

## The radiation budget of the atmosphere over the Arctic compiled from the ISCCP-FD data sets (preliminary results)

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**Abstract:** The technological advancements of the past two to three decades enabled the establishment of space-borne observational systems to measure worldwide clouds and related radiation fields at the top of the atmosphere. This data when combined with further information on the thermodynamic state of the atmosphere and ground allows for estimates of the radiation budget at ground and within the atmosphere. This information is urgently required to calibrate the output of climate models and to understand current changes in the climate system.

Results of the International Satellite Cloud Climatology Project (ISCCP) are here presented and compared with another but similar data set of the Global Energy and Water Cycle Experiment (GEWEX-SRB) and with ground-based measurements. This data describes details in space and time of the variability of radiation budget parameters at the surface and at the top of the atmosphere over the entire globe. Over the Arctic ice fields—our studies concern areas poleward of about 60°N—considerable uncertainties of more than 20 Wm<sup>-2</sup> still exist in both the long-wave and short-wave budget components at ground.

**key words:** Arctic radiation budget, climatology of polar regions, satellite meteorology

### 1. Introduction

The circulation in the atmosphere and oceans is primarily driven by the strong meridional gradient of energy supply from the Sun, where the equatorial regions are subject of a steady surplus and the polar regions of a steady deficit. The required meridional energy transport—at the present state of the climate—can be computed from the radiation budget at the top of the atmosphere (e.g. Trenberth and Caron, 2001). Also numerous other scientific and practical applications require an accurate knowledge of the radiation budget fields and their variability at the top (hereafter TOA) and bottom (hereafter SRB for surface radiation budget) of the atmosphere. Amongst them are studies of the Ocean-Atmosphere-Sea Ice-Snowpack Interactions (OASIS, see Shepson *et al.*, 2003) and their role in Global Change. These require an accurate knowledge of the amount and also spectral distribution of solar radiation reaching the

surface, as also many chemical processes within lower troposphere are driven by solar radiation (e.g. Barrie and Platt, 1997).

Various investigations of these quantities were based on measurements made at many single stations and during a large variety of individual and of coordinated larger expeditions (e.g.: Summary of data from earlier Soviet Stations by Fletcher *et al.*, 1966; the experiments SHEBA—see Perovich *et al.*, 1999—or FIRE-ACE—see Curry *et al.*, 2000). Ikeda *et al.* (2003) explained the role of clouds on the radiation budget above and consequently the life cycle of Arctic sea ice. Walsh and Chapman (1998) and later Intrieri *et al.* (2002) studied the influence of clouds on the net radiation at the surface, as also Yamanouchi and Charlock (1997) described the effect of clouds ice sheet and sea ice on the radiation budget in the Antarctic. Wang and Key (2003) tried to identify trends in clouds and radiation fields over the Arctic area.

Data of the earlier individual satellite experiments onboard the satellites Nimbus 2 and 3 were used by Raschke *et al.* (1968) to estimate with a simple technique the surface albedo over the Arctic. They could show its drastic seasonal change which is partly explained by expanded melt water ponds on the sea ice and by larger areas of open sea during the summer season. The very recent radiation products, which are derived by combinations of satellite and other basic data sets on the state of the atmosphere and grounds within the projects ISCCP (see summaries by Rossow and Duenas, 2004; Zhang *et al.*, 2004, and references quoted therein) and SRB (surface radiation budget) enable now much more detailed studies of radiation fields at the surface of such regions like both polar caps which are hostile for establishing permanent observational stations.

For direct comparison data from some stations of the BSRN (Baseline Surface Radiation Network, see Ohmura *et al.*, 1998) are available. In future—and at lower latitudes—they can be complemented by data of the GEBA (Global Energy Budget Archive; see Gilgen and Ohmura, 1999).

In the following section both data sets and their origin are briefly described. Section 3 introduces to some validations and in Section 4 a few interesting results are described.

## 2. The radiation products of the ISCCP and of the GEWEX-SRB

Both data sets (for the ISCCP see e.g. Zhang *et al.*, 2004; for the GEWEX-SRB see e.g. paper by Stackhouse *et al.*, 2004) are derived from a large variety of input data, which describe cloud fields, mean aerosol climatology, the thermodynamic states of the atmosphere and ground and also on the radiative transfer properties (emittance and reflectance) of the ground. Although most of this data is provided by the same source, there are distinct differences in their treatment. Further, major differences may be due to the use of different radiation codes and information of the radiative properties of the earth's surface.

We restrict here our interest only to the Arctic region poleward of 60°N, which is for the purpose of this study divided into 2 zones: one poleward of 75°N is entirely covered by sea ice almost throughout the year, and the adjacent sub-arctic one covers also vast continental areas in Eurasia and North America.

