Measurements of clouds, and radiation from space for climate studies

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The technological advancements achieved during the past two to three decades enabled considerable progress in establishing space-borne observational systems for clouds and associated radiation fields. Measurements are now available for worldwide studies of climate variations. However they are still lacking in reliable accuracies and stability for global trend identification. This paper concentrates on recent results obtained on clouds and their effects on the radiation budget.

1. Introduction:

The early climatologists, as early astronomers for planets, were with highest priority interested to obtain quantitative information on the radiation budget fields at the top and bottom of the atmosphere, knowing that any spatial gradients of it force redistributions of energy. The equator to pole gradient forces steadily related heat transports in the atmosphere and in the oceans. Furthermore clouds in the troposphere are not only indicators of various dynamical processes. They modify the transfer of radiative energy and they are source of the ever needed precipitation. Therefore already the first meteorological satellites, which were successfully launched in the period between the years 1958 to 1970, carried (in comparison to the present situation) relatively simple sensors to measure clouds and also the components of the radiation budget at the top of the atmosphere. These early measurements formed already the presently accepted general picture on the radiation budget of our planet (Raschke, 1972), which however needs now details on its variations in space and time and on their uncertainty limits.

Since then the drastic advances in instrumental and computer technologies enabled the construction of more complicated instruments with enormous high data rates to be send down to earth and also rather detailed numerical models for the global climate system. The latter produce results on clouds and radiation fields for the present and even for future climate states, which however still do not agree with measurements of the same time period (see project CMIP: Bader (ed.), 2004; Potter and Cess, 2003). Future demands for improvement of climate and weather prediction and of the identification of regional or even (weaker) global climate trends call for much improved models and for more accurate and stable measured information (see NISTIR 2004; and recommendations of various projects of the WCRP).

This paper describes briefly the present status of space-borne cloud and radiation measurements and provides also a possible outline for the future.

2. Cloud observations from space

Tropospheric clouds, due to their composition of particles, modify the short-wave solar and longer-wave terrestrial (infrared) radiation in such ways, that multi-spectral imaging measurements contrast them against the mostly darker (solar) and warmer (infrared) ground. When simultaneous multi-spectral observations are available as with the presently used multi-spectral imager MODIS, this contrast allows not only to estimate the total cloud cover within given areas and often also at 2 to three different altitude ranges. They also allow to estimate the effective optical thickness and mean effective particle size and phase (ice or water). There are now many attempts reported to estimate also some aerosol characteristics from satellite data, since aerosols affect directly and indirectly (e.g. Lohmann and Feister, 2004) the radiative transfer properties and also precipitation efficiency of cloud fields.

The very recent operational network of polar and geostationary satellites provides – in conjunction with all other meteorological and climatological observations – a solid basis to establish longer time series which are superior to the earlier ones, which had to be based on relatively simple ones (one or two spectral intervals, or multi-spectral sounders with relatively course spatial resolution). Numerous new algorithm developments are now being discussed. Some allow for identification and even some characterisation of aerosols within cloud free areas. This information is required to identify quantitatively direct and indirect effects of aerosols on clouds and also on the planetary radiation budget.

Two such time series, covering already time periods of about 20 years are now available. The data series of the International Satellite Cloud Climatology Project (ISCCP: Rossow and Duenas, 2004; Zhang et al., 2004, or their website: http://isccp.giss.nasa.gov) begins during the year 1983. Besides of this satellite-borne information on cloud fields it also contains all supporting data (see Table 1 below), which are used in this retrieval algorithm, and all original and well calibrated radiance measurements. Thus re-analyses on the basis of more recent knowledge might always be possible.

