Parameterization of the downward long-wave radiation at the Earth's surface in polar regions

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Summary. Various parameterization schemes for the downward long-wave radiation at the Earth's surface which have been frequently applied in sea ice and snow cover models are tested with the aid of one year's measurements at the German stations "Koldewey" and "Neumayer" in the Arctic and Antarctic, respectively. All of these concepts are based on the Stefan-Boltzmann radiation law with an empirically derived effective atmospheric emissivity ε_A. Our data confirm the distinct dependency of the latter on cloudiness. But no other influences e.g. due to falling ice crystals (diamond dust) could be detected as significant. And the low level atmospheric water vapour pressure needs not be considered explicitly in the formulae. Thus, we propose a rather simple scheme for ε_A which is competable to the more sophisticated ones at least for polar regions. Our parameterization reproduces the observations with root mean square (RMS) deviations of less than 16 W/m^2.

Parameterisierung der bodennahen Gegenstrahlung in polaren Regionen

Zusammenfassung. Verschiedene Parameterisierungsansätze zur Berechnung der bodennahen Gegenstrahlung mit Hilfe der Stefan Boltzmannschen Strahlungsformel, die häufig in Meereis- und Schneedeckenmodellen verwandt werden, können anhand einjähriger Messungen an den deutschen Polarstationen „Koldewey" und „Neumayer" in der Arktis bzw. Antarktis überprüft werden. Unsere Daten bestätigen erwartungsgemäß die deutliche Abhängigkeit der effektiven atmosphärischen Emissivität ε_A von dem Grad der Bewölkung, hingegen sind andere Einflüsse, z. B. hervorgerufen durch fallende Eiskristalle in der unteren Atmosphäre, nicht erkennbar. Auch scheint es nicht notwendig, den bodennahen Wasserdampfgehalt der Luft explizit in dem Ausdruck für ε_A zu berücksichtigen, wie es gelegentlich vorgeschlagen wird. Dementsprechend empfehlen wir eine besonders einfache Darstellung für ε_A, mit deren Hilfe sich die Meßwerte der Polarregionen mindestens ebenso gut wie mit komplizierteren Ansätzen reproduzieren lassen. Die RMS-Abweichung zwischen den so berechneten und den gemessenen Werten der bodennahen Gegenstrahlung beträgt maximal 16 W/m^2.

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1. Introduction

Radiation measurements at the Antarctic station "Neumayer" (70°39′S, 08°15′W) and at the Arctic Station "Koldewey" (78°56′N, 11°56′E) in Ny Ålesund (Svalbard) are used together with other meteorological observations to test simple parameterization schemes for the downward long-wave radiation under cloudy and cloud free conditions. We limit our considerations to parameterization concepts which are primarily based on the near-surface air temperature and on the total cloud cover. These two values are often available either from observations or from numerical atmospheric models with a reasonable degree of certainty. They are therefore quite suitable to compute the downward long-wave radiation flux at the Earth's surface for investigations which need the surface energy balance. Among others, the latter plays a dominant role in numerical simulations of the sea ice development (HIBLER 1979, KOCH 1986, LEMKE 1987) and in snow cover modelling (SIEMER 1988, LOTH et al. 1992).

Recent high quality radiation measurements which are obtained in the framework of the global Baseline Surface Radiation Network (BSRN) are utilized to test the usefulness of current parameterization schemes of the downward long-wave surface radiation in high latitudes. Reference will be made in particular to concepts of MARSHUNOVA (1961), PARKINSON and WASHINGTON (1979), KIMBALL et al. (1982) and ANDREAS and ACKLEY (1982) which have been repeatedly applied to polar conditions.

2. The observations

Neumayer Station is located near the Antarctic coast on the Ekström Ice Shelf on a flat slightly sloping surface. Weather conditions in the area are mainly governed by high wind velocities, severe snow drifts and frequently overcast skies. The rare clear sky conditions are often accompanied by strong surface inversions (KÖNIG-LANGLO 1992).

Koldewey Station on Svalbard is situated at the shoreline of the Kongsfjord surrounded by mountains of 500 to 1000 m height. Koldewey is warmer and less windy than Neumayer (HANSSEN-BAUER et al. 1990). During summer the Earth's surface at Koldewey is free of snow.

