INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE: CENTRATOM TRIESTE

SMR/406-2

THIRD AUTUMN WORKSHOP ON ATMOSPHERIC
RADIATION AND CLOUD PHYSICS
27 November - 15 December 1989

"Earth Radiation Budget Measurements From Space"

Robert KANDEL
Centre National de la Recherche Scientifique
Laboratoire de Météorologie Dynamique
Palaiseau, France

Please note: These are preliminary notes intended for internal distribution only.

To appear in the Alpbach Summer School proceedings (ESA-SP 301)

EARTH RADIATION BUDGET MEASUREMENTS FROM SPACE

Robert Kandel

Laboratoire de Météorologie Dynamique du CNRS
Ecole Polytechnique, F-91128 Palaiseau Cedex, FRANCE

ABSTRACT

Observations from satellites are essential for determination of the components of the Earth Radiation Budget at the top of the atmosphere. These determinations are far more direct than any other remote sensing measurements from space. However data processing must take into account the sampling characteristics of the satellite-orbit/instrument combination, in relation with the anisotropy and diurnal variation of the radiation reflected and emitted by the Earth-atmosphere system. We review these questions, in particular with reference to the ongoing Earth Radiation Budget Experiment (ERBE) and projects being developed.

Keywords : Earth Radiation Budget, Satellite Climatology, Bidirectional Reflectance, Diurnal Variations.

1. INTRODUCTION

Together with the solar input, many elements of the Earth climate system can be monitored, more or less directly, using instrumented artificial satellites. For much climate research, global data are necessary, and only satellites can provide homogeneous global coverage. As with operational weather services, continuity of coverage is essential, in order to accumulate the long homogeneous time series of data needed for climate research. Finally, certain quantities, in particular the radiation fluxes between the Earth climate system and space, can only be observed from space.

The central problems of climate have to do with the redistribution of solar energy in the Earth-atmosphere system, its ultimate rejection to space in the form of thermal infrared radiation, and the closely associated hydrological cycle (cf. Oort 1985). In the previous lecture we reviewed the importance of the Earth Radiation Budget in understanding climate and climate change. In this review we consider satellite observations of the Earth radiation budget (ERB). Much of this material is taken from a more detailed review article to appear in Space Science Reviews. Reprints will be supplied on request when available.

Observations of the Earth Radiation Budget (ERB) components at the "top of the atmosphere" (TOA) are only possible from space ; they can be made on a spatial scale comparable to that of climate models. Indeed observation from space of the TOA ERB components constitutes an exceptionally direct form of remote sensing ; the satellite instruments measure radiances which are identical to those leaving the top of the atmosphere in the direction of the satellite, and so they are directly sampling the quantity of interest rather than a proxy quantity as when one seeks to determine say precipitation from a radiation measurement.

The radiation balance at the Earth's surface defines the source or sink of energy for storage and horizontal transport in the oceans, and vertical nonradiative fluxes of sensible and latent heat over both land and oceans. The diurnal cycle of the solar radiation reaching the surface drives diurnal variations in temperatures of land surfaces and in turbulent fluxes of latent and sensible heat, which are essential features of surface-air energy flux. It is therefore important to develop methods for using satellite data to estimate the surface radiation budget (SRB) components and their diurnal variation over large areas of the globe, especially tropical land and ocean areas where surface radiation data are rare. It should however be remembered that satellites can only provide indirect data on these quantities, although the corrections required to estimate the upward SRB components from satellite measurements in restricted spectral bands are relatively straightforward for cloud-free areas.

In what follows we consider principally the problems of obtaining unbiased estimates of the TOA ERB from satellite data. In Section 2 we outline the space-time sampling characteristics of different types of instruments as a function of the satellite orbit parameters, and we review instrument hardware and processing software advances over the last decades, in particular with reference to the ongoing NASA Earth Radiation budget Experiment (ERBE). Section 3 summarizes the principal results of past satellite observations of clouds and ERB components. In Section 4 we outline projects under consideration for the next decade. We conclude with an examination of prospects for a truly international satellite global climate monitoring system for the end of the millenium.

2. ORBITAL AND INSTRUMENTAL CONSTRAINTS ; DATA PROCESSING METHODOLOGY

2.1. Introduction

Geographical coverage and space/time sampling characteristics of any satellite system for Earth observations depend both on orbital parameters and on instrument technology, the former placing constraints on the latter. In addition to dealing with the problems of calibration, algorithms for data processing must be constructed so as to correct for orbital and instrumental sampling biases.

2.2. Polar versus Geostationary Satellites

The choice of orbit involves trade-offs in space-time coverage, resolution and sampling characteristics, in relation with the type of instrument and detection technology used. Single-satellite global coverage is only possible with polar orbiters, at a price of limited temporal sampling. For satellites in sun-synchronous polar orbits, the observations are made at local times which are roughly fixed as a function of latitude (e.g. noon and midnight at the equator, for the Nimbus series). Observations made on different days are easily compared, but virtually no information is given on the diurnal cycle which is drastically under-sampled.

For geostationary platforms, only a limited (but large) geographical area can be observed, but it can be observed continuously in time. Because of the large distance, high spatial resolution can be difficult to achieve. Time resolution and sampling that can be achieved depend on spatial resolution and on detector sensitivity.

Because both global coverage and continuous diurnal monitoring are needed in climate and weather research, there is no eluding the need to combine observations made on different satellites, both geostationary and polar. Intercalibration of the different satellite instruments is critical.

2.3. Detection and Calibration

For relatively small instruments on polar orbiters, regular calibration with on-board black bodies and lamps is possible. On geostationary platforms, where a large telescope is needed for high spatial and temporal resolution, it is not possible to fill the beam with calibration sources, and true calibration is not practical.

Where ERB measurements are concerned, the basic problem is obtaining a flat spectral response over the entire SW and LW domains, together with accurate absolute calibration consistent between the two. This requires "black" thermal detectors, together with an optical and filter system that provides a separation at or near a wavelength of 4 μm and spectrally flat transmission on either side. When reflecting surfaces are needed for imagery, problems arise in the SW domain because of the spectral dependence of the reflectance. No LW filters giving a flat transmission from 4 to 50 μm appear to exist; in practice the best estimate of the LW signal is obtained by subtracting a filtered SW signal from an unfiltered signal integrating over the entire electromagnetic spectrum.

Calibration is relatively straightforward in the LW using space and on-board blackbodies calibrated with reference to absolute standards. In the SW, the Sun can be used in some cases; stable incandescent lamps exist, but they must be calibrated with respect to absolute standards.

2.4. Spatial and Temporal Resolution and Sampling Angular Sampling

Because all satellite studies of the state of the atmosphere and surface are strongly affected by the existence of clouds, relatively high spatial resolution (certainly better than 100 km, preferably of order 0.5-2 km, is needed in order to reduce the number of pixels containing mixed clear/cloudy scenes which are difficult to interpret. ERB studies constitute an exception, because the upward radiation is directly sampled, and the final quantities - the TOA ERB components - have little significance on scales smaller than about 100 km : considering the top of the atmosphere to be at an altitude of 30 km, the radiant exitance there depends on contributions from locations as far away as 100 km. However, because of the need for scene-dependent spectral and angular corrections as described below, high-resolution information is needed in order to determine the degree of heterogeneity on the larger scales. Higher resolution is also needed for the determination of cloud radiative forcing, for which it is necessary to determine ERB components separately for cloud-free areas.

The spatial resolution constraint generally imposes a maximum integration time (i.e. temporal resolution) for instruments not on geostationary platforms, because of the satellite motion. This of course depends on the scanning mode or degree of multiplexing, and it must be compatible with detectivity. The combined detectivity / space-time resolution constraint is most acute for narrow sounding channels. On geostationary platforms, temporal resolution is limited by the desired temporal sampling interval, and the degree of multiplexing. This constraint cannot then be neglected even for imaging channels because of the distance factor. Remembering that sounding data are needed for SRB estimates, and that these should be made with good sampling of the diurnal cycle from geostationaries, we see that substantial improvement in sensitivity is needed (cf. Chedin et al. 1986).

Instruments with moderate or high spatial resolution (finer than 100 km) may be said to measure radiances emitted or reflected by the Earth-atmosphere system. However in TOA ERB studies, the objective is the determination of irradiances, i.e. an integration of the emergent radiances over angle. The Earth-atmosphere system is not Lambertian either in the SW or in the LW. From a geostationary satellite, only a single fixed angle is sampled for any given location. From satellites in lower orbits, only one angle is sampled for each location in a cross-track scanning mode ; with conical scanning or continuous 2-dimensional imagery, many angles can be sampled, but integration time for each pixel is reduced in scanning. Along-track scanning provides considerable angular information, in exchange for a very large loss in spatial coverage. These issues are being examined in a NOAA study (Stowe et al 1988).

Fluxes measured by low-resolution fixed-field instruments can be related to spatial averages of TOA ERB components over large areas. The results can be used for climate diagnostics and model validation on large spatial scales, but supply little useful information on smaller scales. The principal attraction of instruments of this type is their simplicity and robustness : the Nimbus-7 ERB wide-field-of-view radiometers have functioned satisfactorily for over 10 years in orbit.