Variables	**Data set of variables**
Cloud Cover, Optical Thickness, Top Temperature by Type	ISCCP satellite radiances
Cloud Particle Size	ISCCP-based Climatology
Cloud Vertical Structure	Combined ISCCP-Rawinsonde Climatology
Atmospheric Temperature and Tropospheric Humidity	TOVS, Oort Climatology for filling
Atmospheric Humidity (Upper Troposphere, Stratosphere)	SAGE Climatology
Atmospheric Composition	Actual record from Various Sources
Stratospheric Total Ozone	TOMS, TOVS for filling
Stratospheric Ozone Profiles	SAGE Climatology
Stratospheric Aerosols	SAGE
Tropospheric Aerosols	Baseline Current-day Climatology
Snow cover	NOAA product
Sea Ice cover	NSIDC product
Diurnal Cycle of Air Temperature over Land	Climatology based on surface weather reports and NCEP reanalysis
Surface Skin Temperature and Visible Reflectance	From ISCCP retrievals
Surface Spectral Albedo and Emissivity by Type	GISS GCM reconstruction by surface type and season

Table 1: Variables to be used in the cloud retrieval from the ISCCP radiance data

Quantity	**global**	**ocean**	**land**
Cloud amount [%]	67 *73*	71 *75*	57 *69*
Cloud-top temperature [K]	261 *261*	266 *264*	251 *256*
Cloud-top pressure [hPa]	587 *607*	631 *631*	489 *547*
Cloud optical thickness/ Effective emittance Cloud water path [gm^{-2}]	4.2 *0.57* 62.0	4.2 *0.57* 58.6	4.1 *0.55* 69.6
Atmospheric water vapour [cm w.e.]	*2.51*	*2.60*	*2.23*

Table 2: Global cloud properties from 5 years of ISCCP / TOVS Path-B (italic)

Table 2 summarizes the major results and compares them with those derived from other – often concurrent measurements with operational sounders (TOVS Path-B – see e.g. Scott et al., 1999; Stubenrauch et al., 1999). This sounding technique, which is performed primarily to obtain operationally information on the vertical temperature structure of the lower and middle atmosphere, allows by proper combination of concurrent measurements in different spectral ranges (called "colour slicing") a sharper contrasting of higher and medium level clouds against the background. This time series, mostly obtained from a single satellite, but in no case from geostationary orbit, covers a period from 1983 to 2001.

3. Radiation fields and cloud effects

3.1 Measured at TOA

Fields of the radiation budget components at TOA can be derived either from measurements with wide-field-of-view radiometers, which "see" the entire disc of the earth under the satellite, or from narrow-field-of-view radiometers. The latter enable budget analyses with a spatial resolution compatible with those of best global models (50 to 100 km grid length). Early measurements began already in 1959 onboard of always single satellites of the TIROS-, ESSA-, and later Nimbus- and NOAA-series (e.g. Raschke, 1972). The first multi-satellite system (ERBE, Earth Radiation Budget System; Barkstrom 1984) has been flown during the early 80th, with scanning and non-scanning radiometers. Further instrumental achievements enabled in particular various scanning techniques and more spectral information within the scope of the multi-satellite experiment CERES, where almost identical instruments are flown onboard of different operational and experimental satellites (Wielicki et al., 1996). A European development, ScaRaB (Scanner for Radiation Budget; Kandel et al., 1998), complemented these latter observations during shorter time periods.

These latter measurements from ERBE and CERES allowed first estimates of the cloud effect on the net solar and net terrestrial radiation budget at TOA by proper selection of measurements over cloud free areas. Global annual averages of the budget components are summarized in Table 3. These annual global averages show, that clouds reduce the absorption of solar radiation but keep also more thermal longwave radiation within the climate system.