Both establishments are equipped with radiation sensors and auxiliary instruments which are mandatory for stations of the Baseline Surface Radiation Network. These include upward and downward looking pyrgeometers and pyranometers, a sunphotometer, a sunshine detector, a cloud laser and a radiosonde system. Furthermore, meteorological surface and cloud observations are carried out routinely. In this note we will primarily refer to radiation measurements of artificially ventilated Eppley "PIR" pyrgeometers. The instruments are regularly calibrated with reference instruments of the Deutscher Wetterdienst in Hamburg. According to various tests and intercomparisons, the mean error of the instruments under polar conditions is found to be less than 5 W/m^2 (KÖNIG-LANGLO et al. 1991). The automatic sampling interval for each sensor is 1 minute but 5 minute averages are stored in a central data recording unit. Weather observations are carried out every three hours from 6 UTC to midnight at Neumayer Station and at 6, 12 and 18 UTC at Koldewey Station.

To cover all seasons for both, the Antarctic and the Arctic regime continuous measurements and observations obtained during the whole year 1993 at Neumayer and Koldewey Stations are taken as a data basis in the subsequent considerations.

3. Parameterization schemes

Simple parameterization concepts for the downward long-wave surface radiation are predominantly based on the Stefan-Boltzmann law

$$L\Downarrow = \varepsilon_A \sigma T_0^4 \qquad (1)$$

with the so-called atmospheric emissivity ε_A, the Stefan-Boltzmann constant σ and the air temperature T_0 (Kelvin) at a given height (normally 2 m). The atmospheric emissivity ε_A which contains all the unknowns like the vertical temperature and water vapour distributions and the cloud effects has to be determined empirically.

Many attempts have been made in the past to gain generally applicable ε_A-values from observations in various geographical regions. In this study we will apply different parameterization concepts (see Table 1) to our data in order to determine the most appropriate scheme for high latitude conditions.

We will subsequently apply these parameterizations to the one year's measurements at each of the German polar stations and we will demonstrate that the representation of the effective emissivity ε_A

$$\varepsilon_A = 0.765 + 0.22c^3 \qquad (2)$$

with c = total cloud cover ($0 \le c \le 1$), provides the best fit to both, the Arctic and the Antarctic data sets.

4. Observational results

The measurements of air temperature T_0 and water vapour pressure e_0 at 2 m height as well as the observed cloud cover c are applied to solve Eq. (1) for the effective emissivities listed in Tab. 1 and defined by Eq. (2). The computed values are then compared with measurements of the downward long-wave radiation. Since we expect the largest contribution to the uncertainty of ε_A from the crude representation of the cloud effects we first consider cloud free conditions separately.

Tab. 1. Parameterizations for the atmospheric emissivity ε_A with T_o, T_{do} = air temperature, dew point temperature in 2 m height (Kelvin), c = total cloud cover ($0 \le c \le 1$), e_o = water vapour pressure in 2 m height (hPa), $L_c\Downarrow$ = cloud influence after KIMBALL et al. (1982), here not specified.

Tab. 1. Parameterisierungsansätze für die atmosphärische Emissivität ε_A mit T_o, T_{do} = Lufttemperatur, Taupunkttemperatur in 2 m Höhe (Kelvin), c = Bedeckungsgrad ($0 \le c \le 1$), e_o = Wasserdampfdruck in 2 m Höhe (hPa), $L_c\Downarrow$ = Wolkeneinfluß nach KIMBALL et al. (1982), hier nicht erläutert.

Author	Parameterization
MARSCHUNOVA	$\varepsilon_A = (1 + 0.275 * c) * (0.67 + 0.05 * \sqrt{e_o})$
KIMBALL et al.	$\varepsilon_A = L_c\Downarrow (c, T_o, T_{do}, e_o) + (0.7 + 5.95 * 10^{-5}\, e_o * \exp (1500/T_{0}))$
PARKINSON et al.	$\varepsilon_A = (1 + 0.275 * c) * (1.0 - 0.261 * \exp (-7.77 * 10^{-4} * (273 - T_0^2)))$
ANDREAS et al.	$\varepsilon_A = (1 + 0.27 * c^2) * (0.601 + 5.95 * 10^{-5} * e_o * \exp (1500/T_{0}))$

4.1. Cloud free conditions

Even in a cloudless atmosphere the emission and transmission of long-wave radiation may be effected not only by dry air, water vapour and other green house gases but also by aerosols, haze, ice crystals and perhaps invisible thin cirrus clouds. In most cases the distribution of these additional constituents of the air is unknown. Thus, results even of complex radiation transfer models deviate considerably from measured values of the downward long-wave surface radiation, see WILD et al. (1994).