2.5. Data Processing Methodology - ERB Studies

Each of the problems mentioned above must be dealt with in the system of algorithms used to process data. Consider the monthly mean TOA ERB components averaged over areas of 2.5° in latitude and longitude. We note that these components are integrations over space, time, angle and wavelength of instantaneous spectral radiances which are imperfectly sampled by the satellite instrument. The first step of data processing is simply the mirror image of the measurement and data transmission process : it is to transform the data and housekeeping signals received from the satellite into an estimate (in physical units, $Wm^{-2}sr^{-1}$) of the radiance reaching the detector after filtering by the optics, for each sample. In the rest of the data processing chain each of the sampling steps must be represented by a correction procedure in which one attempts to take into account the radiances that have not been sampled, on the basis of pre-existing or auxiliary information.

Thus, unless the optics and detection system has a perfectly flat spectral response, there must be a spectral correction for the scene-dependent spectral filtering, followed by (or included in) the "inversion" which is the integration over angle which includes implicit or explicit assumptions regarding the radiances in unsampled directions, in some procedures using angular models which are scene-dependent. Finally, assuming that there are no gaps in spatial coverage, there remains the critical problem of the temporal sampling : unless data from geostationary satellites and/or several polar orbiters are used, some implicit or explicit assumptions regarding the character of the diurnal cycle and other short-term variations are necessary.

2.6. The Earth Radiation Budget Experiment

In the ERBE missions, NASA has attempted specifically to resolve the problems of time sampling and the study of diurnal variations, which could not be treated with a single sun-synchronous satellite such as Nimbus. The satellite system, instruments and data processing algorithms of ERBE are described in a series of papers (Barkstrom 1984, Barkstrom and Smith 1986, Luther et al. 1986, Kopia 1986, Smith et al. 1986, Brooks et al. 1986), and there is a much larger volume of reports of various sorts.

The ERBE system is made up of instrumental packages for ERB measurements, flown on three satellites : two sun-synchronous polar orbiting NOAA satellites (afternoon and morning), and the intermediate-inclination NASA Earth Radiation Budget Satellite (ERBS) for which the precessing orbit yields samples at all local hours after a period of a month. The instrument package mounted on each of these satellites consists of two fixed-field active cavity radiometers (Wide-Field-Of-View - WFOV, and Medium-Field-Of-View - MFOV), a solar monitor, and a Narrow-Field-Of-View (NFOV) scanning radiometer whose spatial resolution is 30-50 km at nadir. Particular care has been given to the problems of absolute calibration.

The system for processing the data was developed by NASA project teams in collaboration with an international science team. Considerable attention has been given to the problem of spectral, angular and diurnal corrections. Information derived from the biaxial scanner on Nimbus-7/ERB and from geostationary satellite data has been used to construct tables of the bidirectional reflectance and anisotropic emission functions for different types of scenes, as a function of latitude and season. The ERBE scanner measurements are used together with these tables (and the measurement geometry) to classify each pixel according to underlying surface and cloud cover, and then to obtain the spectral correction and an estimate of SW and LW radiant exitance for each pixel. The spatial resolution of the ERBE scanners makes it possible to identify cloud-free pixels with reasonable confidence, and "clear-sky" products (albedo, LW radiant exitances) are also being derived for the 2.5°X2.5° latitude-longitude areas of the output grid. In obtaining daily and monthly mean products, the diurnal variation of albedo (through its dependence on solar zenith angle) is taken into account explicitly, and in some cases a simple model of diurnal variation of LW emission is also used, in interpolating between available observations.

3. PRINCIPAL RESULTS OF SATELLITE OBSERVATIONS

Results of the past 30 years of space observations of the Earth Radiation Budget have been reviewed in a number of papers and reports (cf. Stephens et al. 1981, Kandel 1983, Raschke and Kondratiev 1982, WCP-70 1984, Hartmann et al. 1986, House et al. 1986, Kandel 1987), and need not be repeated in detail here. Most of the established results come from NASA's Nimbus series of experiments, in particular Nimbus-3, and Nimbus-6 and -7/ERB, to which now the ERBE results are being added. Launch dates for the ERBE satellites were : ERBS in November 1984 ; NOAA-F-9 in December 1984 ; and NOAA-G-10 in September 1986. Some early results have been published (ERBE Science Team 1986 ; Harrison et al. 1988, Ramanathan et al. 1989, cf. also the proceedings of COSPAR 1988 and IRS 1988). Processing, validation and archival of the results are well under way.

The principal points to be noted regarding TOA ERB components have already been discussed in the previous lecture. We recall the following :

- The global annual mean albedo of the Earth-atmosphere system is close to 0.30, less than pre-satellite estimates (cf. Hunt et al. 1986). The global and hemispheric means have an annual variation between 0.27 and 0.31.

- The global mean radiation balance (or net radiation) goes through an annual cycle with amplitude ±11 Wm-2 about an annual mean which cannot be distinguished from zero (Ellis et al. 1978, Hartmann et al. 1986). This corresponds principally to storage and subsequent release of solar energy absorbed by the Southern Hemisphere oceans during austral summer when the Earth is closest to the Sun. Interannual energy storage cannot be detected.

- The variation with latitude of the annual zonal mean radiation balance yields the annual mean meridional energy fluxes in the combined ocean-atmosphere system. Using meteorological data to estimate the meridional energy flux in the atmosphere, one can then estimate the meridional heat transport by ocean currents (Vonder Haar and Oort 1973, Carissimo et al. 1985). This is found to be of order one half of the total.

- The major deserts of the world are areas in which the radiation balance is smaller than in other areas at the same latitudes, in the annual mean and in the summer. Over the bright Sahara and Arabian deserts, the net radiation is always negative (Raschke et al. 1973). The net radiation over the subtropical oceans is more positive than the corresponding zonal mean in the summer. Apart from these features, there is little land-sea contrast in the longitudinal distribution of net radiation.

- With the spatial resolution of order 450 km of the Nimbus-6 and Nimbus-7/ERB results, the major features of the general circulation appear clearly in the geographic distribution of TOA ERB components. There are deep minima in the outgoing LW over the land centers of deep convection (South America, central Africa, Indonesia) to which correspond albedo maxima ; the reverse holds over the eastern part of the anticyclones over the subtropical oceans. The Nimbus ERB data set extends over more than 10 years (cf. Jacobowitz et al. 1984, Bess and Smith 1987a,b, 1989), and so provides not only excellent mean values but also variances. The intertropical Pacific exhibits particularly high variances in the TOA ERB components (after removal of the annual cycle), and indeed the ERB anomalies correspond to the areas most affected during ENSO events, as shown by the Nimbus-7/ERB observations of the 1982-83 event (Smith and Smith 1987, Ardanuy et al. 1986, 1987, Hucek et al. 1987).

- Analyses of narrow-band data from geostationary and polar satellites (Saunders et al. 1980, Kandel 1983, Minnis and Harrison 1984, Duvel and Kandel 1985, Hartmann and Recker 1986, Duvel 1988, Harrison et al. 1988) provide detailed information on diurnal variations. There can be significant biases in determinations based solely on data from sun-synchronous satellites such as Nimbus. The methodology and observing system developed for ERBE (Brooks et al. 1986) are aimed at eliminating these biases and at characterizing the diurnal cycle of the ERB components.

4. FUTURE PROJECTS

4.1. The Franco-Soviet ScaRaB Project

The ERBE scanner on NOAA-9 ceased to operate early in 1987, that on NOAA-10 in spring 1989, after functioning nominally for more than 2 years. No one can tell how much longer the scanner on ERBS will continue to operate. The non-scanner data cannot furnish regional-scale information on the ERB components. Plans are being made for broad-band ERB observations aboard the "polar platforms" scheduled for 1995 and later, but no such possibility exists aboard the NOAA satellites that will be flying before then.

How can we assure continuity of Earth Radiation Budget observations ? The plans of NASA and NOAA leave the danger of a gap in coverage of several years following the end of the ERBE mission. This would be particularly regrettable just when one expects to see significant climate effects of the CO_2 increase, with the World Climate Research Programme (WCRP) in full swing, and with projects such as TOGA and WOCE yielding results which will only take their full value if ERB measurements are available.

With a view to contributing to the world effort in climate research, and in the framework of the Franco-Soviet Cooperation in Space Research, the U.S.S.R. and France have begun the development and construction of a scanning radiometer for measuring ERB components (ScaRaB, Scanner for Radiation Budget). These instruments will be flown on two or more Soviet satellites of the Meteor family, beginning in 1991.

The instrument, designed to satisfy the scientific needs as well as considerations of economy, simplicity and reliability, and the constraints of flight on the METEOR satellite, is a cross-track scanning radiometer. The satellite orbit is to be circular, at an altitude of 1250 km, and with an inclination of 82.5°. France is building the scanning module (optics, detectors, choppers) and the associated electronics ; the U.S.S.R. is building the overall structure linking the scanning module and the satellite, and is responsible for thermal control, the on-board calibration sources, and integration. The Federal Republic of Germany will contribute to instrument characterization and will participate with France and the U.S.S.R. in developing the data processing system and in validation.