The time series available for this study have been obtained from their authors

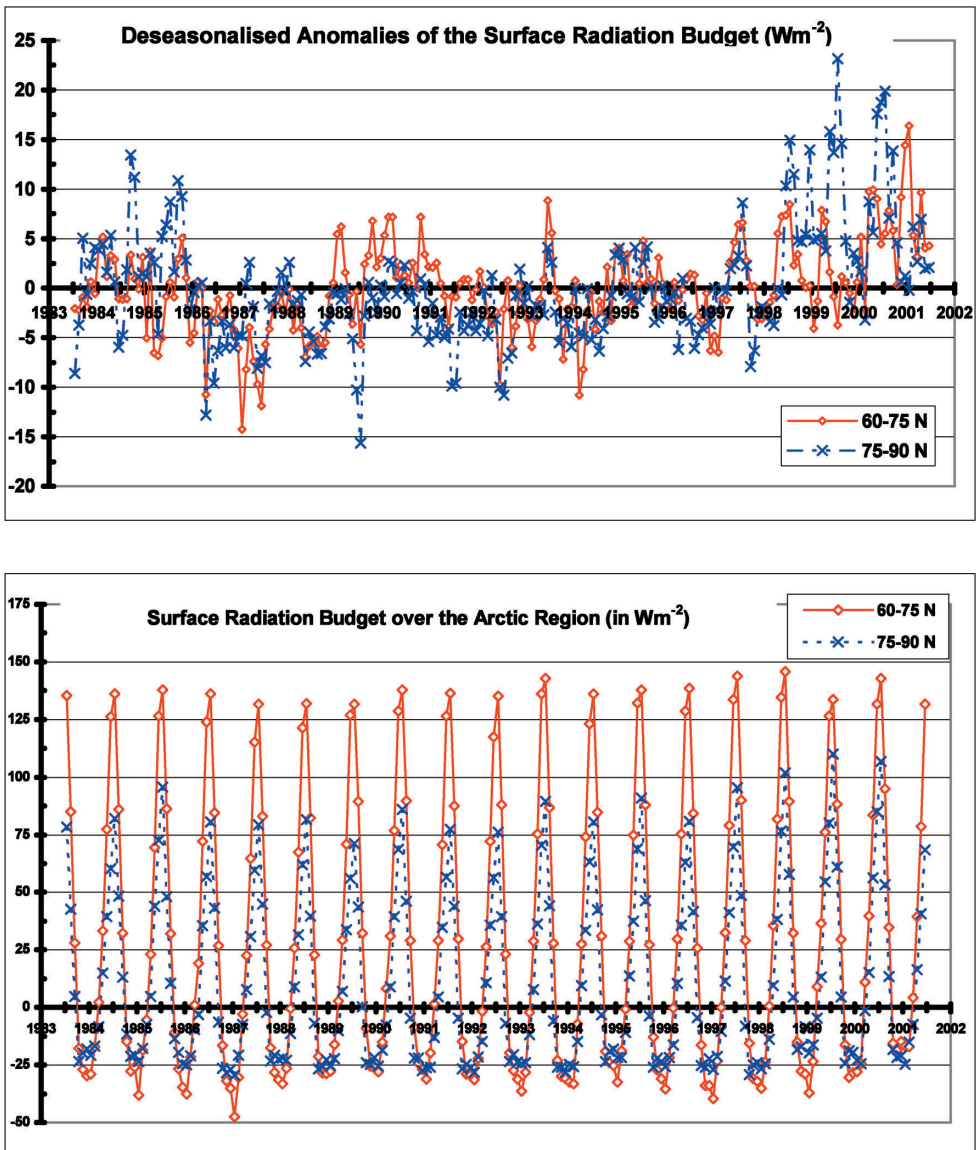


Fig. 1. Monthly averages of the total surface radiation budget over the entire Arctic Region between  $60^{\circ}$  to  $75^{\circ}$  N and  $75^{\circ}$  to  $90^{\circ}$  N as computed within the ISCCP (July 1983 to October 2001). Note the strong seasonal cycle in the averages (lower panel). The mean seasonal signal has been removed to identify easier interannual (weather noise, see top panel) and other variations. The small increase by about  $20 Wm^{-2}$  is due to decreasing values of the surface albedo. Individual spikes, if not correlated to other input might be subject of any error. Units:  $Wm^{-2}$

(ISCCP: Drs. Zhang and Rossow of GISS; SRB: Dr. Stackhouse of LaRC and also from internet sources of the ISCCP (<http://isccp.nasa.gov>) and of the GEWEX-SRB ([http://daac.gsfc.nasa.gov/www/islscp/rad/srb\\_radiation\\_1deg.shtml](http://daac.gsfc.nasa.gov/www/islscp/rad/srb_radiation_1deg.shtml)). They cover at present the periods from July 1983 to June 2001, and from January 1986 to October 1996, respectively. Their horizontal resolution at present is  $2.5^\circ$  and  $1.0^\circ$  in latitude and longitude. Both data sets will be extended soon over larger periods.

