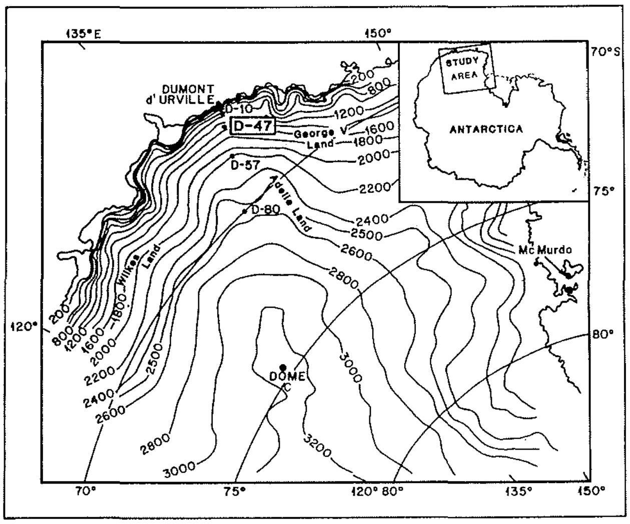

Fig. 1: Location map of our measuring site in Antarctica.

Abb. 1: Lagekarte unseres Meßgebietes in der Antarktis.

rection is 210°. The mean annual temperature is —25.7 °C. Temperatures above the freezing point have never been observed, while the absolute minimum is —46.2 ° C, relatively mild. However, Dumont d'Urville, for which long term (>30 years) climatological data are available, and which is located on an island just off the coast of Antarctica, has never recorded a temperature below —32 ° C, as this area of Antarctica is quite mild. Winds at D-47 are strong (12.8 m/sec mean annual value), and very consistent in their direction. The wind constancy, which is defined by the vectorial wind divided by the mean wind speed, is 0.94, extremely high, and blows about 40 ° to the left of down slope. In summer, when we carried out our measurements, the wind speed is somewhat below the mean annual value. For the three month period from November to January a mean value of 11.3 m/sec was observed, with a maximum of more than twice this amount. The mean summer temperature is —17.2 ° C, with absolute maxima just below the freezing point, and absolute minima down to a chilly —35 ° C.

On 6 November 1985 we flew by ski-equipped LC 130 from McMurdo to D-21, and the return flight took place on 2 January 1986. Surface transport to our measuring site, which is some 90 km from the landing site, erection of the instrumentation, and calibration before and after the experiment left a 33 day period for which a complete data set is available, namely 20 November to 22 December 1985.

INSTRUMENTATION

Radiation measurements were carried out with a PD-4 Davos instrument. This instrument has 4 sensors, 2 looking up and 2 looking down. Two are covered with double glass domes, to measure the incoming and reflected global radiation; two are covered with lupolen domes, and hence measure the all wave incoming and outgoing radiation. The difference between the two types is the long wave radiation, which was also measured with two Eppley pyrgeometers. The incoming short wave radiation was also measured with a second instrument, a star pyranometer. For spot measurements of the albedo, a PD-1 Davos was used, and for calibration purposes a Linke-Feussner actimometer was utilized.

The data were continuously recorded on a CR 7 Campbell Scientific Data Logger, which averaged all data for 10 minute intervals and recorded those on magnetic tape, as well as printed out the data so that a check on the quality of the data was possible in the field. The data recorder was housed in a heated vanagan. The short and all wave sensors were calibrated by the shading method and the Linke-Feussner acti-

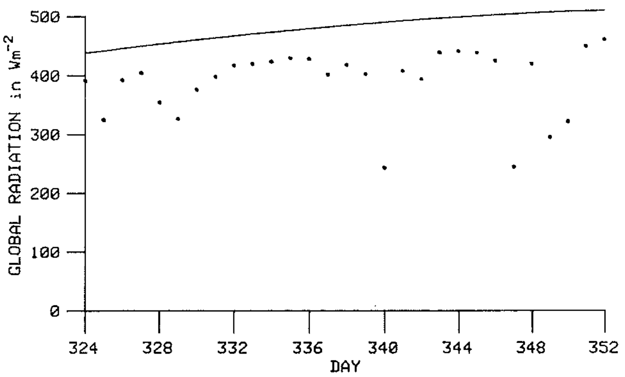

Fig. 2: Daily mean values of global radiation for D-47, Eastern Antarctica. The encompassing curve is the extraterrestrial radiation on the horizontal for this latitude, corrected for Earth-Sun distance.