The ScaRaB instrument will not itself make solar constant measurements, but it appears extremely likely that such measurements will be made on one or more other satellites without any interruption in the series of observations. Indeed it perfectly conceivable that the ERBE solar constant measurements on ERBS (or even on Nimbus-7 ERB, which continues to function) should continue indefinitely.

Observations will be made in four spectral bands - two broad spectral bands yielding the data for the solar and thermal portions of the spectrum of radiation reflected and emitted by the Earth - and two narrower bands, one corresponding to the infrared atmospheric window, the other yielding a separation of the visible and near-infrared portions of the solar spectrum. The radiation in the thermal longwave band (4-50 μm) will be determined from the difference between the measurements in the total (0.2-50 μm) and the short-wave channel (0.2-4 μm).

The instrument will provide measurements of reflected solar and emitted thermal radiation over the entire globe, and these measurements must be calibrated and traceable to internationally recognized absolute standards. The data processing system for ScaRaB will be based on algorithms for transforming the instantaneous measurements of radiances, filtered by the optics and detectors of the instrument, into estimates of the monthly mean values of the radiant exitances in the solar and thermal domains, at the top of the atmosphere. In order to assure continuity with the ERBE series of observations, the structure of the algorithms for angular corrections ("inversion") and for space-time averaging (including taking account of diurnal variations) will have the same basic structure as those used for ERBE. Output products are to be provided on the ERBE spatial grid of 2.5° in latitude and longitude, with a separate clear-sky product as for ERBE.

4.2. The Polar Platforms and the Earth Observing System

Because globally homogeneous Earth observations are possible only from space, continued development of space observing systems is an essential component of ongoing research in "Earth system science" (NASA 1984, ESA 1985, ESSC 1988), in particular with regard to interdisciplinary efforts in the context of the IGBP.

NASA, in association with ESA and NASDA (Japan), propose to satisfy the needs of the geosciences, starting in 1995, by what NASA has named the Earth Observing System (EOS). This extremely ambitious project is described in a considerable mass of documentation (NASA 1984, 1987). Because of what has been called "the intrinsic dynamics of space agencies" (WCP-137 1987, p. 3), EOS is in some ways associated with the US Space Station Program, even though very little Earth science justification exists for a manned space station per se. For the Earth sciences, the essential space components are the EOS polar orbiting platforms, proposed to carry operational and research instruments for a wide variety of objectives. Presumably the platforms will integrate the instruments of the operational weather services of the future (cf. McElroy and Schneider 1985), with instruments for atmospheric and oceanographic research, and land and ocean remote sensing. It is planned to include a CERES instrument (Clouds and the Earth Radiant Energy System), derived directly from the ERBE NFOV scanner, on board both the U.S. and European polar platforms, with a view to continuing observations of the ERB components in relation with observations of cloud cover and attempts at accurately determining surface radiation budget components globally.

Although most of the EOS documentation has to do with instrumentation of the polar platforms, it is clear that geostationary platforms will continue to play a significant role. However, because of the distance of the geostationary orbit, high spatial or spectral resolution is difficult to obtain. Infrared sounding is already conducted on an experimental basis with VAS from GOES, and future generation geostationaries (including not only GOES but also Meteosat 2nd generation) will certainly have IR sounding capability, possibly also microwave sounding. The possibility of adding a broad-band ERB instrument is also under study.

5. CONCLUSIONS

All these improved observational capabilities will be extremely valuable for monitoring of and research on the Earth system, including climate. The simultaneous observation from space of global energy and water fluxes, and of the principal agents (clouds) modifying these fluxes, is essential to the success of the Global Energy and Water Cycle Experiment (GEWEX) being planned for the end of the 1990's (WCP-137 1987). However, it must be noted that all of these cycles undergo significant diurnal variation, especially in the tropics. In order to obtain complete coverage of the diurnal cycle over the entire globe using only polar orbiters, at least 4 polar platforms will be necessary. With international cooperation, including not only NASA, NOAA, ESA, and CNES, but also Japan and the USSR, this is certainly within the range of possibility (Heacock et al. 1986). The Soviet polar orbiting Meteor satellites can accommodate additional instruments (Alexandrov 1983), as for example ScaRaB, and perhaps also TOMS.

It is not therefore unrealistic to envisage a global climate data system integrating basic observations made by several polar orbiting platforms so as to obtain complete diurnal coverage. However, even 6 polar platforms will not provide monitoring of rapidly evolving phenomena. Thus it is practically certain that at least some of the operational weather services will continue to use geostationary platforms, and the future Earth Observing System must include provisions for integration of data from the geostationary and the polar platforms. The success of ISCCP shows that this is well within the realm of the possible, even with today's computing and data storage technology.

Although the prospects for major advances in observational techniques are important for future progress in climate research, we must not forget the requirements for continuity and homogeneity of the data. Here again the broadening of international cooperation to include contributions from all countries and agencies capable of launching satellites is a factor of security, reducing the dependence of the global observing system on a single launcher or a single family of satellite platforms.

Alexandrov, L.A., 1983 : Meteorological satellites and cooperative programmes. Adv. Space Res., 3, No. 7, 119-124.

Ardanuy, P.E., and H.L. Kyle, 1986 : El Nino and outgoing longwave radiation: Observations from Nimbus-7 ERB. Mon. Weather Rev., 114, 415-433.

Ardanuy, P.E., H.L. Kyle, R.R. Hucek, and B.S. Groveman, 1987 : Nimbus 7 Earth Radiation Budget wide field of view climate data set improvement. II. Deconvolution of Earth Radiation Budget products and consideration of 1982-1983 El Nino event. J. Geophys. Res., 92, 4125-4143.

Barkstrom, B.R., 1984 : The Earth Radiation Budget Experiment (ERBE). Bull. Amer. Meteor. Soc., 65, 1170-1185.

Barkstrom, B.R., and G.L. Smith, 1986 : The Earth Radiation Budget Experiment : Science and implementation. Rev. Geophys., 24, 379-390.

Bess, T.D., and G.L. Smith, 1987a : Atlas of Wide-Field-of-View Outgoing Longwave Radiation derived from Nimbus 6 Earth Radiation Budget data set - July 1975 to June 1978. NASA RP-1185, 78 pp.

Bess, T.D., and G.L. Smith, 1987b : Atlas of Wide-Field-of-View Outgoing Longwave Radiation derived from Nimbus 7 Earth Radiation Budget data set - November 1978 to October 1985. NASA RP-1186, 174 pp.

Bess, T.D., G.L. Smith, and T.P. Charlock, 1989 : A ten-year monthly data set of outgoing longwave radiation from Nimbus-6 and Nimbus-7 satellites. Bull. Amer. Meteor. Soc., 70, 480-489.

Brooks, D.R., E.F. Harrison, P. Minnis, J.T. Suttles, and R.S. Kandel, 1986: Development of algorithms for understanding the temporal and spatial variability of the Earth's radiation balance. Rev. Geophys., 24, 422-438.

Carissimo, B., A.H. Oort, and T.H. Vonder Haar, 1985 : On estimating the meridional energy transports in the atmosphere and oceans. J. Phys. Oceanogr., 15, 82-91.

Charney, J., 1975 : Dynamics of desert and drought in the Sahel. Quart. J. Roy. Meteor. Soc., 101, 193-202.

Chedin, A., D. Pick, R. Rizzi, and P. Schluessel, 1986 : Second-Generation Meteosat Definition Studies on Microwave and Infrared Vertical Sounders. ESA STR-219, European Space Agency, Paris, 103 pp.

Darnell, W.L., S.K. Gupta, and W.F. Staylor, 1983: Downward longwave radiation at the surface from satellite measurements. J. Climate Appl. Meteor., 22, 1956-1960.

Duvel, J.P., 1988 : Analysis of diurnal, interdiurnal and interannual variations during Northern Hemisphere summers using Meteosat infrared channels. J. Climate, 1, 471-484.

Duvel, J.P., and R.S. Kandel, 1985 : Regional-scale diurnal variations of outgoing infrared radiation observed by Meteosat. J. Climate Appl. Meteor., 24, 335-349.

Duvel, J.P., S. Dalle, M. Stoll, and R.S. Kandel, 1985 : Variations of cloud cover over the South Atlantic on diurnal and longer time scales. Proc. 5th Meteosat Scientific Users' Meeting, ESA/ESOC, Darmstadt, III.3.

Ellis, J.S., T.H. Vonder Haar, S. Levitus, and A.H. Oort, 1978 : The annual variation in the global heat balance of the earth. J. Geophys. Res., 83, 1958-1969.

ERBE Science Team, 1986 : First data from the Earth Radiation Budget Experiment (ERBE). Bull. Amer. Meteor. Soc., 67, 818-824.

ESA, 1985 : Looking Down - Looking Forward : Earth Observation - Sciences and Applications - A Perspective. ESA SP-1073, 53 pp.

ESSC, 1988 : Earth System Science - A Closer View. Rept. of the Earth System Sciences Committee, NASA Advis. Council, Washington, 208 pp.

Gautier, C., G. Diak, and S. Masse, 1980 : A simple physical model to estimate incident solar radiation at the surface from GOES satellite data. J. Appl. Meteor., 19, 1005-1012.