Over this area of the globe all radiation quantities are considerably dominated by the seasonal variability. Therefore the seasonal signal in those data had been reduced subtracting from individual monthly values a mean seasonal value, as it is demonstrated in Fig. 1 for the radiation budget at the surface computed from the ISCCP data set. The “de-seasonalised anomaly” shows a strong month-to-month variability, which might primarily due to the inter-annual variability of the weather. However, also some longer-periodic patterns have been made more visible in this treatment. For instance the increase of the surface radiation budget after the year 1998 can be attributed to the observed decrease of sea ice cover and thickness (see *e.g.* summary on sea-ice changes in the Arctic region by Johannessen *et al.*, 2004).

The monthly anomalies of the planetary albedo over all zones of the globe, are shown in Fig. 2. A small maximum of the albedo of our planet between the years 1992 and 1994 is possibly due to the aerosols of the Pinatubo eruption. It penetrated from the equatorial regions over both poles. The small minima of the albedo during the

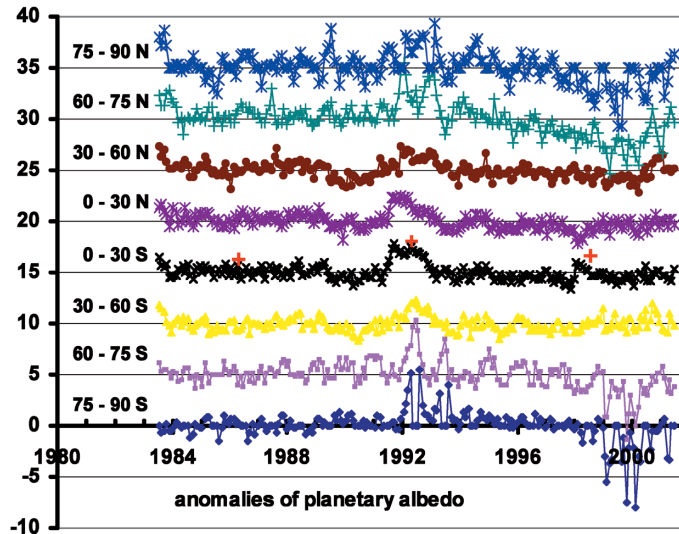


Fig. 2. anomalies of monthly averages (July 1983 to October 2001) of the planetary albedo over each latitudinal zone as computed by the ISCCP. Each curve has been moved by 5 units (%) from the lower neighbour. Albedo values during the polar night have been set to zero. Note the small maximum between 1992 and 1994, which is possibly due to aerosols of the eruption of Mt. Pinatubo. It expands from the equator to both poles. The decrease of the albedo during the period 1999 to 2001 at higher latitudes of both polar regions cannot yet be explained. + El Niño events.

period between about 1998 and 2001 over both polar regions can only be explained by the respective known temporary retreat of polar sea ice.

### 3. Initial validation of the ISCCP and GEWEX-SRB radiation products at ground

An initial validation of both data sets is made here by a simple comparison of monthly zonal averages of both and with concurrent measurements of downward radiation fluxes at the very few stations of the BRSN. Figure 3 summarizes the monthly averages of the downward atmospheric radiation for both zones. We see here a relative good agreement (within about  $2\text{--}4\text{ Wm}^{-2}$ ) between both during the respective summer months. However, during the winter months the ISCCP data indicate much (up to about  $15\text{K}$ ) higher effective temperatures in the lower troposphere than it is seen