In view of the complex atmospheric effects on the long-wave radiation the scatter of the measurements in Fig. 1 is not surprising. The observed values of L⇓ are reasonably reproduced by the ε_A-formulae of MARSHUNOVA (1961), KIMBALL et al. (1982) and the notation of Eq. (2), (see also Tab. 2). The approach of ANDREAS et al. (1982), which was adopted to the rather dust free polar conditions by the authors, produces in our cases systematically too low radiation values. The concept of PARKINSON et al. (1979) tends to overestimate L⇓ for temperatures below the freezing point due to their consideration of the effect of ice crystals which is obviously absent in our observations. While the RMS deviations of the parameterization of MARSHUNOVA (1961), KIMBALL et al. (1982) and of Eq. (2) range below 14 W/m^2 the uncertainty of the other two formulae is distinctly higher as shown in Tab. 2.

4.2. Cloudy conditions

The full set of observations for both stations in Fig. 2 contains all cloudy and all cloud free conditions. About 97 % of all data can be framed by curves of the Stefan-Boltzmann law with $\varepsilon_A = 0.70$ for the lower and $\varepsilon_A = 1.0$ for the upper level of radiative fluxes. The values exceeding the black body curve were obtained mainly at Neumayer station and reflect conditions with strong surface inversions in conjunction with low-level stratus clouds when T_0 at 2 m height is too low to represent the long-wave emission of the lower atmosphere. The relatively low radiation fluxes which are observed occasionally in the temperature range from –15 to –30° C at both stations cannot be explained either by instrumental defaults or by any other features detectable in the data.

At both stations the emissivity ε_A increases quite similarly with increasing cloudiness as displayed in Fig. 3. No systematic difference appears between the approximations of the Arctic and Antarctic measurements so that we suggest $\varepsilon_A = 0.765 + 0.22\, c^3$ as the best empirical fit for the entire data set.

The results of the different parameterization schemes for cloudy conditions are compiled in Tab. 2. Again, the ε_A-formulae of MARSCHUNOVA (1961), KIMBALL et al. (1982) and Eq. (2) achieve a closer simulation of the measured radiation fluxes than those of PARKINSON and WASHINGTON (1979) and of ANDREAS and ACKLEY (1982).

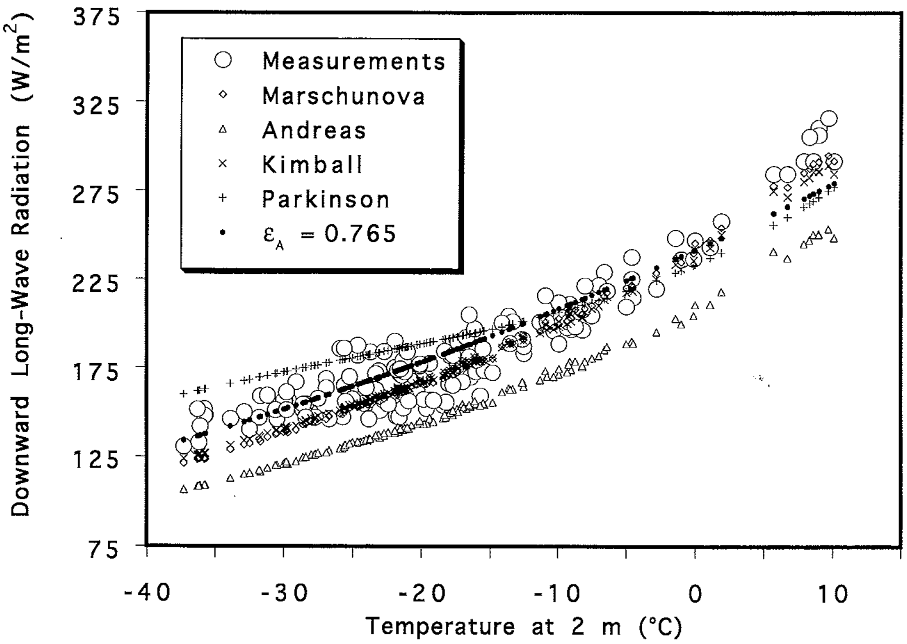

Fig. 1. Downward long-wave radiation versus air temperature at 2 m height for cloud free skies.

