Annals of Glaciology 17 1993

Retrieval of surface radiative fluxes on the marginal zone of sea ice from operational satellite data

CLAUDE KERGOMARD, BERNARD BONNEL AND YVES FOUQUART
Laboratoire d'Optique Atmosphérique, Université des Sciences et Technologies de Lille, F-59655 Villeneuve d'Ascq Cedex, France

ABSTRACT. With the development of coupled atmosphere–ocean models for the polar seas, there will be a great need of surface radiation budget data over partially ice-covered sea surfaces of the marginal ice zones. This paper presents an attempt to retrieve the surface radiation budget components over the Fram Strait area from operational satellite data, i.e. AVHRR visible and infrared radiances and SSM/I passive microwave brightness temperatures. The cloud optical thickness, which is the main modulator for the incoming solar flux, is retrieved from AVHRR visible radiances through a radiative transfer model, assuming surface conditions deduced from the SSM/I ice concentrations. The cloud base emissivity, required for the downwelling infrared flux computation, is linked to the optical thickness through the liquid water path. The results presented show a good agreement with field measurements and little sensitivity to the cloud and aerosol properties extracted from the literature rather than from the satellite data. Infrared fluxes retrievals would however require a better knowledge of the atmosphere temperature profile and cloud base altitude.

INTRODUCTION

The surface radiation budget determines the source or sink of heat for the surface water and sea ice in the polar oceans. It is therefore an important component of the mass budget of polar sea ice (Makyut, 1986). Improvements in the treatment of polar sea ice in global climate models and the development of regional coupled ocean–ice models are at present in the scope of the polar climate research community. They would require a systematic record, over the full extent of the sea-ice field, of the surface radiation budget with a desired accuracy better than 5–10 W m^{-2} for monthly averages of regional fluxes (WRCP, 1991). Satellite remote sensing is the only way to sample adequately such data over polar oceans, but present sensors on board operational satellites provide only narrow-band, directional radiances from the top of the atmosphere rather than large-band solar and infrared fluxes from and to the surface. This requires extensive radiative transfer modelling in order to retrieve the surface radiation budget components.

The surface radiation budget over the polar oceans in summer (daytime) can be written as:

$$Q_{\text{net}} = S\downarrow(1-\alpha) - \epsilon\sigma T^4 + L\downarrow$$

where $S\downarrow$ is the downwelling solar (shortwave) irradiance, α the surface albedo, $\epsilon\sigma T^4$ the emitted (longwave) upwelling flux density and $L\downarrow$ the longwave downwelling flux density. The main modulators for the surface radiation budget over polar oceans are:

(1) The cloud cover acting on both the solar and longwave downwelling fluxes. As pointed out by Herman and Goody (1976), extensive layers of stratiform clouds (Arctic stratus) are frequently observed over the ice-covered oceans, where the mean cloud amount in summer rises up to 90%. Their effect on the incoming solar flux by reflecting the incident solar radiation back to space (albedo effect) is related to their optical thickness; their effect on the downwelling longwave flux by absorbing and reradiating the longwave radiation emitted from the surface (greenhouse effect) is related to their emissivity and to the cloud base temperature.

(2) The ice cover acting on the surface albedo and the surface temperature, that is to say the emitted longwave flux. In the Marginal Ice Zone (MIZ) of the polar oceans, fractional sea ice cover (ice concentration) may vary in a wide range from 0 to 100%: surface albedo will therefore vary between 0.1 and 0.6 or even more when snow cover persists on the sea ice. In summer conditions however, the effect of the ice cover on the emitted longwave radiation is slight because the surface temperature of sea ice and water do not vary much around the freezing point.