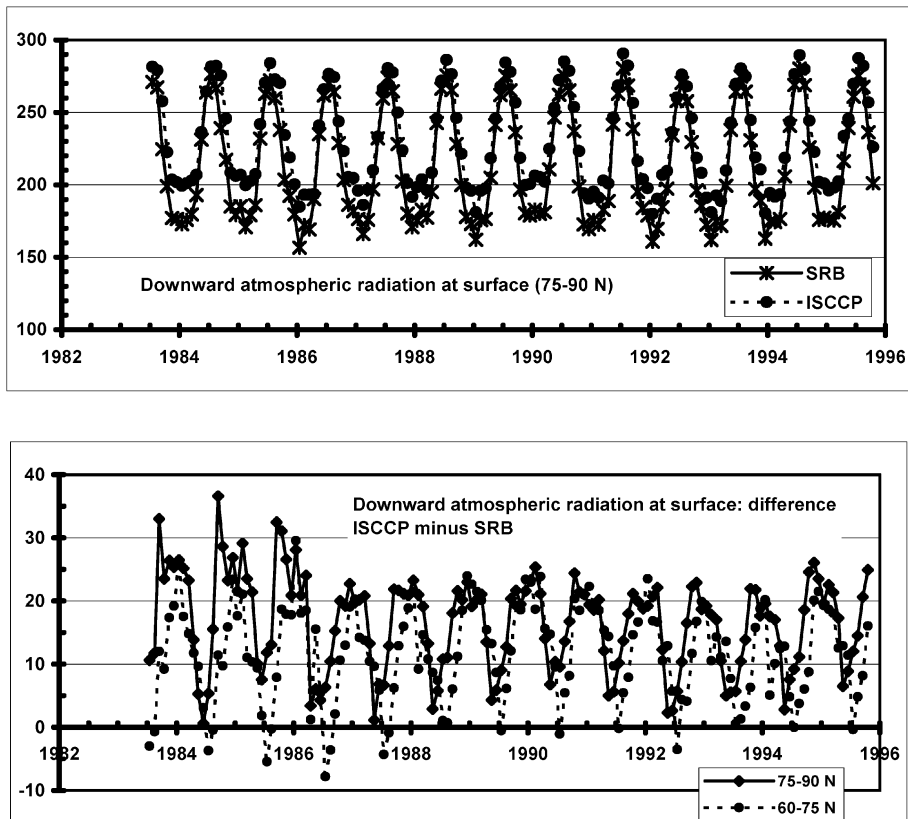


Fig. 3. Comparison between monthly averages (July 1983 to October 1996) of the downward atmospheric radiation as computed within the ISCCP (straight curves) and the GEWEX-SRB (dashed curves) over both zones in the Arctic. The ISCCP values are generally higher than those of the GEWEX-SRB, in particular during the polar winter differences of up to  $40\text{ Wm}^{-2}$  are obtained. Note the different vertical scales in both panels. Both data sets may miss the often strong inversion layers topped by clouds.

in the GEWEX data. Similar patterns and discrepancies occur also in the upward long-wave radiation at ground.

Also direct comparisons between the ISCCP downward radiation over several BSRN sites (South Pole, Georg von Neumayer, Ny-Ålesund and Point Barrow) show a similar disagreement (as described later). Consequently in the near future a detailed inspection of the surface temperature values, which were used in both analyses, is required.

We further compare also the solar components in the surface radiation budget. Scatter diagrams between the net values at ground for solar and terrestrial (long-wave)

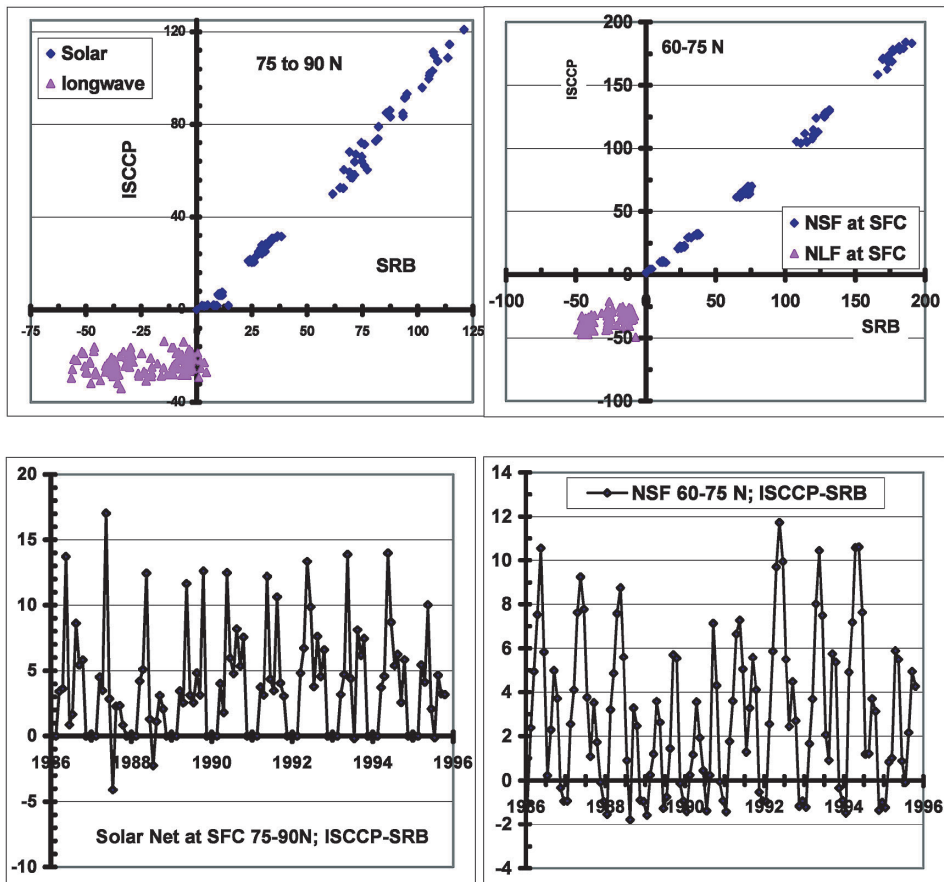


Fig. 4. Top row: Scatter diagrams of solar (NSF) and terrestrial (NLF) net radiation at the surface over the zones 75–90°N and 60–75°N, as computed with the methods and data of the ISCCP (ordinate) and the GEWEX-SRB (abscissa). Both methods produce solar budgets, which deviate up to 5 to 15  $Wm^{-2}$ , while the longwave budgets appear not to be correlated (for more details see text). Bottom row: Differences between net solar radiation at the surface between the ISCCP and GEWEX-SRB data sets. Since the SRB algorithm for the incoming solar radiation cuts off the low sun angle than the ISCCP algorithm negative differences are found during the northern winter.

radiation are reproduced in Fig. 4, showing an almost perfect correspondence between the solar radiation budgets of both data sets, but the mean difference between monthly values amounts to about  $5\text{--}15\text{ Wm}^{-2}$ . The largest differences occur during the mid-summer periods. The ISCCP computes generally a higher solar budget at ground than the GEWEX-SRB. There are also relatively high differences in the surface albedo and downward solar flux between both data sets.