Quantities at top of the atmosphere (TOA)	**Mean values**	**For cloudless earth**	**Effect of clouds**
Outgoing terrestrial radiation	-234 Wm^{-2}	-266 Wm^{-2}	+32 Wm^{-2}
Absorbed solar radiation	239 Wm^{-2}	288 Wm^{-2}	-49 Wm^{-2}
Net radiation	**+5 Wm^{-2}**	**+22 Wm^{-2}**	**-17 Wm^{-2}**
Albedo	30%	15%	+15%

Table 3: Global averages of the radiation budget components at TOA and the effects of clouds (last column) on the outgoing terrestrial radiation, computed from earlier ERBE data. The small positive value of the net radiation is considered within the error range of this analysis ***and should not interpreted as a heating of our planet.***

3.2 Computed at TOA

The ISCCP data sets – see Table 1 for all complementary data – allows for direct calculations of up- and downward radiation fluxes between TOA and the surface for both cloudy (as given by the ISCCP clouds) and cloud free atmosphere. The radiation fields at TOA are not identical with those observed simultaneously, showing regional differences between 10 to 20 Wm^{-2} for annual averages. But the general spatial patterns are quite similar showing also the already with early Nimbus data computed annual radiation deficits over the major terrestrial desert regions.

As an example we show here a global map of the cloud effect on the total radiation budget at TOA, whose numbers are differences between the net radiation at cloudy and at clear skies. Thus positive (negative) values mean, that the net radiation at cloudy skies is larger than at clear skies. The generally negative values mean, that cloudy generally reduce the net radiation budget, dominantly due to the reflective power for solar radiation (see Table 3).

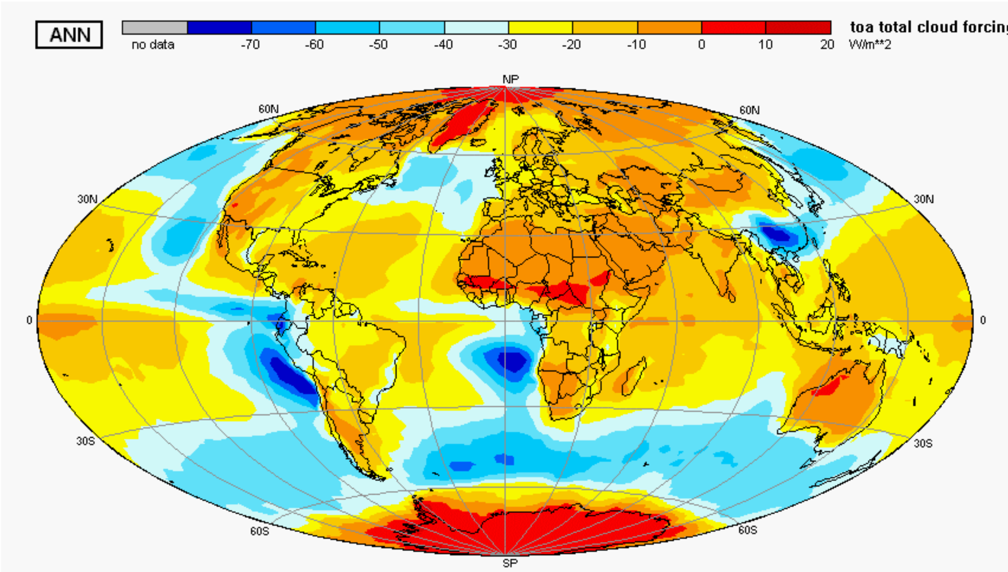

Fig. 1: Annual average of the effect of clouds on the net radiation budget *(in Wm^{-2}) during the period 1991 1995, computed as the difference between the net radiation at cloudy and clear skies. Over most areas clouds tend to reduce the net gain of radiative energy by the climate system (negative values), while over some small areas with high and persistent convection they tend to enhance it. Over both Polar Regions this effect is relatively more inaccurate due to large uncertainties in cloud identifications. Highest and lowest values: +13 and -80 Wm^{-2}; global average: -24 Wm^{-2}.*

3.3 Fields at surface

Radiation fields at the surface cannot be measured directly from space, but they can be inferred from such measurements with inclusion of various complementary data on the state of the atmosphere and of the ground (see e.g. Table 1). Numerous techniques have now been developed. Most recently Stackhouse et al. (November 2004, GEWEX NEWS) summarized their work within the CERES project. An analysis of the ISCCP results obtained for the years 1991 to 1995 has been provided by Raschke et al., (2005, in print). Most of these and other results are compared to simultaneous measurements with ground-bases radiometers for solar and terrestrial radiation, which are performed within different networks. These comparisons signal an uncertainty range for annual regional averages of the order of 10 to 20 Wm^{-2} where errors are possibly largest over both polar regions.