The main difficulty in retrieving the surface radiation budget from satellite data follows from the fact that both sea-ice concentration and cloud cover properties have to be observed simultaneously. Strong radiative interactions occur between them and have to be accounted for when deriving the radiative fluxes incoming to the surface from satellite radiances measured at the top of the atmosphere. In this paper, we present and discuss an attempt to retrieve surface radiative fluxes from operational satellite data using rather sophisticated radiative transfer models. We focus on the method and therefore limit the presented results to one day in late summer (31

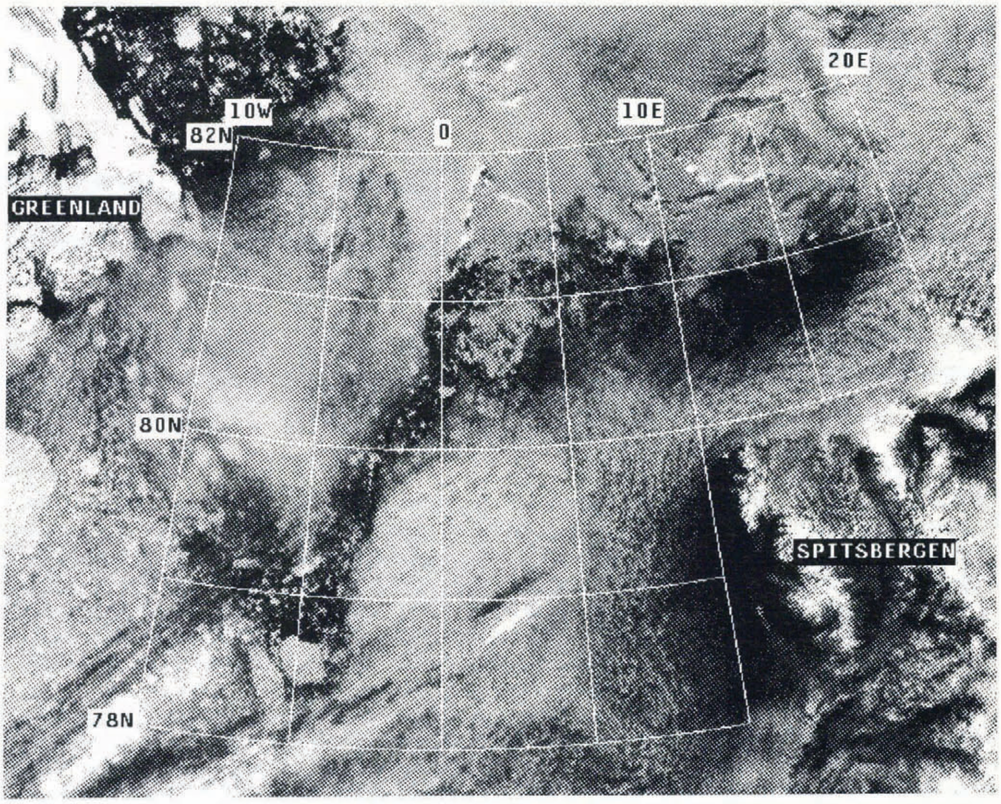


Fig. 1. NOAA-9/AVHRR channel 1 image over Fram Strait for 31 August 1988, 1030 h UT. The latitude and longitude grid delineates the area of interest.

August 1988) and to the Fram Strait area (78–82° N, 10° W–20° E). This date and these areas were selected according to the availability of in situ measurements acquired during the ARCTEMIZ 88 oceanographic campaign and AVHRR data from Tromsø Satellite Station selected during the same experiment. The Fram Strait area is a typical marginal ice zone (MIZ) with ice concentrations varying in a wide range from 0 (ice-free ocean) to more than 80% in the polar pack-ice north of Fram Strait. The selected satellite scene is typical for late-summer conditions with an extensive arctic stratus cloud cover over the pack ice and stratocumulus over the ice-free ocean along the coasts of Spitsbergen; cloud-free areas extend along the ice edge (Fig. 1).

CLOUD OPTICAL THICKNESS RETRIEVAL

Variations of solar flux incoming at the ocean surface depend mainly on the sun angle and on the cloud optical thickness; other factors, like the atmospheric absorption and scattering by molecules and aerosols, are of second order and may be considered constant over the area. In the same manner, incoming longwave flux is mainly controlled by cloud-base temperature and cloud emissivity. In climate models, optical thickness and emissivity of liquid water clouds are both linked to the liquid water path through realistic parameterizations, which allows us to deduce emissivity from the optical thickness.