However, both long-wave budgets at ground show almost no correlation over the Arctic basin. When plotted *vs.* time the budget of the ISCCP data is almost 5 months out of the solar forcing phase although both individual components of it are “in phase” with the solar forcing.

There is only one single ground station of the BSRN (Ny-Ålesund on the island Svalbard) located in the area of interest. Another (Point Barrow, Alaska) is located further south, but its measurement should also be typical for this area. Therefore we combined in Fig. 5 scatter diagrams of monthly averages of downward solar radiation (top row) measured at both stations and also at the stations Syowa and Georg-von-Neumayer, located on the Antarctic Continent.

These show a close correlation with simultaneous ISCCP-FD results, but the individual data points scatter often by more than  $20\text{ Wm}^{-2}$  around the 1-to-1 line which may also correspond to the limits of accuracy of ground-based measurements of the downward solar radiation over those areas. In general the downward solar fluxes generated in the ISCCP model correspond to those measured at ground, while the atmospheric model in the SRB data set (see lower row in Fig. 4) are somewhat less transparent.

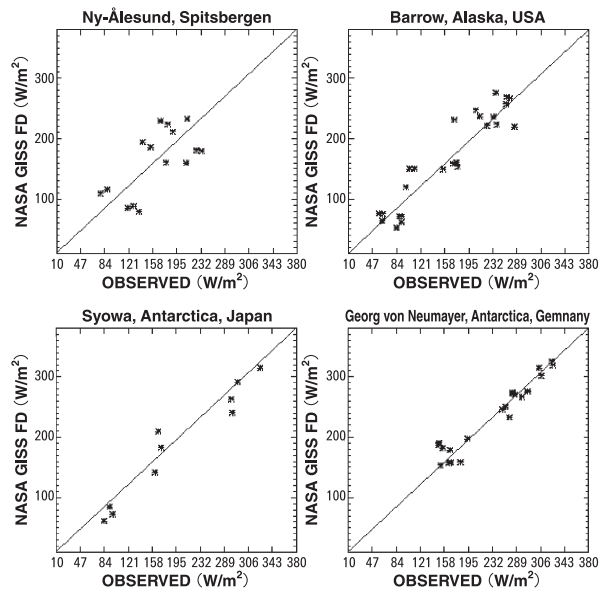


Fig. 5. Comparison of monthly averages of downward solar radiation computed by ISCCP-FD and measured directly at 4 stations of the BSRN in polar regions (communicated by M. Wild, Zürich).