Harrison, E.F., et al., 1988 : First estimates of the diurnal variation of longwave radiation from the multiple-satellite, Earth Radiation Budget Experiment (ERBE). Bull. Amer. Meteor. Soc., 69, 1144-1151.

Hartmann, D.L., and E.E. Recker, 1986 : Diurnal variation of outgoing longwave radiation in the tropics. J. Climate Appl. Meteor., 25, 800-812.

Hartmann, D.L., V. Ramanathan, A. Berroir, and G.E. Hunt, 1986 : Earth radiation budget data and climate research. Rev. Geophys., 24, 439-468.

Heacock, E.L., Yu. A. Afanasiev, C. Honvault, T. Yoshida, and U.V. Gopala Rao, 1986 : Future world meteorological satellite systems. Acta Astronautica, 14, 277-285.

House, F.B., A. Gruber, G.E. Hunt, and A.T. Mecherikunnel, 1986 : History of satellite missions and measurements of the Earth radiation budget (1957-1984). Rev. Geophys., 24, 357-377.

Hucek, R.R., H.L. Kyle, and P.E. Ardanuy, 1987 : Nimbus 7 Earth Radiation Budget wide field of view climate data set improvement. I. The Earth albedo from deconvolution of shortwave measurements. J. Geophys. Res., 92, 4107-4123.

Hunt, G.E., R. Kandel, and A.T. Mecherikunnel, 1986 : A history of presatellite investigations of the Earth's radiation budget. Rev. Geophys., 24, 351-356.

Jacobowitz, H., R.J. Tighe, and Nimbus 7 ERB Experiment Team, 1984 : The Earth radiation budget derived from the Nimbus 7 ERB experiment. J. Geophys. Res., 89, 4997-5010.

Kandel, R.S., 1983 : Satellite observation of the Earth radiation budget. Beitr. Phys. Atmos., 56, 322-340.

Kandel, R.S., 1987 : Le bilan radiatif du système terre atmosphère et ses variations spatiales et temporelles, in CNES, Climatologie et Observations Spatiales. Cepadues-Editions, Toulouse, 259-310.

Kopia, L.P., 1986 : Earth Radiation Budget Experiment scanner instrument. Rev. Geophys., 24, 400-406.

Lee III, R.B., B.R. Barkstrom, and R.D. Cess, 1987 Characteristics of the Earth Radiation Budget Experiment solar monitors. Appl. Optics, 26, 3090-3096.

Lee III, R.B., A. Mecherikunnel, H.L. Kyle, M.A. Gibson, and S.M. Natarajan, 1988 : Recent increasing trend in total solar irradiance detected using NASA Earth Radiation Budget Satellite solar monitor. EOS, 69, 314.

Luther, M.R., J.E. Cooper, and G.R. Taylor, 1986 : The Earth Radiation Budget Experiment non-scanner instrument. Rev. Geophys., 24, 391-399.

McElroy, J.H., and S.R. Schneider, 1985 : Earth Observations and the Polar Platform. NOAA Tech. Rept. NESDIS 18, Washington, 16 pp.

Minnis, P., and E.F. Harrison, 1984 : Diurnal variability of regional cloud and clear-sky radiative parameters derived from GOES data. Part I : analysis method; part II : November 1978 cloud distributions; part III : November 1978 radiative parameters. J. Climate Appl. Meteor., 23, 993-1051.

NASA, 1984 : Earth Observing System, Science and Mission Requirements Working Group Report, Vol. I and Appendix, NASA TM-86129, Washington, 58 + 59 pp.

NASA, 1986 : From Pattern to Process : The Strategy of the Earth Observing System, EOS Science Steering Comm. Report, Vol. II, 140 pp.

NASA, 1986 : Earth Observing System Data and Information System, Report EOS Data Panel, Vol. IIa, NASA TM-87777, Washington, 62 pp.

NASA, 1987 : Earth Observing System, Instrument Panel Reports, Vol. IIb-IIh, Washington.

National Research Council, 1983 : Toward an International Geosphere- Biosphere Program - A Study of Global Change. National Academy Press, Washington, 81 pp.

NOAA and NASA, 1987 : Space-Based Remote Sensing of the Earth. (A Report to the Congress). U.S. Government Printing Office, Washington, 123 pp.

Oort, A.H., 1985 : Balance conditions in the Earth's climate system, in Manabe, S. (ed.), Issues in Atmospheric and Oceanic Modeling. Part A - Climate Dynamics. Adv. Geophys., 28, 75-98, Academic Press.

Ramanathan, V., 1987 : The rôle of Earth radiation budget studies in climate and general circulation research. J. Geophys. Res., 92, 4075-4095.

Ramanathan, V., B.R. Barkstrom, and E.F Harrison, 1989 : Climate and the Earth's radiation budget. Phys. Today, 42, No 5, 22-32.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, 1989 : Cloud-radiative forcing and climate : Insights from the Earth Radiation Budget Experiment. Science, 243, 57-63.

Raschke, E., and K. Ya. Kondratiev, 1982 : Radiation Budget of the Earth and Its Atmosphere. WCP-40, 31 pp.

Raschke, E., T.H. Vonder Haar, W.R. Bandeen, and M. Pasternak, 1973 : The annual radiation balance of the earth-atmosphere system during 1969-70 from Nimbus-3 measurements. J. Atmos. Sci., 30, 341-364.

Saunders, R.W., and G.E. Hunt, 1980 : Meteosat observations of diurnal variation of radiation budget parameters. Nature, 283, 645-647.

Schiffer, R.A., and W.B. Rossow, 1985 : ISCCP global radiance data set - a new resource for climate research. Bull. Amer. Meteor. Soc., 66, 1498-1505.

Schmetz, P., J. Schmetz, and E. Raschke, 1986 : Downward longwave radiation at the surface from satellite and grid point data. Theoret. Appl. Climatol., 37, 136-149.

Sèze, G., and W. Rossow, 1987 : Time-cumulated visible and infrared histograms used as descriptor of cloud cover. Adv. Space Res., 7, (3)155-(3)158.

Smith, E.A., and M.R. Smith, 1987 : Atlas of Earth Radiation Budget Measurements from Nimbus 7 ERB (1979-1983). Florida State Univ., Tallahassee, 254 pp.

Smith, E.A., T.H. Vonder Haar, J.R. Hickey, and R. Maschhoff, 1983 : The nature of the short period fluctuations in solar irradiance received by the Earth. Climatic Change, 5, 211-235.

Smith, G.L., R.N. Green, E. Raschke, L.M. Avis, J.T. Suttles, B.A. Wielicki, and R. Davies, 1986 : Inversion methods for satellite studies of the earth's radiation budget : development of algorithms for the ERBE mission. Rev. Geophys., 24, 407-421.

Smith, G.L., B.R. Barkstrom, and E.F. Harrison, 1987 : The Earth Radiation Budget Experiment: early validation results. Adv. Space Res., 7, (3)167-(3)177.

Stephens, G.L., G.G. Campbell, and T.H. Vonder Haar, 1981 : Earth radiation budgets. J. Geophys. Res., 86, 9739-9760.

Stowe, L.L., P. Abel, H. Jacobowitz, P. Ardanuy, R. Hucek, and P. Cheng, 1988 : An Earth Radiation Budget Orbital Simulation, -- NOAA/NESDIS preliminary report, Washington.

Suttles, J.T., and G. Ohring (eds.), 1986 : Report of the Workshop on Surface Radiation Budget for Climate Applications. WCP-115, 139 pp.

Vonder Haar, T.H., and A.H. Oort, 1973 : New estimate of annual poleward energy transport by Northern hemisphere oceans. J. Phys. Oceanogr., 3, 169-172.

WCP-6, 1981 : The International Satellite Cloud Climatology Project. WMO, Geneva, 62 pp.