As a first step, we therefore concentrated on optical thickness retrieval. We used a radiative transfer model, called GAME, specially designed to simulate directional AVHRR channel 1 or channel 2 radiances at the top of the atmosphere, with realistic atmospheric conditions including gaseous absorption and diffusion due to aerosol and cloud layers. The code is based upon the discrete ordinate methode (Stamnes and others, 1988). The requested inputs are spectral reflectance of the surface, atmospheric content of absorbing gases (mainly ozone and water vapour), aerosol optical properties, vertical distribution and density (i.e. optical thickness), and cloud layer altitude, geometrical thickness, droplet size distribution and optical thickness. The standard outputs are the simulated AVHRR radiances for the selected sun and satellite viewing-angle conditions. In this study, the model has been used in an iterative scheme to obtain the optical thickness of the stratus cloud cover.

Some of the requested input data have been extracted from the literature. This is the case for most of the aerosol parameters (optical properties and vertical distribution), which have been choosen according to D'Almeida and Koepke (1990); aerosol optical thickness has been adjusted from the AVHRR reflectance of cloudless and ice-free ocean pixels. For Arctic stratus cloud properties, including altitude, geometrical thickness and droplets size distribution, we selected a typical case from the large data set of Herman and Curry (1984). The ozone content of the atmosphere has been taken from SAGE II satellite data, while water vapour content and vertical distribution were set according to radiosounding from Bear Island (Bjørnøya), about 500 km southeast of Fram Strait. All these data were considered constant over the area. The other input data have been obtained from the satellite data, and averaged on a polar stereographic grid with a spatial resolution of 25 km. The Fram Strait area as delimited on Figure 1 is made of 300 pixels (or gridpoints) with this resolution, including each about 550 AVHRR pixels.

DMSP-SSM/I passive microwave data provided sea-ice concentrations for the 300 pixels of the Fram Strait area (Fig. 2); the SSM/I 19 GHz (vertical and horizontal polarisations) and 37 GHz (vertical polarisation) brightness temperatures were converted into ice concentrations by using the NASA SSM/I algorithm (Cavalieri and others, 1984). Ice concentrations provided the surface spectral reflectance requested by GAME according to ice-free water and sea-ice values read from the AVHRR data. Infrared radiances from AVHRR channels 3 and 4 were used to get the fractional cloud cover for every gridpoint: the difference in daytime radiances between AVHRR channel 3 (3.7 μm) and 4 (11 μm) is a very efficient ice/cloud discriminator, since such water clouds as Arctic stratus are highly reflective in the longwave part of the solar spectrum (Fig. 3) and ice or snow surfaces may be considered blackbodies at the same wavelengths (Raschke and others, 1992). AVHRR channel 1 (0.6 μm) reflectances were calibrated as accurately as possible and averaged for every gridpoint: these average reflectances were compared with the values simulated by GAME to obtain the optical thicknesses of the stratus cloud cover (Fig. 4).

The main difficulty in optical thickness retrieval arises from the fact that, for high ice concentrations, i.e. high surface reflectances, reflectance observed at the top of the atmosphere first decreases with increasing optical thicknesses for small values, and then increases with higher

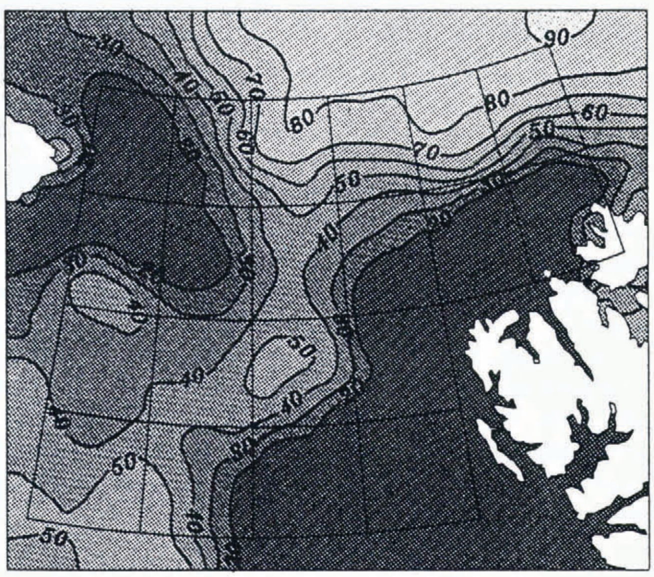


Fig. 2. Ice concentration over the Fram Strait area, obtained from SSM/I brightness temperatures.