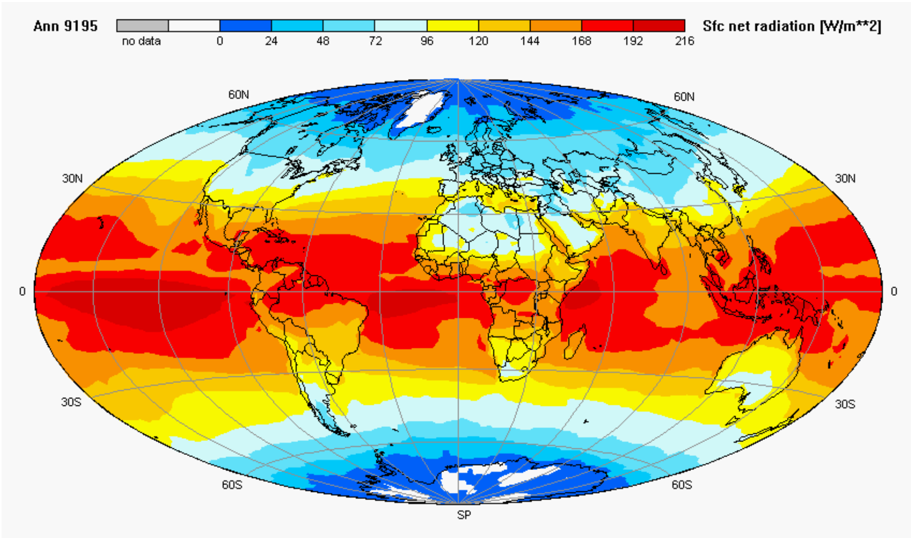

Fig. 2: Annual average of the total net radiation (or of the radiation budget) at the surface *during the period 1991 to 1995, in Wm*$^{-2}$*. All values, with a few exceptions over Greenland and Antarctica, are positive indicating, that the Earth's surface is everywhere heated by radiation. The small negative white areas are very close to zero. They are possibly caused by errors in both components over those regions, due to inaccurate cloud identification over those regions. Highest and lowest values: + 211 and –16 Wm*$^{-2}$*; global average: +116 Wm*$^{-2}$*.*