Abb. 1. Gegenstrahlung in Abhängigkeit von der Lufttemperatur in 2 m Höhe bei wolkenlosem Himmel.

Tab. 2. Computed minus observed mean values and root mean square (RMS) deviations for different parameterization schemes of L⇓ in W/m^2 for a) cloud free cases and b) for all conditions at Neumayer and Koldewey Station.

Tab. 2. Differenz zwischen berechneter und gemessener Gegenstrahlung sowie die RMS-Abweichung in W/m^2 für die verschiedenen Parameterisierungen a) für wolkenfreien Himmel, b) für alle Bedingungen an der Neumayer- und der Koldewey-Station.

	MARSCHUNOVA	KIMBALL et al.	Eq. (2)	PARKINSON et al.	ANDREAS et al.
a) cloud free conditions					
Mean	–6.5	–6.4	2.3	11.2	–30.5
RMS	13.6	13.3	14.0	20.4	32.8
b) all conditions					
Mean	3.3	1.7	–0.5	8.4	–35.3
RMS	18.4	16.9	15.4	20.9	38.5

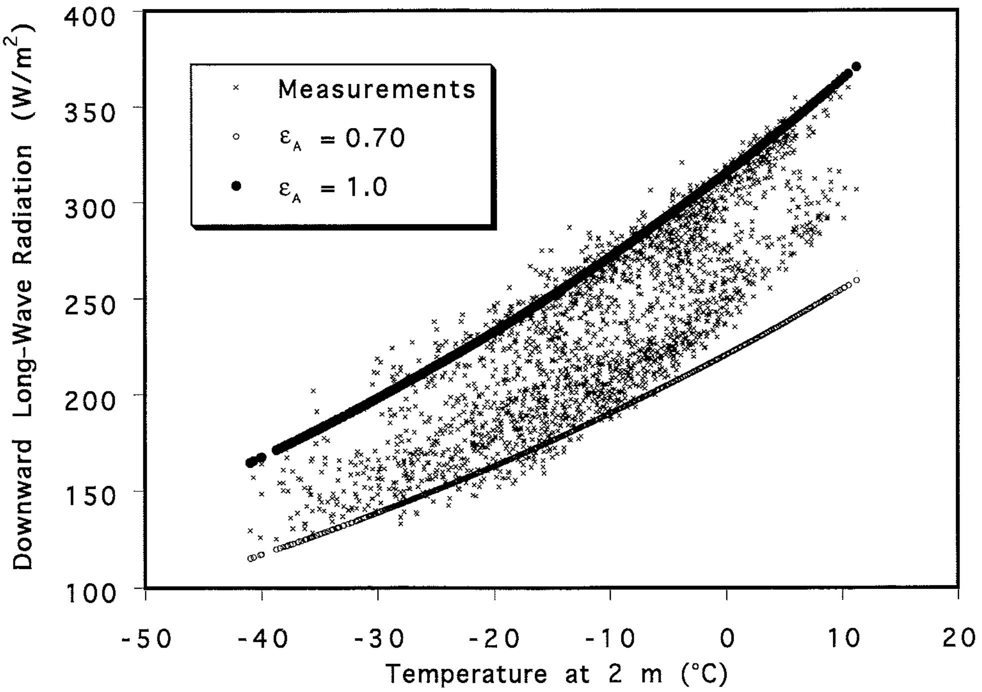

Fig. 2. Downward long-wave radiation versus air temperature at 2 m height for all cloud conditions.

Abb. 2. Gegenstrahlung in Abhängigkeit von der Lufttemperatur in 2 m Höhe für alle Wolkenbedingungen.