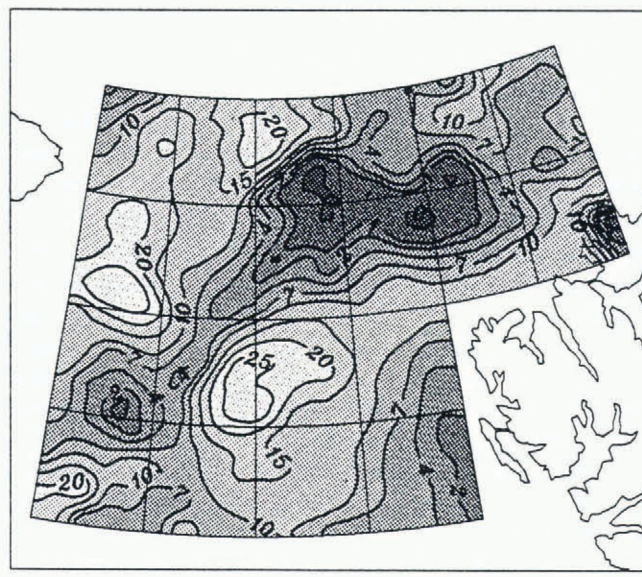


Fig. 4. Retrieved Arctic stratus clouds optical thickness.

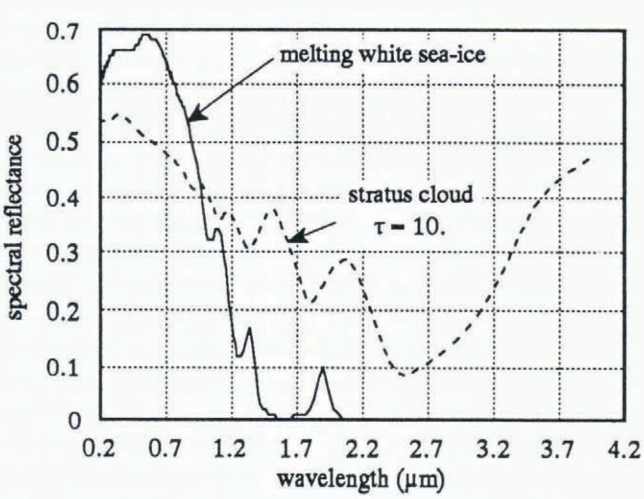


Fig. 3. Spectral reflectance curves for sea ice and stratus clouds. The ice curve is for melting white ice (Grenfell and Perovich, 1984). The stratus curve is computed for a typical stratus with optical thickness τ = 10 over the sea and solar zenith angle θ_0 = 70°.

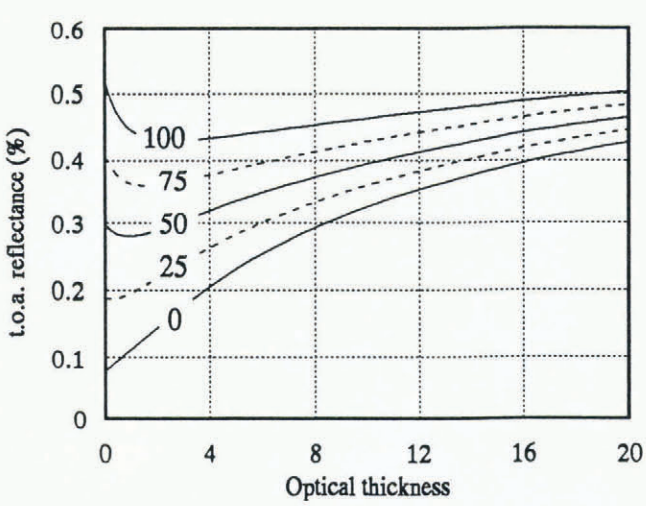


Fig. 5. Variations of the simulated AVHRR channel 1 reflectance with the cloud optical thickness and ice concentration. (Solar zenithal angle θ_0 = 75°. Radiometer viewing angle θ_v = 0°.)

https://doi.org/10.3189/S0260305500012842 Published online by Cambridge University Press

values (Fig. 5). This leads to two different solutions for the computation of the stratus optical thickness. The problem has been avoided by the previous fractional cloud cover determination using channels 3 and 4 of the AVHRR: the gridpoints with very low cloud cover were considered cloud-free and the optical thickness set to 0; for cloudy gridpoints, the highest optical thickness (considering a continuous stratus layer) was considered more likely.