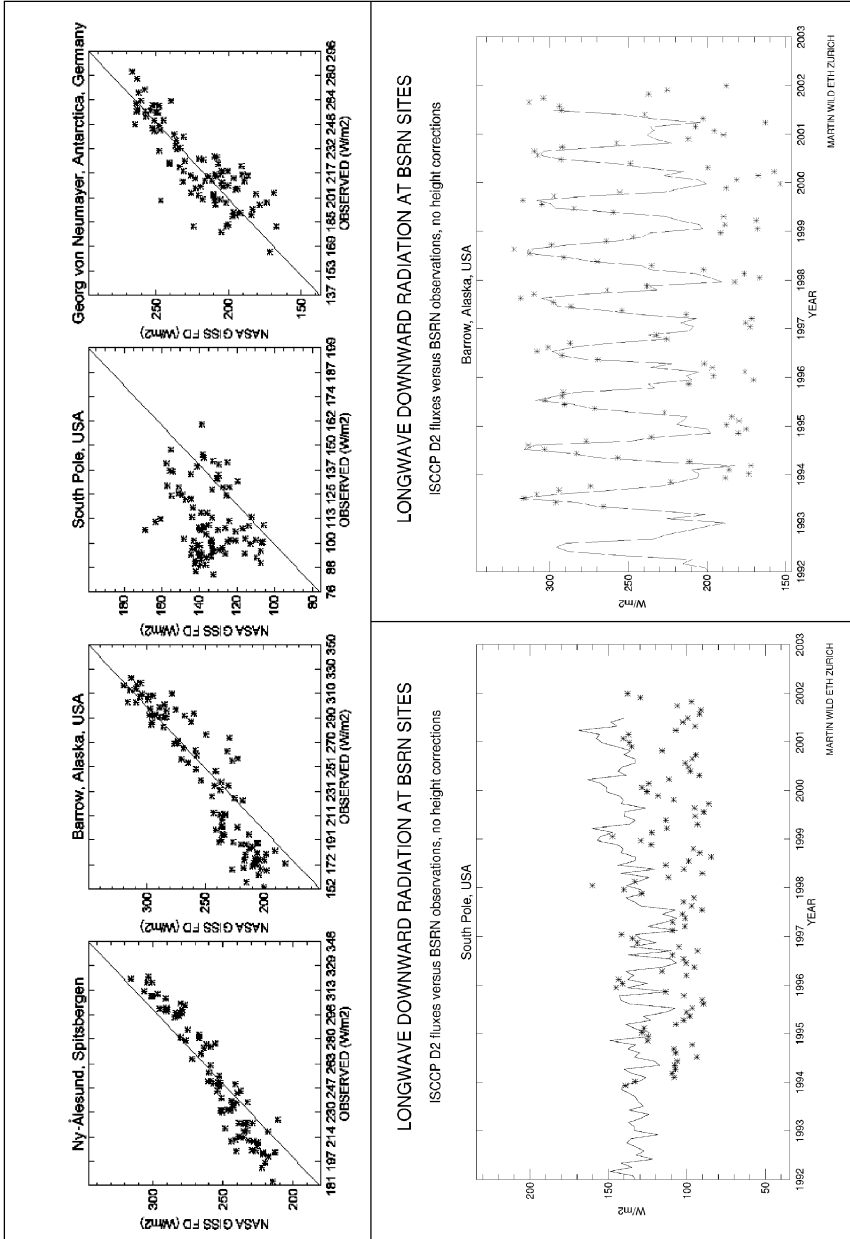


Fig. 6. Downward atmospheric heat radiation values, which have been measured at several polar stations of the BSRN, are compared with ISCCP-FD products. The time series shown in the bottom row (x=BSRN, lines=ISCCP) explain with more detail the large scattering shown in the diagrams above. Apparently at this stage of the data analysis, the temperature fields used in this retrieval show little correspondence to the reality.



Much larger (and unacceptable) differences are found in simultaneous data of the downward fluxes of atmospheric heat radiation at those for stations, as shown in Fig. 6. The ISCCP downward fluxes seem to be too high in particular during the polar winter over both hemispheres. The correspondence between the direct measurements and the values derived from the ISCCP data set is not very satisfying. This comparison also demonstrates, that at the present stage the ISCCP-FD results are possibly based on too high values of the temperature in the lower troposphere, in particular during the polar night, when lowest values of atmospheric downward radiation are measured. The temperature profiles used in this method need a more careful adjustment with respect the presence of the strong temperature inversions near ground. These direct comparisons confirm the finding described above, that the ISCCP-FD is probably too warm during the polar winter, which is a large error in their input data sets.

Over the sub-polar region in the North, which covers also larger continental surfaces, both data sets seem to agree better during winter, while the ISCCP is too warm (by often more than  $20 \text{ Wm}^{-2}$ ), during the winter months (Fig. 3 lower panel).

#### 4. A summary of all radiation budget components derived within the ISCCP

In the following we present a few samples of other components of the radiation budget over the entire Arctic region between  $75^\circ$  and  $90^\circ \text{ N}$ . In Table 1 we summarize for this purpose the mean seasonal range, the inter-annual (weather) and total ranges of the anomalies of the radiation budget components. Also mean annual averages for the 18-year period of this data set are given. For most of these quantities the seasonal cycles of monthly averages explain more than 80% of the variation during this period. The inter-annual (mostly weather-related, hence called here “weather range”) variability exceeds seldom a range of more than  $5 \text{ Wm}^{-2}$ . However in this data set often single spikes are found which need more study to explain them either by natural variability or caused by errors in the manifold input data. The (quite low) mean annual value for the surface albedo is based on averages of the solar radiation budget and the downward solar radiation at surface. Thus it represents the low albedo during the summer months when water ponds form on top of the sea ice and often large open ice-free areas occur.

This table lists also the effect (CE) of clouds on the respective budget components, which in principle describes the amount of radiative energy added to or subtracted from the up- or downward fluxes at clear skies, but for the same climate conditions. This quantity has often been misquoted as a force, henceforth it was called cloud radiative forcing.

For instance during winter clouds tend to increase slightly the planetary radiation budget (here ERB) at TOA, while during the summer season they enhance slightly the albedo at TOA and thus reduce the amount of solar radiation which is available for absorption by the climate system. On the other side, clouds enhance the amount of downward long-wave radiation reaching the surface.

As an example for the spatial pattern of the total radiation budget at TOA over both Polar regions is given in Fig. 7 for annual averages of the period 1991 to 1995. These values are typically negative, since the atmosphere is steadily loosing radiatively energy to space and therefore must be heated by sensible and latent heat from below.

Table 1. Ranges of various radiation budget quantities and of the cloud frequency of occurrence over the Arctic region ( $75^{\circ}$  to  $90^{\circ}$ N) as computed from the ISCCP-FD data sets. The “weather range” is primarily due to interannual changes of the circulation over this area, while the “maximal range” contains both long-term variations and also spikes, which might be due to errors in the input data and need specific analyses. Values with CE describe the effect of clouds on the related quantity, where positive (negative) values mean an increase (decrease) in comparison to the cloud free atmosphere. Su and wi mean summer and winter, OLR is the outgoing longwave radiation at TOA.