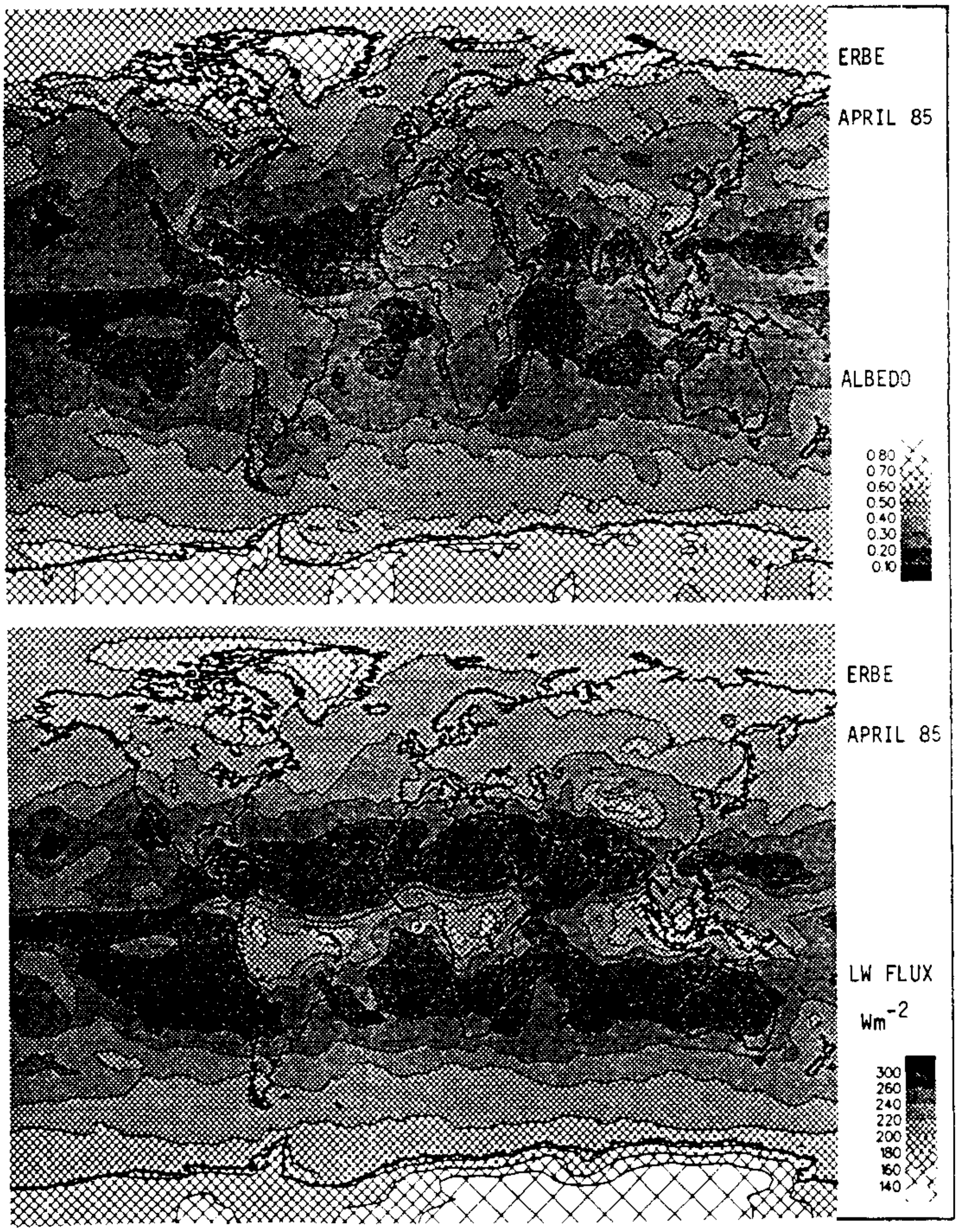
WCP-70, 1984 : Report on Satellite Systems to Measure the Earth's Radiation Budget Parameters and Climate Change Signals. (Igls, 29/8-2/9/83) WMO, Geneva, 36 pp.

WCP-136, 1987 : Report of the Joint Scientific Committee Ad Hoc Working Group on Radiative Flux Measurements. WMO, Geneva.

WCP-137, 1987 : Report of a WCRP Workshop on Space Systems Possibilities for a Global Energy and Water Cycle Experiment. WMO, Geneva.

Willson, R.C., 1984 : Measurements of solar total irradiance and its variability. Space Sci. Rev., 38, 203-242.

Willson, R.C., H.S. Hudson, C. Fröhlich, and R.W. Brusa, 1986 : Long-term downward trend in total solar irradiance. Science, 234, 1114-1117.



Monthly mean SW albedo and LW radiant exitance for April 1985, as determined on a 2.5° latitude-longitude grid using the data from the ERBE scanners on board ERBS and NOAA-9.

To appear in the Alpbach Summer School proceedings (ESA-SP 301)

EARTH RADIATION BUDGET AND CLIMATE

Robert Kandel

Laboratoire de Météorologie Dynamique du CNRS
Ecole Polytechnique, F-91128 Palaiseau Cedex, France

ABSTRACT

We review the role of radiative processes in climate and climate change, considering the relations between the Earth Radiation Budget and climate in the conceptual framework of relatively simple models. We note in particular the critical role of clouds and the uncertainties related to cloud radiative forcing and feedback.

Keywords : Earth Radiation Budget, Climate, Clouds, Cloud Radiation Forcing, Cloud Radiation Feedback.

1. INTRODUCTORY POINTS

(1) - Energy exchange between the Earth-atmosphere system and its cosmic environment takes place practically entirely by radiation.

(2) - The overwhelmingly dominant source of energy is the Sun; all of space (4π steradians) is the sink.

(3) - The climate system has two essential functions : (a) the degradation and geographical redistribution of the incoming solar radiant energy flux; (b) the circulation of water, in particular provision of water to land areas remote from the oceanic reservoirs. The cloud phase of the hydrological cycle is the major modulator of radiation fluxes.

(4) - Nearly all scenarios of climate change involve perturbation of the radiation budget.

(5) - For radiation budget studies, it is practical to divide the electromagnetic spectrum into two domains : the shortwave SW : 0-4 μm) domain corresponding nearly entirely to incident, scattered and reflected solar radiation; and the longwave (LW : > 4 μm) domain corresponding nearly entirely to thermal radiation emitted at the Earth's surface or in the atmosphere and clouds. We consider the transfer of radiation separately in these two domains, neglecting thermal emission in the SW, considering only terrestrial and atmospheric thermal emission and neglecting the extra-terrestrial solar source in the LW. The two domains are linked through the condition of conservation of energy, allowing for non-radiative energy transport in the atmosphere and oceans, and storage in oceans and below land surfaces.

(6) - Detailed realistic physical models generally must be developed first at the local level and on short time scales. Similarly, observations are also initially made on limited spatial and temporal scales, and only later can they be integrated and averaged over larger and larger scales. On the contrary, we shall begin here with the simplest conceptual model relating Earth radiation budget and climate; this is a zero-dimensional model of the climate system, applying to global annual mean quantities. We then shall go on to consider the relations between ERB and climate at increasing degrees of complexity. We shall in particular consider the problems connected with clouds, and their role in climate change. Although we do not systematically cite references in the text, we provide an introductory bibliography.

2. RADIATION BUDGET, GLOBAL MEAN CLIMATE MODELS AND CLIMATE CHANGE

The global annual mean zero-dimensional model can only represent the degradation of solar photons, but not the geographical redistribution of solar energy. In the equilibrium state, solar SW input equals thermal LW outflow, i.e. with solar constant S (= 1365 Wm^{-2}) and with a planetary albedo α (= 0.30), the net radiation or radiation balance is zero :

$$R_N = S (1 - \alpha) / 4 - M_{LW} = 0. \qquad (1)$$

Using the blackbody law to define effective temperature T_e we have :

$$M_{LW} = \sigma T_e^4 = S (1 - \alpha) / 4 \qquad (2)$$

This yields an effective temperature of 255 K fairly typical of the atmosphere at an altitude of about 5 km. This is not an unreasonable ~~mean~~ for the Earth-atmosphere system, but it does not usefully characterize climate at the surface.

We can characterize surface climate with global mean **surface** temperature T_s by introducing a planetary emittance ϵ defined as the ratio of the global mean LW flux emergent at the top of the atmosphere, to the global mean (assumed blackbody) emission of the surface. The equilibrium condition is :

$$M_{LW} = \epsilon \sigma T_s^4 = S(1-\alpha)/4 \qquad (3)$$

for the present climate, $T_s = 288$ K, $\epsilon = 0.615$.

We then have one parameter, S, which is truly external to the system, and one explicit climate parameter, T_s. We can consider the effect of a change in the solar constant, one of the classic examples of a climate change mechanism involving perturbation of the ERB.

$$4\,\delta T_s/T_s = \delta S/S + \delta(1-\alpha)/(1-\alpha) - \delta\epsilon/\epsilon \qquad (4)$$

A one percent change in S corresponds to a forcing of 3.4 Wm^{-2}, or a temperature change of 0.72 K in the absence of feedbacks. However, the other parameters, planetary albedo and atmospheric emittance, certainly are sensitive to the climate state, measured here by surface temperature, and according to various calculations, their feedbacks multiply the temperature response by a factor of 2 to 4. The planetary albedo depends on cloud, ice and snow cover, and the planetary emittance depends on both cloud cover and the atmospheric humidity; all of these are sensitive to climate.

One element of climate is the annual cycle. Because of the ellipticity of the Earth's orbit, solar irradiance at the top of the atmosphere varies by ±3.2%. Strong asymmetry exists in the land-sea and therefore in the surface albedo distribution between northern and southern hemispheres, affecting significantly the effective global mean albedo as a function of season, apart from atmospheric changes. The substantial thermal inertia and energy storage differences between land and sea also have a strong influence on the response of the global system to the annual cycle of insolation. The result is an annual cycle of the global mean radiation balance, which has been shown to have an amplitude of about ±11 Wm^{-2}.