SURFACE RADIATIVE FLUXES RETRIEVAL

From the retrieved optical thickness, the incoming, absorbed and reflected solar fluxes were computed by using a two-stream narrow band model based on the method of Zdunkowski and others (1980). This model accounts for gaseous transmission, aerosol and cloud absorption and scattering in 198 spectral intervals between 0.25 and 2.8 μm; its accuracy was proved within the framework of the Intercomparison of Radiation Codes in Climate Models (IRCCM). As gaseous and aerosol effects are considered constant over the area, and variations of the solar zenith angle are of second order, the map of retrieved incoming shortwave flux is very similar to that of optical thickness. At the time of the satellite pass (1030 h UT), the incoming solar flux $S\downarrow$ varies in the range of 250 W m^{-2} for the cloud-free areas to less than 60 W m^{-2} under a stratus cover with an optical thickness around 20. The map of the absorbed solar flux $S\downarrow(1-\alpha)$ (Fig. 6) is very different due to the albedo of sea ice cover: the higher values are found over cloud-free and ice-free areas (up to 190 W m^{-2}), while the pack-ice areas with dense stratus cover show values of 50 W m^{-2} or less. The spectrally averaged albedo of the sea ice cover does not depend only on ice concentration: due to the sharp contrast of the spectral reflectance of sea ice between visible and infrared wavelengths and the filtering of infrared by stratus clouds, the total albedo of sea ice increases with the optical thickness of the cloud cover.

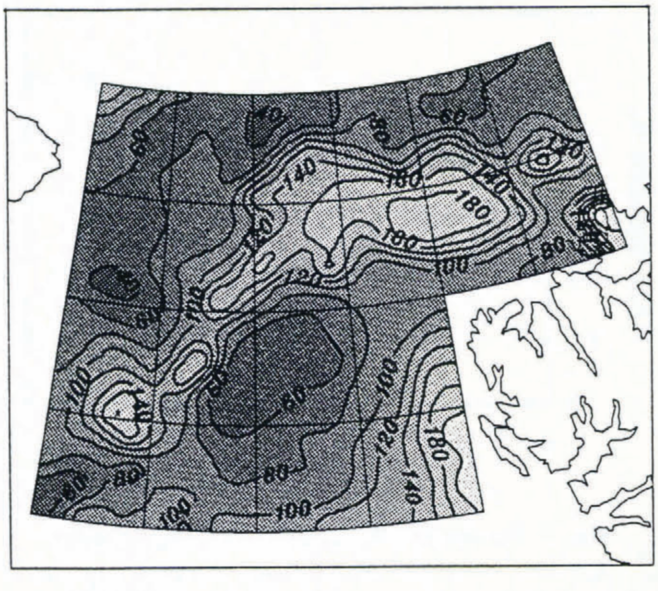


Fig. 6. Retrieved absorbed solar flux for 31 August 1988 at 1030 h UT.

The downwelling longwave flux was computed using a narrow-band model (Morcrette, 1984), where scattering effects are neglected and cloud droplets are considered as purely absorbing particles. In such a model, the longwave flux is related to surface temperature, water vapour amount and vertical distribution, cloud height (cloud base temperature) and emissivity. The first four of these parameters were fixed according to surface observations and radiosonde data for Bear Island. The cloud emissivity ϵ has been linked to the optical thickness τ through the cloud liquid water path (LWP) using:

$$\epsilon = 1 - \exp(-k\mathrm{LWP}) \qquad \text{and} \qquad \tau = \frac{3.\mathrm{LWP}}{2.r_e}$$

where k is the mean over the whole longwave spectrum of the mass absorption coefficient of liquid water and r_e is the effective radius of the cloud droplets ($r_e = 8.7\,\mu$m for the chosen stratus). As emissivity is the only parameter assumed to vary over the area, the map of the retrieved longwave flux is similar to that of the optical thickness, but with values ranging from 230 W m^{-2} for the clear areas to about 300 W m^{-2} under the dense stratus cover.