3.4 : The total radiation budget of the atmosphere

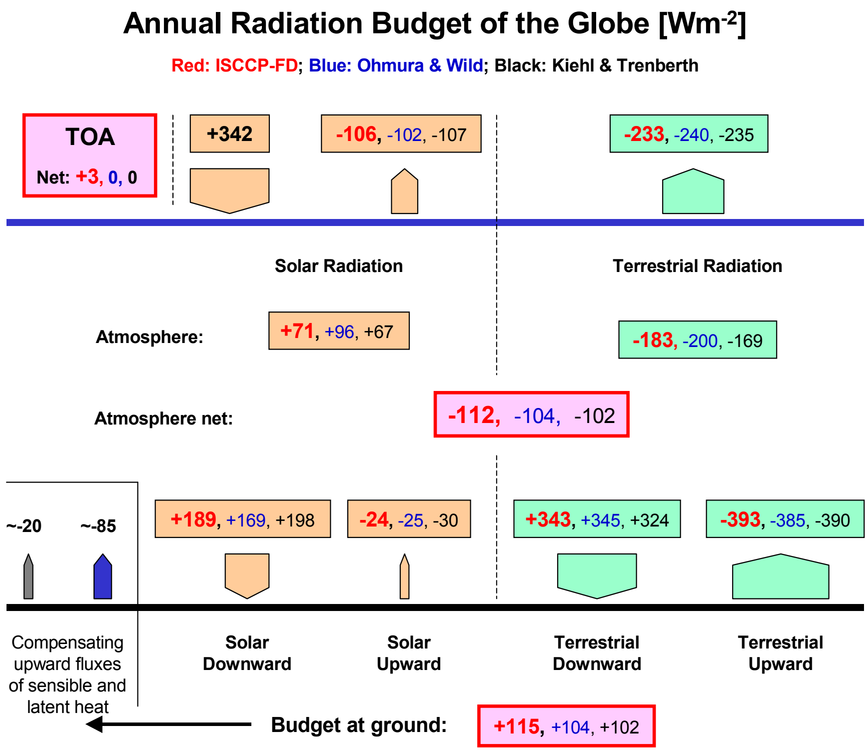

Fig. 3: Annual radiation budget of the climate system(in Wm^{-2}*) calculated from the ISCCP data set (red numbers) and compared with results from Ohmura and Wild (blue numbers) and Kiehl and Trenberth (black numbers). Respective values for the total flux divergence in the atmosphere are –112, -104, -102 Wm*$^{-2}$*, respectively.*

For global annual averages of the total radiation budget at TOA and at the surface quite similar values are found by these and other methods, however systematic differences occur in the two components. Particular high discrepancies occur the vertical divergences of both components urging for more intensive data validations. As an example, in Fig 3 are summarized the results of the ISCCP analysis by Raschke et al. (2005) and compared with others (Kiehl and Trenberth 1997; Ohmura and Wild, 2004, priv.comm.).

Fig. 4 summarizes the zonal averages of annual and seasonal values of the total radiation flux divergence within the atmosphere as computed from the ISCCP data set. All values are negative indicating, that within the mechanisms of the global heat engine the atmosphere is generally emitting radiation back to space, thus it must be heated from below by upward fluxes of latent and sensible heat. Note the large discrepancies between values for the solar and terrestrial vertical divergence, which were derived by those author teams. There are also significant regional differences in this budget.

Clouds, see Fig. 5, generally diminish this deficit at near-equatorial regions between about 30 degrees latitude, and enhance it elsewhere. The absorption of solar radiation in the clouds appears to be very low in this figure due to two causes: clouds reflect often more than 50% of the incident solar radiation back to space and they reduce considerably the amount of solar radiation into the lower tropospheric layers where most of the atmospheric water vapor rests. Various maps of these quantities will be shown during the presentation.