The last 20 years of satellite observation have failed to reveal climatically significant fluctuations of the solar constant. On the other hand, the last 30 years of Mauna Loa and other data show the significant trend of increase in atmospheric concentrations of CO_2 and other radiatively active gases (notably CH_4 and chlorofluoromethanes), which if continued must lead to a decrease in planetary emittance. We can write the greenhouse forcing associated with this anthropogenic global change in atmospheric composition as $-\delta\epsilon_0/\epsilon$ so as to distinguish it from the greenhouse feedback term $-\delta\epsilon'/\epsilon$ which results from cloud cover and humidity changes. For a constant Sun, the surface temperature change restoring equilibrium is given by :

$$4\,\delta T_s/T_s = -\delta\epsilon_0/\epsilon - \delta\epsilon'/\epsilon + \delta(1-\alpha)/(1-\alpha) \qquad (5)$$

Various estimates suggest that effective CO_2 doubling may occur in as little as 50 years and involve a forcing $\delta\epsilon_0/\epsilon = -0.017$ or about 4 Wm^{-2} in the radiation budget of the surface-troposphere system. This forcing corresponds to a temperature increase of 1.2 K in the absence of feedbacks. The critical question for climate change is the magnitude and sign of the feedbacks.

It seems likely that both ice-albedo feedback and atmospheric humidity feedback are positive, i.e. they have the same sign as $\delta T_s/T_s$: increasing surface temperature should lead to reduced sea ice and land snow cover (i) : $\delta(1-\alpha)(i)/(1-\alpha) > 0$, while constant or increasing atmospheric relative humidity (h) implies definitely increased atmospheric water vapor content and LW opacity. This leads to further reduction in ϵ, $-\delta\epsilon'(h,i)/\epsilon > 0$. The situation is more complex for clouds, for which the albedo and the greenhouse effects are usually opposite in sign.

Let us again consider the radiation budget changes associated with the greenhouse forcing. In an equilibrium climate, the radiation balance or net radiation R_N is zero (global annual or multi-annual mean). Present observations do not give a value which can be distinguished from zero. With a greenhouse forcing $-\delta\epsilon_0/\epsilon = X > 0$, we have initially :

$$\delta R_N = S(1-\alpha)/4 - \epsilon\sigma T_s^4 = X\epsilon\sigma T_s^4 > 0 \qquad (6)$$

i.e. a nonzero radiation balance. When a new equilibrium is attained, with various feedbacks, we will again have $R_N = 0$. Moreover, if the new equilibrium involves no changes in global mean albedo (admittedly unlikely), the individual terms of the global mean radiation budget return to their initial values. In particular the outgoing longwave radiation

$$M_{LW} = \epsilon\sigma T_s^4 = (\epsilon + \delta\epsilon_0 + \delta\epsilon')\,\sigma(T_s + \delta T_s)^4 \qquad (7)$$

is the same although the surface climate has changed significantly. The essence of the greenhouse effect is that it changes the vertical gradient of temperature in the atmosphere without necessarily changing the flux of energy through the atmosphere. The radiation budget has to do with energy fluxes, and at the global mean scale, it is not a very sensitive indicator of climate response to the greenhouse forcing, rather a detector of lack of climate change. Nevertheless observation of the Earth radiation budget on regional and monthly scales is essential because it contains information on cloud radiation feedback which is difficult to model. Observation of radiation flux emergent in the more restricted infrared atmospheric window domain (8-13 μm, or better 11.5-12.5 μm to exclude the ozone band and the water vapor continuum) gives more direct information on surface temperature response to greenhouse forcing.

3. CLOUD RADIATIVE FORCING AND CLOUD FEEDBACK

The introduction of cloud cover parameters into a global mean model approach is artificial, but it is instructive. We consider fractional cloud cover f, and we write global mean albedo α and global mean emergent LW flux M_{LW} as :

$$\alpha = (1-f)\,\alpha_{clr} + f\,\alpha_{cld} = \alpha_{clr} + f\,(\alpha_{cld} - \alpha_{clr}) \qquad (8)$$

$$M_{LW} = (1-f)\,M_{LW}^{clr} + f\,M_{LW}^{cld} = M_{LW}^{clr} - f\,(M_{LW}^{clr} - M_{LW}^{cld}) \qquad (9)$$

The radiation balance, which must be zero for equilibrium on a global (multi-)annual mean basis, can be written :

$$R_N = (S/4)\ (1-\alpha) - M_{LW}$$
$$= (S/4)\ (1-\alpha_{clr}) + C_{SW} - M_{LW}^{clr} + C_{LW}$$
$$= R_N(clr) + C_{SW} + C_{LW} \qquad (10)$$

$$C_{SW} = (S/4)\ (\alpha_{clr} - \alpha)$$
$$= -(S/4)\ f\ (\alpha_{cld}-\alpha_{clr}) \qquad (11)$$

$$C_{LW} = M_{LW}^{clr} - M_{LW}$$
$$= f\ (M_{LW}^{clr} - M_{LW}^{cld}) \qquad (12)$$

All of the following considerations can be applied to studies involving smaller spatial and temporal scales, replacing (S/4) by the appropriate insolation (dependent on latitude, date and time), and recalling that R_N generally is not zero on such scales, depending on meridional energy transport in atmosphere and ocean, other advections, and energy storage in the atmosphere or below the surface.

Here the SW and LW cloud radiative forcing terms are : C_{SW} (the cloud albedo forcing) which is generally negative (except perhaps over snow), and C_{LW} (cloud greenhouse forcing), generally positive (except for warm clouds over a colder surface, as in polar inversions). Equilibrium climate models exhibit considerable disagreement regarding the magnitude of the cloud forcing terms, and even the sign of $C = C_{SW} + C_{LW}$ is not certain, although most results are negative, between 0 and -40 Wm^{-2}. From the point of view of observation, it appears easier to determine the cloud radiative forcing from the difference between overall mean fluxes and the mean clear-sky fluxes, rather than from determination of cloud fraction f and cloud parameters α_{cld} and M_{LW}^{cld}.

In what sense is this a forcing ? If we consider the equilibrium climate with clouds, then the cloud radiative forcing terms are the negative of the forcing that would apply in the event of instantaneous removal of the cloud opacity, e.g. with $C_{SW} = -50\ Wm^{-2}$, rendering the clouds transparent in the SW alone leads to a heating of 50 Wm^{-2} of the climate system, as less solar radiation is reflected to space. With $C_{LW} = +30\ Wm^{-2}$, rendering the clouds transparent in the LW alone cools the climate system by 30 Wm^{-2} as more thermal radiation escapes to space. The total forcing of -20 Wm^{-2} often interpreted as meaning that clouds cool the climate system as it now operates, more precisely means that instantaneous removal of cloud optics from the present climate would produce an initial heating of 20 Wm^{-2}. This sort of experiment is easy to carry out in model simulations. If one then determines the new equilibrium state corresponding to the situation in which clouds are transparent in either or both the SW and LW domains, both the clear-sky and the cloud radiative forcing terms will have changed.

<u>Climate 1</u> :

$$R_N^{(1)} = 0 = R_N^{1}(clr) + C_{SW}^{(1)} + C_{LW}^{(1)} \qquad (13)$$

<u>Transition</u> :

$$R_N^{(t)} = R_N^{1}(clr) =$$
$$= -(C_{SW}^{(1)} + C_{LW}^{(1)}) \text{ initially} \qquad (14)$$

<u>Climate 2</u> :

$$R_N^{(2)} = 0 = R_N^{2}(clr) + C_{SW}^{(2)} + C_{LW}^{(2)}$$
$$= R_N^{2}(clr) \qquad (15)$$

Note that in climate 2 the cloud radiative forcing terms are equal to zero, so that in this case the change in clear-sky net radiation from climate 1 to climate 2 is equal in magnitude to the cloud forcing for climate 1.

<u>Change</u> :

$$R_N^{2}(clr) - R_N^{1}(clr) = C_{SW}^{(1)} + C_{LW}^{(1)} \qquad (16)$$

More generally, in any type of climate change, the cloud-radiation feedback is the change in the cloud radiative forcing.

<u>Climate 1</u> :

$$R_N^{(1)} = 0$$
$$= (S/4)\ (1-\alpha_{clr}^{(1)}) - \epsilon_{clr}^{(1)}\sigma T_{s1}^{4}$$
$$+ C_{SW}^{(1)} + C_{LW}^{(1)} \qquad (17)$$

<u>Greenhouse gas forcing</u> :

$$-\delta\epsilon_{clr}^{(0)}/\epsilon_{clr}^{(1)} = x \qquad (18)$$

<u>Transition</u> :

$$\delta R_N = x\epsilon_{clr}^{(1)}\sigma T_{s1}^{4} = x\ M_{LW}^{clr}(1) \qquad (19)$$

<u>Climate 2</u> :

$$R_N^{(2)} = 0 = (S/4)(1-\alpha_{clr}^{(2)}) - \epsilon_{clr}^{(2)}\sigma T_{s2}^{4}$$
$$+ C_{SW}^{(2)} + C_{LW}^{(2)} \qquad (20)$$

<u>Climate change</u> :

$$\frac{4\ \delta T_s}{T_s} = \frac{x\epsilon_{clr} - \delta\epsilon'_{clr}(h)}{\epsilon_{clr}} - \frac{\delta(1-\alpha_{clr})(i)}{(1-\alpha_{clr})}$$
$$- \frac{\delta C_{SW}}{C_{SW}} - \frac{\delta C_{LW}}{C_{LW}} \qquad (21)$$

In addition to the greenhouse gas forcing and the humidity feedback on the planetary LW emittance, we have included a possible (ice) albedo feedback, and finally the cloud radiation feedbacks. These are a critical source of uncertainty in climate sensitivity studies.