Looking further at the results shows that the mean daily cloud forcing of an Arctic stratus cover with optical thickness $\tau = 12.5$, in late summer conditions (31 August), may be estimated to -30 W m^{-2}, with a shortwave forcing about -85 W m^{-2} and a longwave forcing about $+55$ W m^{-2}. Assuming a surface temperature of $+1$°C over the open sea and -1°C over the ice, such a cloud cover should lead to a decrease of the daily-averaged surface radiation budget about -20 W m^{-2} over the open sea and to an increase of $+15$ W m^{-2} over a continuous sea-ice cover. This points the need to account accurately for cloud–ice interactions in future coupled ocean–atmosphere models.

ACCURACY AND DISCUSSION

Two different methods have been used to assess the accuracy of the retrieved fluxes. The first consisted of a comparison of the retrieved values with in-situ measurements, the second in a few tests of the sensitivity of the results to the choice of parameters extracted from the literature.

Validation data were obtained for 31 August from a pyranometer and a pyrgeometer on board the oceanographic ship *Cryos*, with only a short break in the morning (Fig. 7). During this day the ship moved in the area 80°30′ N to 81° N and 7–10° E. In the morning, cloud conditions were overcast, with a low stratus cloud cover, clearing at about 1100 h UT. In the afternoon the sky remained clear with occasional passing cloud-banks. From satellite data, we found that the ship crossed the edge between a stratus-covered area with optical thickness $\tau \approx 12.5$, and a cloud-free area. When comparing the simulated fluxes with the measured ones, a very good agreement was found, within the ± 10 W m^{-2} interval for both the shortwave and longwave downwelling fluxes. However, the longwave flux appeared very sensitive to surface and cloud-base temperatures: we had to correct the values provided by the radiosonde data from Bear Island, according to the local observations by

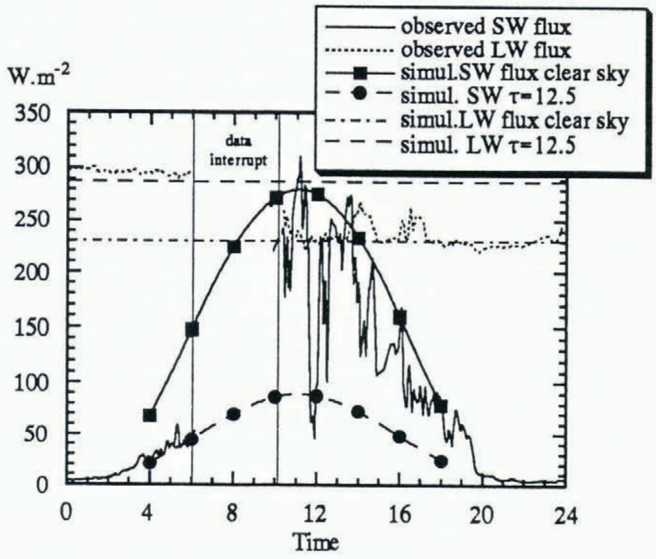


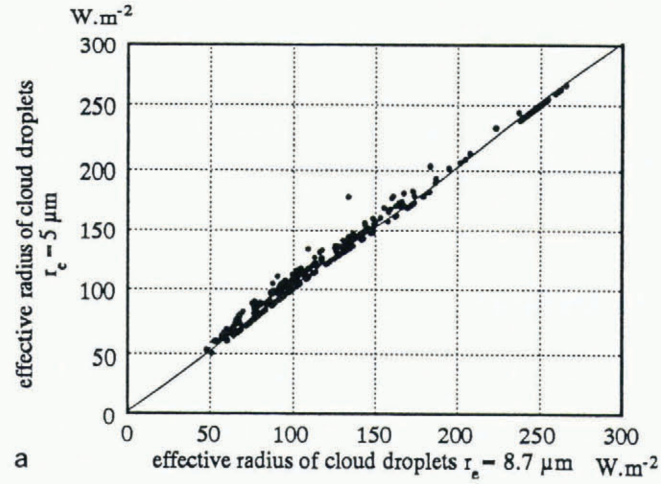
Fig. 7. Comparison of observed and computed radiative fluxes for 31 August 1988.

the crew of the *Cryos*, in order to retrieve reasonable values of the longwave flux.