Product	Seasonal range	Weather range	Max. range	Annual average	Product	Seasonal range	Weather range	Max. range	Annual average
ERB at TOA	0 to -180	5	25	-110	Total SRB	-25 to +85	5	25	-2
OLR at TOA	-170 to -225	8	12	-188	CE of SRB	0 to 45	3	5	30
Planetary albedo	54 to 64 %	2 %	6%	60 %	LW SRB	-17 to -27	5	15	-23
CE of ERB	+15 (wi) to -32 (su)	2	5	-4	Total divergence	-80 to -160	6	20	-135
CE of OLR	7 to 14	4	20	12					
CE of Albedo	4 to 11 %	1	2	8 %	CE of total divergence	-28 to -38	3	10	-34
LW down at surface	190 to 280	5	20	225	LW divergence	-140 to -200	5	18	-168
CE of LW down	39 to 51	5	10	44	SW divergence	40 to 60	5	20	50
SW down at surface	0 to 290	5	20	100	Cloud frequency	60 (su) to 75% (wi)	5	15	66 %
LW up at surface	225 to 315	4	15	260	Albedo of surface	45 to 72 %	2 %	10 %	55 %

Also the ground is cooling, where meridional heat transports by the oceans and the atmosphere are keeping this situation at an equilibrium. The spatial pattern over both hemispheres reflect the mean lower tropospheric temperatures and also extremes in the orography (high plateaus over Antarctica and Greenland) as areas of smaller deficit than warmer (and lower) areas. More quantities in maps, showing also the seasonal variability, have been discussed already by Raschke *et al.* (2005).

We made also several comparative studies of time series of anomalies (“de-seasonalised”) of various radiation budget quantities in order to find both, inconsistencies in the computational procedure and flow of input data, which may often show up by spikes, and also to identify potential long-term changes in the Arctic radiation budget. One example is shown in Fig. 8. Several large spikes in those data series call for a closer inspection of their origin. Some of them, occurring towards the end of the series, might be due to the observable steady increase of the surface

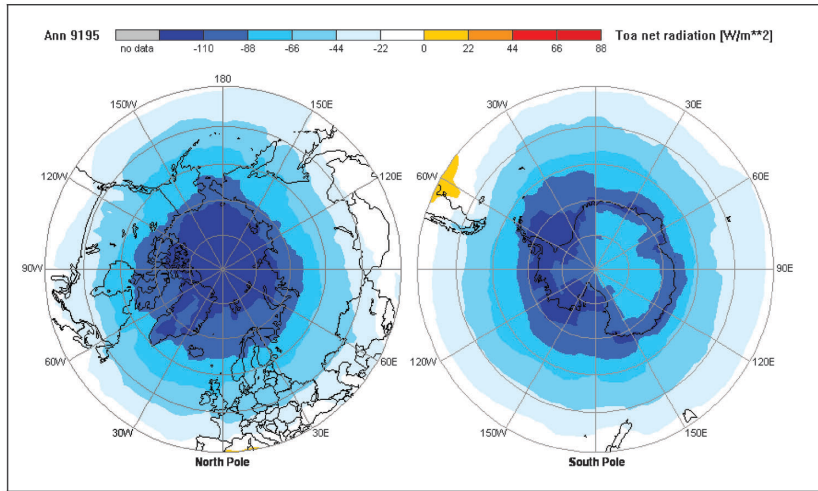


Fig. 7. Annual (1991 to 1995) averages of the planetary radiation budget (=ERB at TOA) over both polar regions, computed from the ISCCP data set.