Abb. 2: Globalstrahlungs-Tagesmittel für die Station D-47 in der Ost-Antarktis. Die obere Hüllkurve entspricht der breitenspezifischen extraterrestrischen Einstrahlung auf horizontale Flächen, korrigiert um die Erde-Sonne-Entfernung.

mometer, which in turn had been calibrated in Boulder, Colorado at NOAA's National Calibration Center. The Eppley pyrgeometers, which were new, were only intercompared with the long wave fluxes calculated from the PD-4 Davos, as a direct calibration in the field was not possible.

RESULTS

Global radiation and cloudiness

In Fig. 2 the daily mean values of the global radiation (G) are presented. The encompassing curve represents the extraterrestial radiation (ET*) which was reduced to the horizontal surface, and corrected for the Earth-Sun distance. Calculating the ratio of G/ET*, which is also called the clearness index (K_t), a mean value of 0.81 was found. A mean value of 0.89 was found for 0/10 cloudiness, a very high value indeed, even for totally clear skies. This shows that the atmosphere in Antarctica is not only very clear, but contains very little water vapor. The lowest values were observed for 10/10 cloudiness (mean 0.57). In Fig. 3, the clearness index is plotted against cloudiness. The decrease of K_t with increasing cloudiness can be seen. More scatter is evident for overcast than for totally clear skies, indicating that variations in the opacity of the clouds is larger than the variation in turbidity. Furthermore, the dependancy of K_t on cloudiness is less pronounced when compared to areas where the surface albedo is lower. WENDLER & KODAMA (1986) found values of 0.23 for 10/10 cloudiness in the subarctic setting of southern Alaska, which compares to a value of 0.57 in Antarctica for the same amount of cloudiness. The reason for this large discrepancy is believed to be twofold:

1) Our site in Antarctica has a higher latitude, displaying colder temperature. Therefore, the atmosphere

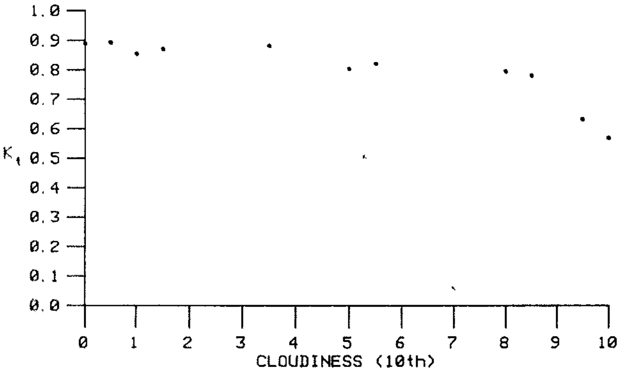

Fig. 3: The clearness index (K_t), plotted against cloudiness for D-47, Eastern Antarctica.

Abb. 3: Der Durchlässigkeitsindex (K_t), gegen die Bewölkung aufgetragen für die Station D-47 in der Ost-Antarktis.

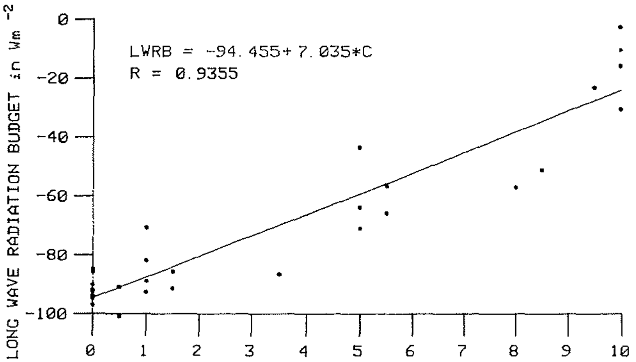

Fig. 4: The long wave radiation budget (LWRB) as a function of cloudiness. A correlation factor of r = 0.94 was found.