Among the parameters used in the cloud optical thickness retrieval, polar aerosol optical properties and stratus cloud droplet-size distribution were extracted from the available literature. Although the particular choice we made appears the most reasonable, it remains arbitrary; we thus tested the sensitivity of the retrieved shortwave irradiance to these parameters. We compared the retrieved fluxes obtained in the most likely case of polar aerosol (single scattering albedo $\varpi_0 = 0.964$) with values retrieved assuming a highly absorbing aerosol ($\varpi_0 = 0.8$), like soot or industrial dust (Fig. 8a); the modified value has been used in both the cloud optical thickness retrieval and flux computation. In the same manner, we compared the fluxes computed in our case of low stratus (droplets effective radius $r_e = 8.7\,\mu m$) to those obtained assuming high clouds with considerably smaller droplets ($r_e = 5\,\mu m$) (Fig. 8b). The results show a slight sensitivity of the retrieved values to these changes, with differences in the retrieved fluxes smaller than $\pm 10\,W\,m^{-2}$.

From the study as a whole we conclude that shortwave fluxes over polar oceans might be obtained on a climatological basis from joint use of AVHRR and SSM/I data, with the desired accuracy for coupled ocean–atmosphere models. It implies that the different cloud types occurring in high latitudes were previously discriminated from the AVHRR imagery and accurately parameterized, as we did for Arctic stratus. Infrared radiation fluxes computation is more problematic and would require accurate additional data on surface and cloud-base temperature. In a further work, we will test if the present satellite sounding sensors, like the TOVS on board the NOAA satellites, could provide this additional information with the desired accuracy.

Cess and Vulis (1989) proposed to infer the net surface solar flux directly from satellite observations of the radiation budget at the top of the atmosphere. This method is independent of the surface albedo, and is thus particularly interesting in the case of highly variable surface albedo, for example in marginal ice zones. However, satellite observations do not provide a direct measurement of radiation fluxes, i.e. spectrally integrated irradiances, but radiances in narrow spectral intervals. The problem thus lies in the conversion of narrow band to broad band and of radiances to irradiances. These conversions are strongly dependant on the spectral characteristics of the scene. With the availability of broad band observations from the Earth Radiation Budget Experiment (ERBE), the approach of Cess and Vulis may be the most accurate; however ERBE data are available only for a limited period of time and the accuracy of the radiance to irradiance conversion over sea ice is known to be one of the poorest. Finally, this



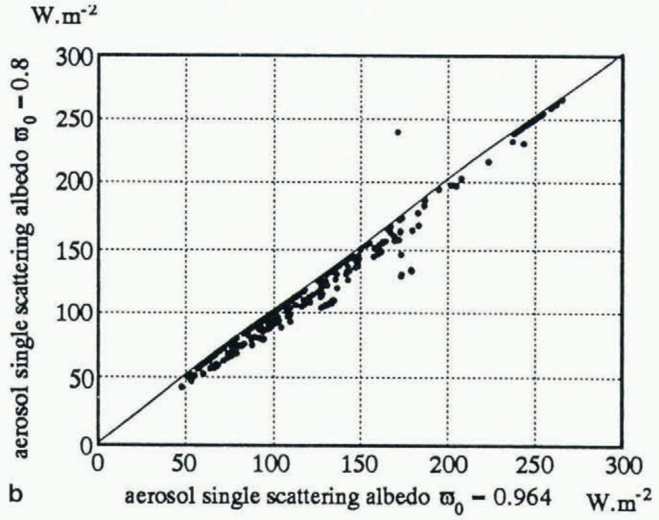


Fig. 8(a). Sensitivity tests for the parameters extracted from the literature. Aerosol single scattering albedo ϖ_0: comparison between retrieved solar fluxes with a single scattering albedo $\varpi_0 = 0.964$ (our case from the literature) and a single scattering albedo $\varpi_0 = 0.8$ (highly absorbing aerosol). (b). Sensitivity tests for the parameters extracted from the literature. Cloud droplets size: comparison between retrieved solar fluxes with a typical droplet size distribution for low Arctic stratus (our case from literature) with effective radius $r_e = 8.7\,\mu m$ and a case of higher clouds with smaller droplets ($r_e = 5\,\mu m$).

approach makes comparisons with surface observations extremely difficult, since one needs to measure the spatially averaged net surface fluxes, i.e. downward and upward fluxes. Since the upward fluxes are extremely dependent on surface conditions, experimental validations are nearly impossible in such inhomogeneous regions as the marginal ice zones. It is however possible to compare surface net fluxes as derived from both methods; this will be done in a forthcoming paper.