Before the concept of cloud radiative forcing was introduced, the sensitivity of the radiation balance to cloud cover fraction was studied in terms of Schneider's (1972) sensitivity parameter

$$\delta = \frac{\partial R_N}{\partial f} = -\frac{S}{4}\frac{\partial \alpha}{\partial f} - \frac{\partial M_{LW}}{\partial f} \qquad (22)$$

where the cloud albedo effect dominates if $\delta<0$, the cloud greenhouse effect if $\delta>0$. If one assumes that changes in α and M_{LW} are solely due to changes in f, one can also write

$$\delta = (S/4)(\alpha_{cld}-\alpha_{clr}) + (M_{LW}^{clr}-M_{LW}^{cld}) \qquad (23)$$

or alternatively, using the absorbed solar flux $Q_a = (S/4)(1-\alpha)$, one can consider the quantity originally called $\in$ (Cess et al. 1982), which we shall denote s to avoid confusion with planetary emittance :

$$s = \partial M_{LW}/\partial Q_a \qquad (24)$$

where the cloud albedo and greenhouse effects compensate when s=1, and the albedo effect dominates when s<1. There is a considerable literature regarding attempts to estimate s and δ from satellite observations of clouds and ERB components and their interannual, seasonal, intraseasonal and geographical variations. It should however be remembered that none of these variations may be a good analog of what occurs in a true climate change.

4. ONE-DIMENSIONAL CLIMATE MODELS AND EARTH RADIATION BUDGET STUDIES

There are two families of one-dimensional climate models : global mean climate models with resolution of the vertical dimension, and zonally averaged "energy balance" models in which the dimension is latitude, allowing consideration of meridional energy transport processes, latitudinal climate zones and seasonal changes.

4.1. Global mean radiative-convective models

The first family of models has played an important role in elucidating the physics of vertical energy transport through the atmosphere, in particular with regard to the greenhouse effect, using what are called radiative- convective models. In fact most absorbed solar radiation flux is transformed into heat at the surface of the Earth. The temperature gradient required for purely radiative (LW) transport of this energy back to space is often unstable against "convection", so that vertical transport of sensible and latent heat plays an important role in the global mean energy budget. This means that within the atmosphere and at the surface in particular, the global mean radiation balance is not zero. We do not at present have anything near global coverage in measurements of radiation fluxes within the atmosphere. One can of course make rough estimates of what these should be, and compare the global mean values thus obtained with model results. Efforts are under way to obtain estimates of the components of the radiation budget at the surface, using satellite data. These estimates will be quite indirect and the global validity of existing algorithms has by no means been demonstrated. The surface radiation balance is intimately related to the nonradiative vertical energy transport. On a global mean basis, we can write:

$$R_N(\text{surface}) = LE + H = LE(1+\beta) = P(1+\beta) \qquad (25)$$

where L is the latent heat of evaporation (say in Joules per kg), E and P are the global mean evaporation and precipitation rates respectively (expressed in kg m^{-2} s^{-1}), H is the global mean sensible heat flux (in $Wm^{-2}s^{-1}$), and β is the global mean Bowen ratio. The surface radiation budget is perturbed directly if one changes the surface albedo, or changing the atmospheric LW opacity (say by adding CO_2 or increasing the atmospheric water vapor content). There have been many studies of the climate impact of increased atmospheric CO_2 (on the surface temperature, affecting the LW components of the surface radiation budget) from this point of view. However the feedbacks in the nonradiative terms make this approach quite delicate. These questions can be discussed more fruitfully in the context of regional radiation budget studies.

4.2. Vertically integrated, zonally averaged energy balance models

In these models the dimension of latitude is retained, and there is no detailed consideration of vertical transport processes. With regard to radiation budget components, LW radiant exitance is generally parametrized in terms of zonal mean surface temperature, incorporating implicitly the effects of zonal mean cloud amount. This can be made explicit, using a cloud fraction dependent on latitude and season. The zonally averaged energy balance climate models are interesting in that they make it possible to include explicitly the principal motor of the global circulation, namely the latitudinal gradients of insolation and their changes in the course of the annual cycle. These models include parametrisations of the meridional energy transport in atmosphere and oceans as an essential feature. The latitudinal variation of the global mean albedo is also included, thereby representing the solar zenith angle dependence of albedo, the north-south sea-land asymmetry and the annual cycle of cloud, sea ice, and snow cover. A major application of this type of model is in the study of glacial/interglacial changes, where snow and ice cover (and so albedo) are parametrized as a function of surface temperature. One can then consider the "Milankovitch" changes of the latitude dependence and annual cycle of insolation, on time scales of tens and hundreds of thousands of years.

4.3. Analysis of zonally averaged radiation budget

We now have available 10-20 years of high-quality observational data on the zonal mean components of the Earth radiation budget at the "top of the atmosphere", allowing comparisons with models for the present climate including the annual cycle, interannual variations, and particular climate anomalies such as the ENSO events. We already mentioned the annual cycle of global mean net radiation. Consideration of the hemispheric means helps to elucidate the principal phenomena, in particular the stronger northern hemisphere cycle of LW radiant exitance, leading to a maximum effective temperature for the Earth at the time (northern summer) when the Earth is near aphelion and the solar flux is weakest. One also notes that the southern hemisphere cycle of radiation balance is the stronger, no doubt as a result of southern summer coinciding with perihelion and of the greater ocean area.

Assuming that on an annual mean basis energy storage can be neglected, one can use the annual zonal mean radiation balance to derive the meridional transport of energy in the Earth-atmosphere system. As early as 1973, Vonder Haar and Oort showed this to reach values as high as $6 \cdot 10^{15}$ W (6 petawatts) near latitudes 40° north and south, with approximately equal atmospheric and oceanic contributions. This result is basic to understanding ocean circulation and climate. Smith and Smith (1987) have recently announced the existence of apparently significant trends, over the 5 years from December 1978 to November 1983, of the radiation balance, zonally organized, with values ranging from -6 $Wm^{-2}yr^{-1}$ in southern midlatitudes, to +6 $Wm^{-2}yr^{-1}$ in the north. These results need to be confirmed and understood.

5. REGIONAL CLIMATE AND EARTH RADIATION BUDGET

The face of the Earth is such that zonal means constitute at best a gross simplification of many essential features. The satellite observations yield quite naturally a 2-dimensional picture of the reflected SW and emitted LW radiation fluxes (radiant exitances), at the "top of the atmosphere". Depending on the type of instrument used, spatial resolution may range from several thousand to a few tens of kilometres, quite compatible with the resolution of typical general circulation models used for climate studies, a few hundreds of km. Thus Earth radiation budget observations provide an excellent climate model validation tool, especially considering that these observations are relatively "direct" : the instruments actually sample the photons whose distribution is predicted by the model.

The striking departures from zonal symmetry of the land-sea distribution appear clearly in the SW and LW components of the radiation budget. In addition to the surface albedo difference, there are the tropical areas of deep convection over South America, Africa, and the "maritime continent" of Indonesia. For these areas, albedo is very high, absorbed solar radiation and emitted LW radiation are very low. Thus the departure from zonal symmetry is reduced in the radiation balance and in the cloud radiative forcing. At certain seasons, low clouds over ocean areas appear to enhance the albedo with little effect on emergent LW, and lead to strongly negative cloud radiative forcing.

Early (Nimbus-3) satellite results showed (Raschke et al. 1973) that albedo of Saharan desert areas was quite high (>30%) under cloud-free conditions, so that the radiation balance was zero or negative even during the summer. This observation is fundamental to the biogeophysical feedback mechanism proposed by Charney (1975) for the metastability of desert margin areas, and very much discussed in connection with the prolonged drought period in the Sahelian zone of Africa. The negative radiation balance requires sinking and drying of upper-level air, quite consistent with the lack of clouds and precipitation. Over a marginal area, natural (drought) or anthropogenic (e.g. overgrazing) stress on plant covering a light soil can lead to an increase in surface albedo, reinforcing the negative radiation balance and the trend to drought. This need not be inconsistent with the fact that removal of vegetation (and the associated evapotranspiration when moisture is available in the soil) almost invariably leads to increased soil temperature, even when the surface albedo increases and the surface radiation balance is reduced. Reality is of course complex, as shown by the few analyses that exist of albedo changes and by the history of Sahelian rainy seasons. The major role played by the non-radiative surface processes (soil moisture, roughness) must be balanced against that of the surface radiation and of the larger-scale circulation anomalies that depend on ocean-air interactions.

Results of the past decade (Bess et al 1989) include observations of SW and LW anomalies associated with ENSO, in particular the strong 1982-83 event. The LW anomalies reach several tens of Wm^{-2} (-70 near Tahiti, + 50 at Darwin, between December 1982 and March 1983), partly compensated in the SW inasmuch as the changes are mostly caused by cloud anomalies. The ENSO anomalies are the major contributors to the interannual variability of the radiation budget components at the top of the atmosphere, as derived after removal of the annual cycle from monthly mean satellite determinations.