Abb. 4: Die langwellige Strahlungsbilanz (LWRB) als Funktion der Bewölkung. Es ergab sich ein Korrelationskoeffizient von r = 0,94.

can hold less water vapor, and clouds, when formed are normally "thinner", with a lower opacity.

2) Multiple reflection between the surface and the base of the cloud becomes important if the surface albedo is high (WENDLER et al, 1981), as observed in Antarctica. It enhances the global radiation in times of overcast.

Long wave radiation budget and cloudiness

In Fig. 4 the long wave radiation budget (LWRB) is plotted against cloudiness. Under overcast conditions the long wave radiation budget is slightly negative, but it becomes strongly negative under clear sky con-

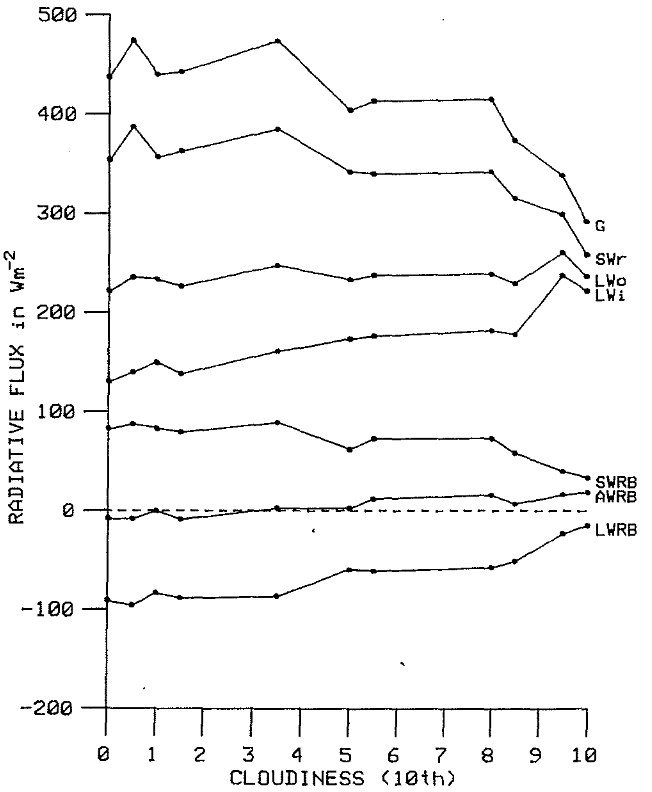

Fig. 5: Daily mean values of the radiant fluxes as a function of cloudiness.

Abb. 5: Tagesmittel der Strahlungsflüsse als Funktion der Bewölkung.

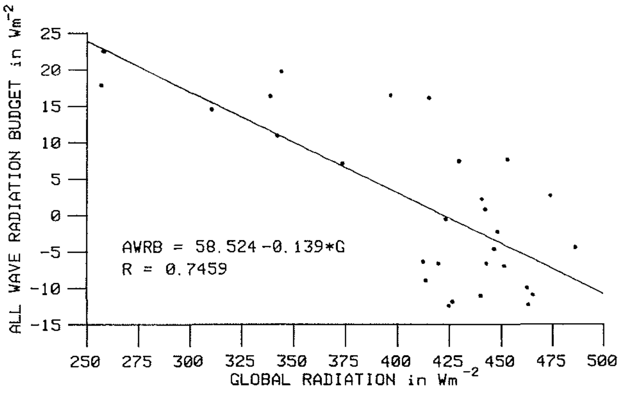

Fig. 6: Relation between global radiation (G) and all wave radiation budget (AWRB).