ACKNOWLEDGEMENTS

The work of Ph. Dubuisson, who set up the GAME radiative transfer code, is gratefully acknowledged. J. C. Vanhoutte, M. Fily and the crew and scientific team of the ARCTEMIZ 88 experiment were involved in collecting the field measurements on board N/O *Cryos*. AVHRR imagery was provided by the Tromsø Satellite Station in Norway and SSM/I data are extracted from the CD-ROM distributed by NSIDC in Boulder, CO. This work was supported by the Centre National de la Recherche Scientifique under contract of the Programme National Télédétection Spatiale.

REFERENCES

Cavalieri, D.J., P. Gloersen and W.J. Campbell. 1984. Determination of sea ice parameters with the NIMBUS 7 SMMR. *J. Geophys. Res.*, **89**(D4), 5355–5369.

Cess, R.D. and I.L. Vulis. 1989. Inferring surface solar absorption from broadband satellite measurements. *J. Climate*, **2**, 974–985.

Curry, J.A. and G.F. Herman. 1985. Infrared radiative properties of summertime Arctic stratus clouds. *J. Climate Appl. Meteorol.*, **24**, 525–538.

D'Almeida, G.A. and P. Koepke. Unpublished. Atmospheric aerosols, global climatology and radiative characteristics. Report, University of Munich.

Fouquart, Y., J. C. Buriez, M. Herman and R. S. Kandel. 1990. The influence of clouds on radiation: a climate-modeling perspective. *Rev. Geophys.*, **28**(2), 145–166.

Grenfell, T.C. and D.K. Perovich. 1984. Spectral albedos of sea ice and incident solar irradiance in the southern Beaufort Sea. *J. Geophys. Res.*, **89**(C3), 3573–3580.

Herman, G.F. and J.A. Curry. 1984. Observational and theoretical studies of solar radiation in Arctic stratus clouds. *J. Climate Appl. Meteorol.*, **23**, 5–24.

Herman, G.F. and R.M. Goody. 1976. Formation and persistence of summertime Arctic stratus clouds. *J. Atmos. Sci.*, **33**, 1537–1553.

Maykut, G. A. 1986 The surface heat and mass balance. *In* Untersteiner, N., *ed. The geophysics of sea ice.* New York, Plenum Press, 395–463. (NATO ASI Series. Ser. B. Physics, **146**.)

Morcrette, J.J. 1984. On the radiative parameterisation in a general circulation model. (Ph.D. thesis, Université de Lille.)

Raschke, E., P. Bauer and H.J. Lutz. 1992. Remote sensing of clouds and surface radiation budget over polar regions. *Int. J. Remote Sensing*, **13**(1), 13–22.

Schmetz, J. 1991. Retrieval of surface radiation fluxes from satellite data. *Dyn. Atmos. Oceans*, **16**, 61–72.

Stamnes, K., S. C.Tsay, W. Wiscombe and K. Jayaweera. 1988. Numerically stable algorithm for discrete ordinate method of radiative transfer in a multiple scattering and emitting layered media. *Appl. Opt.*, **12**, 2502–2509.

World Climate Research Programme. 1991. *Report of the Twelfth Session of the Joint Scientific Committee, Bremen, Germany, 18–23 March 1991.* Geneva, World Meteorological Organization Secretariat. (WMO/TD 432.)

Zdunkowski, W. G., R. M. Welch and G. Korb. 1980. An investigation of the structure of typical two-stream methods for the calculation of solar fluxes and heating rates in clouds. *Beitr. Phys. Atmosph.*, **53**, 147–166.

The accuracy of references in the text and in this list is the responsibility of the authors, to whom queries should be addressed.