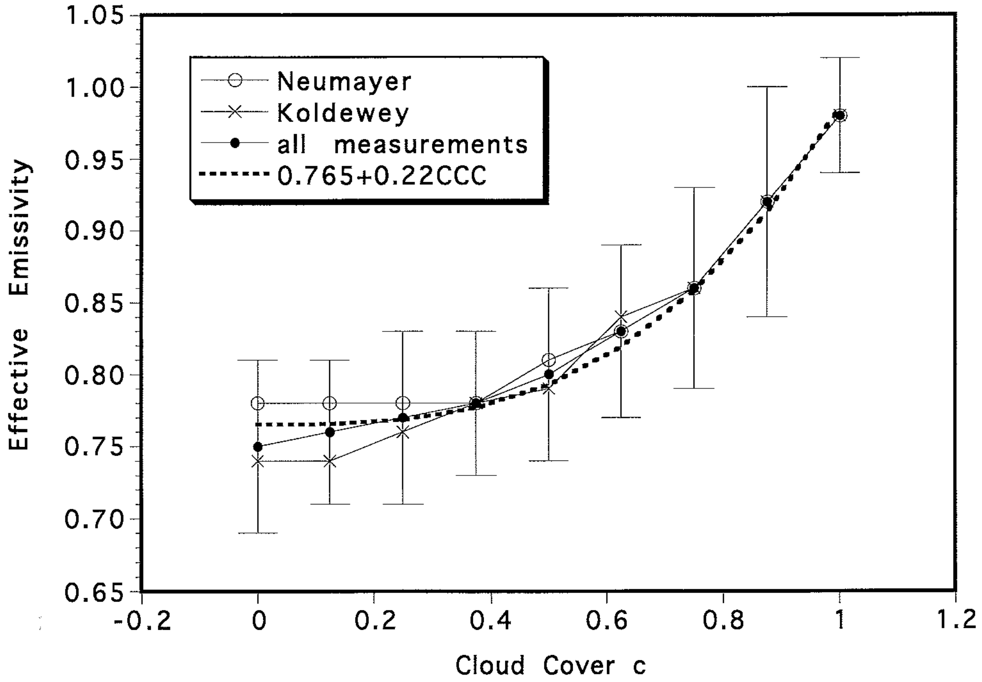

Fig. 3. Mean effective atmospheric emissivities versus total cloud cover c ($0 \leq c \leq 1$) for Neumayer, Koldewey and Eq. 2. The error bars represent the standard deviation for all measurements.

Abb. 3. Mittlere effektive atmosphärische Emissivität in Abhängigkeit vom Gesamtbedeckungsgrad c ($0 \leq c \leq 1$) für Neumayer, Koldewey und Gleichung 2. Die Fehlerbalken repräsentieren die Standardabweichung aller Messungen.

The application of daily averaged air temperature and cloud observations led to similar results as the instantaneous values. But due to the nonlinearities of Eq. (1) and Eq. (2) significant errors are caused for longer time averages which are occasionally used in model investigations.

5. Conclusion

We conclude from the intercomparison of two high-latitude Baseline Surface Radiation Network (BSRN) data sets with different parameterization schemes for the downward long-wave radiative flux that:

— The Stefan-Boltzmann radiation law (Eq. (1)) with empirically derived effective emissivities ε_A provides a reasonable first-order approximation of the downward long-wave radiation at the Earth's surface.

— The parameterization schemes for ε_A provided by MARSCHUNOVA (1961), KIMBALL et al. (1982) and by Eq. (2) are able to reproduce the annual mean of the observations to an accuracy of better than 4 W/m² with a RMS deviation of less than 20 W/m².

— Our Arctic and Antarctic data of the downward long-wave radiation can be approximated by the same parameterizations of ε_A in spite of different large-scale atmospheric flow and Earth surface conditions at both stations.

— The Stefan-Boltzmann law with $\varepsilon_A = 0.765 + 0.22\,c^3$ may be applied to instantaneous values as well as to daily averages of the near-surface air temperature T_0 and the total cloud cover c to achieve a satisfactory approximation of the observed downward long-wave radiation at the Earth's surface.

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