Abb. 6: Beziehung zwischen Globalstrahlung (G) und der Gesamt-Strahlungsbilanz (AWRB).

ditions. Assuming a linear relationship, the following relation holds:

$$\text{LWRB} = -94.455 + 7.035c$$

with c = cloudiness in tenths. This relationship between long wave radiation budget and cloudiness is well established, and has been found by many authors, e. g. for Antarctica first by LILJEQUIST (1957).

RADIATION BUDGET AND CLOUDINESS

In Fig. 5, all radiative fluxes are plotted against cloudiness. Global (G) and reflected (SW_r) radiation decrease with cloudiness, the long wave incoming radiation (LW_i) increases strongly with cloudiness and the long wave outgoing (LW_0) does not show a strong dependancy. As the short wave radiation budget (SWRB) decreases with cloudiness, and the long wave radiation budget (LWRB) increases strongly with cloudiness, the all wave radiation budget (AWRB) increases with increasing cloudiness, which is the so called radiation paradox. This was caused by the fact that the increase in the LWRB is greater than the corresponding decrease of the SWRB.

In Fig. 6 the global radiation (G) is plotted against the all-wave radiation budget (AWRB). Even though there is substantial scatter in the data points, with increasing AWRB the global radiation decreases. The long wave incoming radiation (LW_i) shows the opposite trend (Fig. 7). With increasing AWRB, the long wave incoming radiation increases.

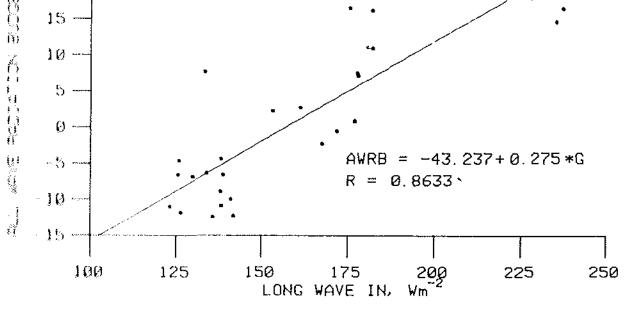

Fig. 7: Relation between incoming long wave radiation (LW_i) and the all wave radiation budget (AWRB).

Abb. 7: Beziehung zwischen einfallender langwelliger Strahlung (LW_i) und der Gesamt-Strahlungsbilanz (AWRB).

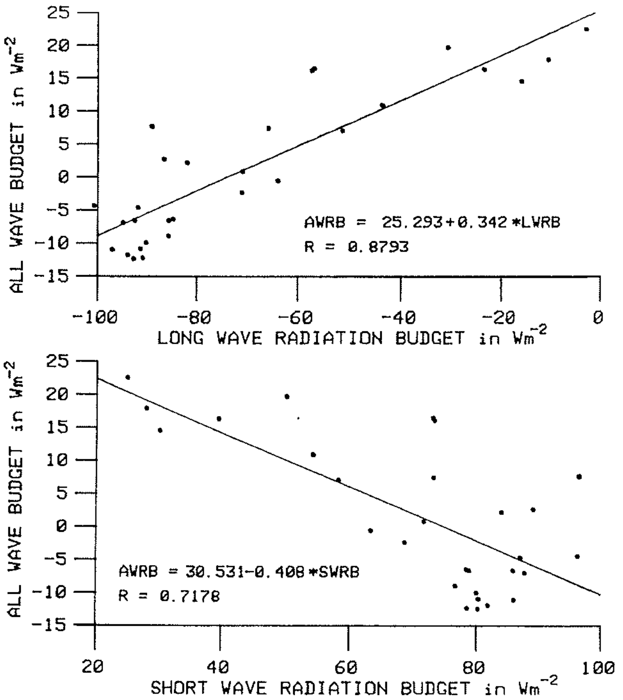

Fig. 8: Relation between all wave radiation budget (AWRB) and the long wave radiation budget (LWRB) and the short wave radiation budget (SWRB).

Abb. 8: Beziehung zwischen Gesamt- (AWRB), langwelliger (LWRB) und kurzwelliger Strahlungsbilanz (SWRB).