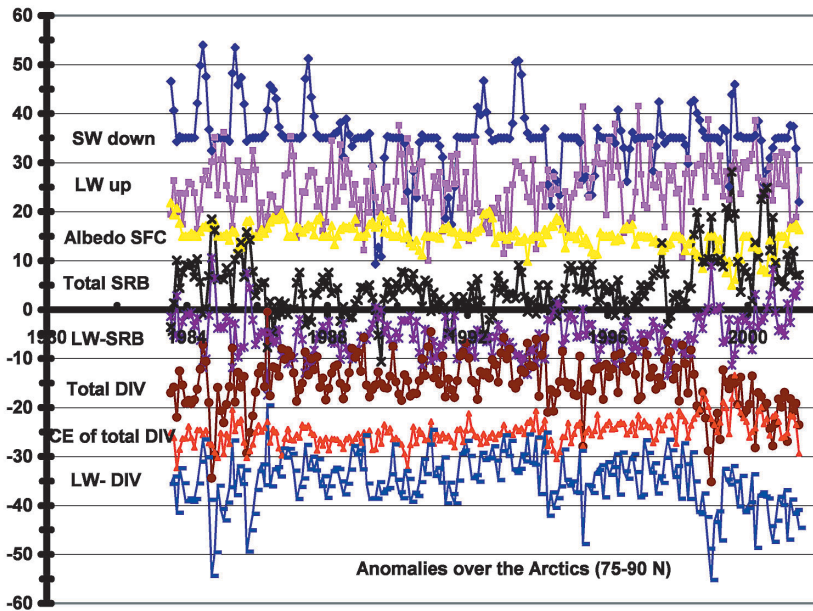


Fig. 8. Time series of monthly values of de-seasonalised anomalies of various radiation budget quantities (products of the ISCCP) over the Arctic region show the explained weather noise (interannual variability) but also some major changes which might be due to changes in the surface albedo and temperature. Some other similarities, e.g. the large amplitudes between the years 1984 and 1986, need further investigation. Due to the still large error ranges it is too early to identify natural “trends”, although the decrease of the surface albedo and increase of the upward long-wave radiation could be interpreted as such a longer-period variation. Units (except for the albedo in%) are in  $Wm^{-2}$ , and the vertical scale is shifted to allow for better discrimination between the different curves. SW=solar, LW=terrestrial, SFC=surface, DIV=vertical radiative flux divergence

temperature and decrease of the surface albedo during the later years. Of particular interest in this figure are the time series of the vertical radiative flux divergence in the atmosphere and the cloud effect (CE) on it. It seems that the CE increased with time during that period, forcing the longwave loss to space (LW divergence) to decrease. A similar behaviour was also found over the Antarctic plateau by Yamanouchi and Charlock (1995).

The various radiation budget parameters show often small similarity with time due to either long-term changes in the respective part of the climate system. For instance the increasing retreat of the Arctic sea ice during the last 3 to 5 years of the observational period causes higher surface temperatures and lower surface albedo values during the summer months.

## 5. Final discussion

It has been demonstrated here the feasibility to derive quite realistic values on the various components of the surface radiation budget by combination of appropriate satellite based observations of cloud fields with other data sets containing further information on this energy exchange. This additional data is based on both actual observation and analyses, respectively, and on some climatological information. Within the scope of the World Climate Research Programme two major project make use of this technique. One of them, the ISCCP (see Zhang *et al.*, 2004 and various previous papers quoted therein), produced already a time series spanning over 18 years from July 1983 to June 2001. The other data set is produced with the surface radiation budget project (SRB) of GEWEX and spans at present over 10 years (*e.g.* Stackhouse *et al.*, 2004).

The preliminary comparisons made here between both and with concurrent surface based measurements of the downward solar and atmospheric radiation demonstrate several errors inherent in these results. These comparisons confirmed in principle the estimates of uncertainty made by Zhang *et al.* (2004), which are to be placed within a range of  $\pm 15$  to  $20 \text{ Wm}^{-2}$ . The stability of such estimates might be better but it depends extremely strong on the stability of all ancilliary data sets required for the computation of such radiation values. In a recent study of required accuracies, of required stabilities of measurements and in particular of the derived radiation products much smaller values have been requested of about better than  $\pm 5 \text{ Wm}^{-2}$  and about 1/10 of this value for the stability (Ohring *et al.*, 2004). Both data sets are still far away from this request.

The ISCCP-FD data might be in particular be too warm during the polar winter. Both data sets show a disagreement in their results on the solar radiation budget at ground of more than  $15 \text{ Wm}^{-2}$ . There are several spikes in the time series, which need very careful re-analyses of the related input data sets. More intensive work is still required to enhance the scientific value of the ISCCP-FD sets. Observable longer-term climate changes, such as the increase of surface temperatures and possibly also decreases of the mean surface albedo, which appear in this data, are due to the related data input. One part of all uncertainties might be also due to the fact, that aerosols and clouds play a major role in the atmospheric heat budget. Both are difficult to observe with passive

sensors. Therefore in future active sensors on ground or in space (see *e.g.* Shiobara *et al.*, 2003) should provide more observations to improve such radiation products.

Both data sets use as input the cloud information as determined in the ISCCP, which is in particular quite uncertain during the polar night, when strong inversions near the ground make cloud surfaces warmer than the cloud-free surface nearby. The ISCCP radiation products confirm however the other findings by Walsh and Chapman (1998) and by Intrieri *et al.* (2002), that during the polar summer months the cloud fields tend to reduce the total radiation budget at ground (cooling) and enhance it during the polar winter and transitional months. Our preliminary studies can not yet confirm the trends in Arctic clouds and radiation fields, which Wang and Key (2003) describe, due to inherent uncertainties, discussed above.

Despite of these and other uncertainties, which definitely will be subject of an already planned assessment of all those data sets, both time series should be used in current research to validate related model output and to study in particular the role of clouds on the radiative energy transfer within the climate system. The computed signs (and also amplitude ranges) of cloud effects appear quite realistic.

We, however recommend an intensive use of these data sets, in particular of their capabilities to provide information on the horizontal distribution of radiation fields, whose amplitudes then need careful adjustment to simultaneous ground-based measurements.

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