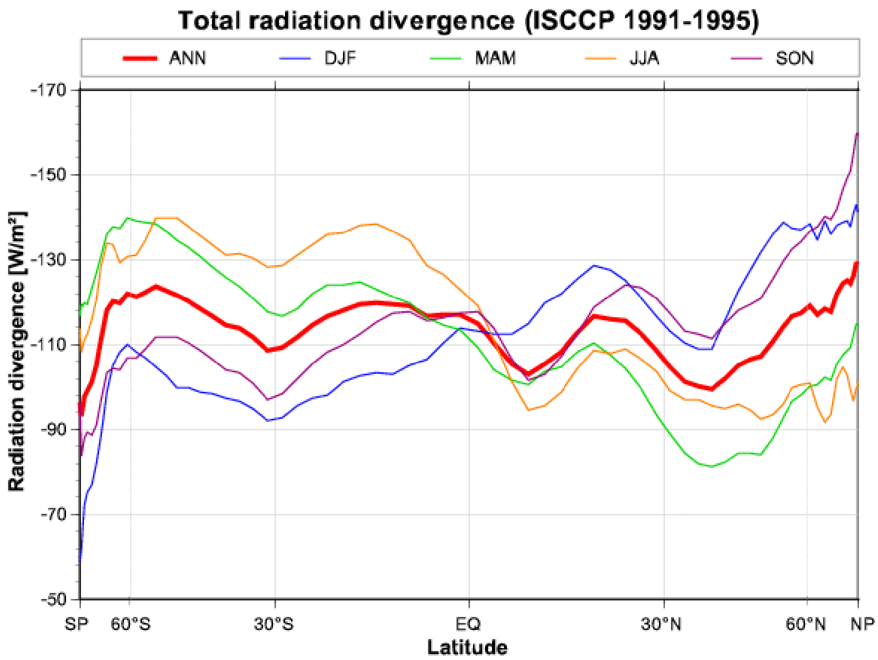

Fig. 4: *Zonal averages of the total radiant flux divergence in the atmosphere during all seasons. These graphs are obtained for all seasons and for the annual average.*

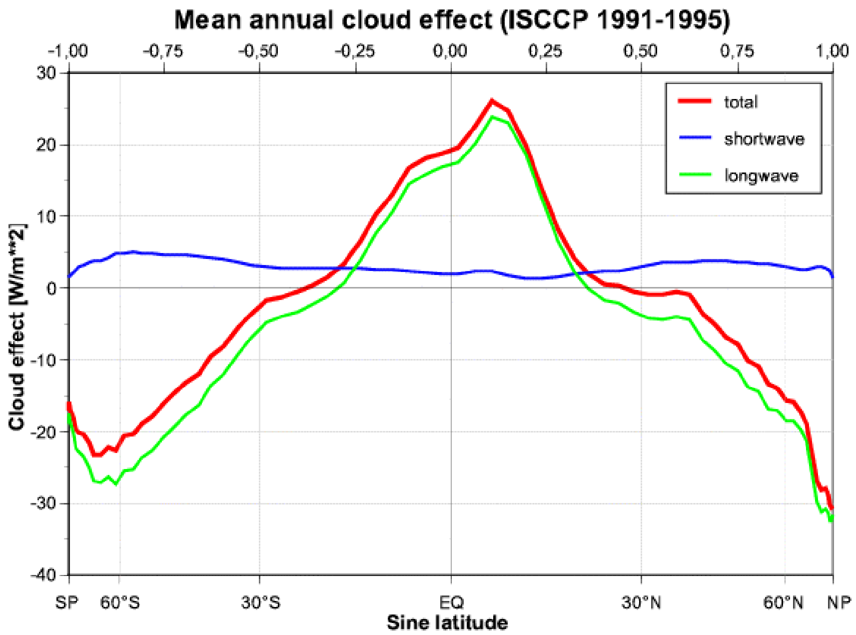

Fig. 5: Mean annual effect of clouds on the total radiant energy flux divergence in the atmosphere. *Positive values indicate that clouds contribute to the heating of the atmosphere. Clouds reduce the absorption of solar radiation below their bottoms and may slightly increase the absorption of radiant energy in the stratospheric ozone layer. The cloud effect in the infrared is due to partly compensating effects of emission from cloud tops and cloud bottoms at different altitudes and also the emission of lower atmospheric water vapor to ground.*

4. Some discussion

This paper can provide only a short overview on existing and hopefully future data sets, which are required to identify climate changes and to verify respective model results.

There is a need establish between different data sets more transparency about their weaknesses and strengths. In particular uncertainty range must be justified (e.g. Zhang et al., 2004) which should not exceed about 1 to 3 W m^{-2} for regional monthly averages and about one tenth of this limit for the annual stability to identify "trends", as they occur in the radiation budget quantities. As at present already the satellite ICE-Sat and other radar satellites, in future there will be dedicated active measurements with lidar and cloud radar, which will provide more information on he cloud geometry and internal structure, enabling then higher accuracies in calculating their radiative transfer properties and identifying even interactions between clouds and aerosols (e.g. Stephens et al., 2002). These new observational capabilities are a challenge for the research community.

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