In Fig. 8, the SWRB and the LWRB is plotted against the AWRB. LWRB and AWRB show a good positive correlation, while the correlation between SWRB and AWRB is negative and somewhat weaker. A very nice negative correlation could be established between the short and long wave radiation balances (Fig. 9). One can see from the slope of this figure (note that axes have identical scales), that with increasing positive short wave radiation budget, the long wave radiation budget decreases by a larger amount, which is another way of expressing the radiation paradox.

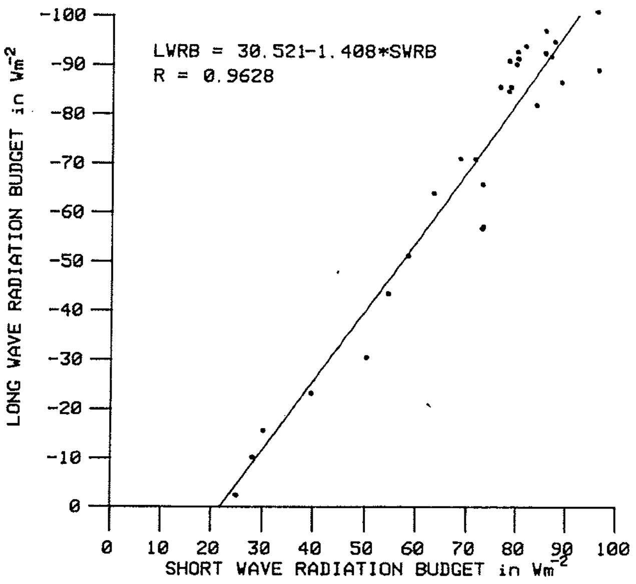

Fig. 9: Relation between the short wave radiation budget (SWRB) and the long wave radiation budget (LWRB) (note: y-axis is inverted).

Abb. 9: Beziehung zwischen kurzwelliger (SWRB) und langwelliger Strahlungsbilanz (LWRB).

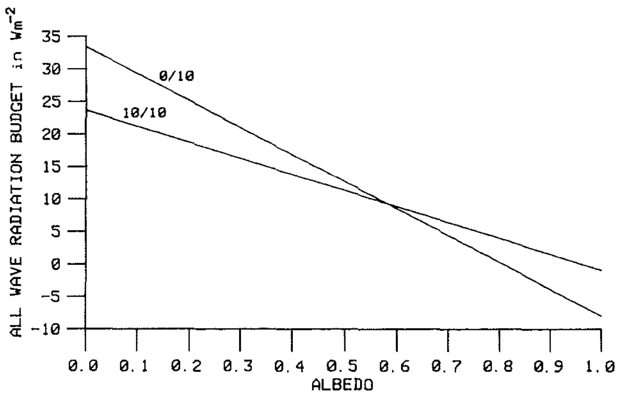

Fig. 10: All wave radiation budget as a function of surface albedo for specific amounts of cloudiness (modelled).

Abb. 10: Die Gesamt-Strahlungsbilanz als Funktion der Oberflächenalbedo für ausgewählte Bewölkungsbeträge (modelliert).

MODELLING

Prevoiusly, we had established relationships between cloudiness and global radiation, and long wave radiation budget, respectively, (Fig. 5). The following equation holds:

$$AWRB = [\, G_0 - (G_0 - G_{10})*(c/10)]*(1-\alpha) + LWRB_0 + (LWRB_{10} - LWRB_0)*(c/10)$$

with α = surface albedo, c as cloudiness (in tenth), and 0 and 10 as subscript the amount of radiation at 0 and 10 tenths cloudiness. Now we are able to model the dependancy of the all wave radiation budget on the albedo for a specific cloudiness, or on the cloudiness for a specific albedo. In Fig. 10, the all wave radiation balance as a function of albedo is presented for the two extreme cases, clear skies and total overcast. The figure shows that up to an albedo of 60.1% the radiation budget is more positive for clear skies. Values below 60% are found for most natural surfaces of our planet, and even deserts display values below 60% (GEIGER, 1975). Only in the high polar latitudes are values above 60% observed. Dry snow typically has values around 80% (HOINKES, 1960; CARROLL & FITCH, 1981) while wet snow has values below 60% (DIRMHIRN, 1953). Hence, with the exception of high latitudes and possibly high altitudes, this phenomenon cannot be found. Even for the coastal areas of Antarctica, this paradox cannot be observed in summer, as the temperature can rise above the freezing point, lowering the albedo substantially.

Using our data set once again, the dependence of the AWRB on the cloudiness was modelled for fixed albedos. In Fig. 11, three cases were calculated, 40%, 60% and 80% albedos. For 40%, the all wave radiation budget increases with decreasing cloudiness, a result that is expected considering studies at low latitu-

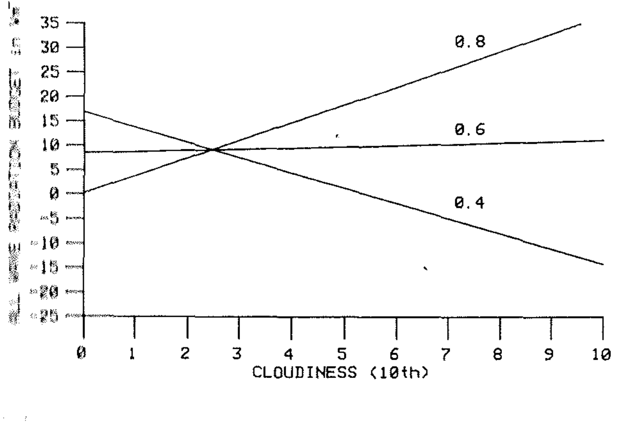

Fig. 11: All wave radiation budget as a function of cloudiness for specific albedo values (modelled).

Abb. 11: Die Gesamt-Strahlungsbilanz als Funktion der Bewölkung für ausgewählte Albedo-Werte (modelliert).

des. It should be pointed out that 40% is already a high surface albedo for natural surfaces, typically found only for wet snow (DIRMHIRN, 1953) or deserts (GEIGER, 1975). For a reflectivity of 60% the curve is flat, and no dependancy of the all wave radiation budget on cloudiness can be detected. Under these conditions, the decrease in SWRB is just balanced by the increase in LWRB. 80% is typical for the interior of Antarctica — we found a mean value of 82% — and for the interior areas of Greenland (AMBACH, 1974). That this phenomemon occurs in winter with weak global radiation is understandable, however we also observe it in midsummer with large daily values of global radiation. Our daily sums of global radiation are similar to those in the tropics.

It should be pointed out that our model is simplistic. It does not consider the effects of the albedo on the surface temperature, and the resultant outgoing long wave radiation. Any change in the surface temperature would further change eddy fluxes in the atmosphere and with it the temperature and moisture profile of the atmosphere, and hence the long wave incoming radiation. Furthermore, and even more complex, is the formation mechanism of the clouds, which is of course a function of moisture in the air. Cloudiness will change not only the short wave, but also the long wave fluxes. However these complicated feedback mechanisms are outside the scope of this study.

CONCLUSION

The interdependancy of the different radiative fluxes has been demonstrated for a site in Eastern Antarctica. Even in midsummer, the global radiation was negatively correlated with the all wave radiation budget. This counterintuitive result can be explained by a simple model which showed that high surface albedo (>60%) is responsible for this effect. Measurements previously carried out by HANSON (1961) and HOLMGREN (1971) indicated such a behavior. Furthermore, AMBACH (1974) showed it clearly for Greenland. In comparison to his data, the surface reflectivity may be even lower in Antarctica, and still this phenomenon is observed. This is an indication that the atmosphere in Eastern Antarctica is even drier and cleaner (less incoming long wave radiation for clear skies) than in Greenland. The results found above may also explain the long survival of the continental ice sheet of the Pleistocene.

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