When considering radiation budget and climate on the regional scale, diurnal variations must be considered. Even when comparisons between models and observations are being made on a monthly or seasonal mean basis, incomplete temporal sampling can lead to bias. Moreover the diurnal cycle can be a fundamental part of the physics and of the climatology, especially (but not only) in tropical regions. At the surface, the nonradiative vertical transport processes of evapotranspiration and turbulent convection tend to follow the diurnal cycle closely. Over many areas cloud cover also exhibits a strong diurnal cycle, as does precipitation. The evaluation of cloud radiative forcing must take this into account, because the SW term is obviously weighted by insolation, whereas the LW term is not. Climate model simulations have shown that failure to include the diurnal variation can lead to significant systematic errors, in particular with regard to precipitation. From the observational side, the problem is that a single satellite cannot provide both global and complete diurnal coverage.

The radiation balance at the top of the atmosphere is generally not zero at the regional scale. Considering a box extending sufficiently deeply below the land or ocean surface, we can write

$$S = G + R_N(TOA) + A(H, LE) + Oc \qquad (26)$$

where S is the storage of heat in the box (mostly in the sea, possibly in the ground), A is the atmospheric advection of sensible and latent heat into the box, and Oc is the oceanic transport (if applicable) of heat into the box. The term G is the regional non-solar energy generation (including especially so-called waste heat); although on a global mean basis this term is small (several tens of milliwatts/m^2) it is not necessarily negligible in the case of a strongly populated industrialised region such as the Ruhr, especially in winter). At the surface we can write

$$S = R_N(\text{surface}) - (LE + H) + Oc \qquad (27)$$

where LE and H are respectively the surface-to-atmosphere fluxes of latent and sensible heat. Considering that over periods greater than several days, storage of energy in the atmosphere is negligible, we can write the energy balance of the atmosphere in our regional box as :

$$0 = G + R_N(\text{TOA}) - R_N(\text{surface}) + (LE + H) + A(H, LE) \qquad (28)$$

Satellite observations can readily provide R_N(TOA), A(H, LE) can be obtained more or less accurately from analysed meteorological fields based on conventional and satellite data, G can be estimated from industrial data. Again the surface radiation balance (the net radiation flux into the surface) appears intimately related with the nonradiative energy fluxes between surface and atmosphere. Estimating these fluxes from satellite data is necessarily indirect and uncertain, and consistency checks will be useful. For example, if precipitation data are available, neglecting storage of water in the atmosphere, the atmospheric water balance yields the condition :

$$P = E + A_w \qquad (29)$$

where A_w is the atmospheric advection of water (in all forms) into the box, and can be derived from the same analyses which give A(H, LE). Note that although one may often observe correlations between net radiation at the surface and at the top of the atmosphere, assuming this to be generally true for the purposes of deriving a satellite climatology of surface radiation balance, amounts to assuming a very particular behavior for (LE+H)+A(H,LE), and this may lead one to miss the interesting phenomena.

6. BIBLIOGRAPHY

Augustsson, T., and V. Ramanathan, 1977 : A radiative-convective model study of the CO_2 climate problem. J. Atmos. Sci., 34, 448-451.

Barkstrom, B.R., 1984 : The Earth Radiation Budget Experiment (ERBE). Bull. Amer. Meteor. Soc., 65, 1170-1185.

Barkstrom, B.R., and G.L. Smith, 1986 : The Earth Radiation Budget Experiment : Science and implementation. Rev. Geophys., 24, 379-390.

Berger, A., 1981 : A critical review of modeling the astronomical theory of paleoclimates and the future of our climate, in Soleil et Climat (Proc. Internat. Conf. on Sun and Climate, 1980), CNES, Toulouse, 325-355.

Bess, T.D., G.L. Smith, and T.P. Charlock, 1989 : A ten-year monthly data set of outgoing longwave radiation from Nimbus-6 and Nimbus-7 satellites. Bull. Amer. Meteor. Soc., 70, 480-489.

Broecker, W.S., 1987 : How to Build a Habitable Planet, Eldigio Press, Palisades, NY, 294 pp.

Carissimo, B., A.H. Oort, and T.H. Vonder Haar, 1985 : On estimating the meridional energy transports in the atmosphere and oceans. J. Phys. Oceanogr., 15, 82-91.

Cess, R.D., and G.L. Potter, 1987 : Exploratory studies of cloud radiative forcing with a general circulation model. Tellus, 39A, 460-473.

Cess, R.D., B.P. Briegleb, and M.S. Lian, 1982 : Low-latitude cloudiness and climate feedback comparative estimates from satellite data. J. Atmos. Sci., 39, 53-59.

Charlock, T.P., and V. Ramanathan, 1985 : The albedo field and cloud radiative forcing produced by a general circulation model with internally generated cloud optics. J. Atmos. Sci., 42, 1408-1429.

Charlson, R.J., J.E. Lovelock, M.O. Andreae, and S.G. Warren, 1987 : Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. Nature, 326, 655-661.

Charney, J., 1975 : Dynamics of desert and drought in the Sahel. Quart. J. Roy. Meteor. Soc., 101, 193-202.

Crane, R.G., and R.G. Barry, 1984 : The influence of clouds on climate with a focus on high latitude interactions. J. Climatology, 4, 71-93.

Duvel, J.P., 1988 : Analysis of diurnal, interdiurnal and interannual variations during Northern Hemisphere summers using Meteosat infrared channels. J. Climate, 1, 471-484.

Ellis, J.S., T.H. Vonder Haar, S. Levitus, and A.H. Oort, 1978 : The annual variation in the global heat balance of the earth. J. Geophys. Res., 83, 1958-1969.

GARP, 1978 : JOC Study Conf. on Parametrization of Extended Cloudiness and Radiation for Climate Models (Oxford, England). WMO, Geneva.

Hartmann, D.L., V. Ramanathan, A. Berroir, and G.E. Hunt, 1986 : Earth radiation budget data and climate research. Rev. Geophys., 24, 439-468.

Herman, G.F., M.-L.C. Wu, and W.T. Johnson, 1980 : The effect of clouds on the Earth's solar and infrared radiation budgets. J. Atmos. Sci., 37, 1251-1261.

Kandel, R.S., 1980 : Earth and Cosmos. Pergamon Press, Oxford and New York, 254 pp.

Kandel, R.S., 1983 : Satellite observation of the Earth radiation budget. Beitr. Phys. Atmos., 56, 322-340.

Kandel, R.S., 1987 : Le bilan radiatif du système terre-atmosphère et ses variations spatiales et temporelles, in CNES, Climatologie et Observations Spatiales. Cepadues-Editions, Toulouse, 259-310.

Kiehl, J.T., 1985 : Searching for the radiative signal of increasing carbon dioxide and other trace gases, in MacCracken, M.C., and F.M. Luther (eds.) Detecting the Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0235, 13-28.

Kyle, H.L., K.L. Vasanth, and the Nimbus-7 ERB Experiment Team, 1986 : Some characteristic differences in the Earth's radiation budget over land and ocean derived from the Nimbus-7 ERB experiment. J. Climate Appl. Meteor., 25,, 958-981.

Luther, F.M., and R.G. Ellingson, 1985 : Carbon dioxide and the radiation budget, in MacCracken, M.C., and F.M. Luther (eds.) Projecting the Climatic Effects of Increasing Carbon Dioxide, DOE/ER-0237, 25-55.

Marchuk, G.I., K.Ya. Kondratyev, V.V. Kozoderov, and V.I. Khvorostyanov, 1986 : Oblaka i Klimat Gidrometeoizdat, Leningrad, 511 pp.

Mitchell, J.F.B., C.A. Wilson, and W.M. Cunnington, 1987 : On CO_2 climate sensitivity and model dependence of results. Quart. J. Roy. Meteor. Soc., 113, 293-322.

NASA, 1981 : Clouds in Climate : Modeling and Satellite Observations. Workshop Report, NASA Goddard Inst. for Space Studies, New York.

Ohring, G. and A. Gruber, 1982 : Satellite Radiation Observations and Climate Theory. Adv. Geophys., 25, 237-304.

Oort, A.H., 1985 : Balance conditions in the Earth's climate system, in Manabe, S. (ed.), Issues in Atmospheric and Oceanic Modeling. Part A - Climate Dynamics. Adv. Geophys., 28, 75-98, Academic Press.

Ramanathan, V., 1987 : The role of Earth radiation budget studies in climate and general circulation research. J. Geophys. Res., 92, 4075-4095.

Ramanathan, V., et al., 1987 : Climate-chemical interactions and effects of changing atmospheric trace gases. Rev. Geophys., 25, 1441-1482.

Ramanathan, V., B.R. Barkstrom, and E.F Harrison, 1989 : Climate and the Earth's radiation budget. Phys. Today, 42, No 5, 22-32.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmad, and D. Hartmann, 1989 : Cloud-radiative forcing and climate : Insights from the Earth Radiation Budget Experiment. Science, 243, 57-63.

Rampino, M.R., and T. Volk, 1988 : Mass extinctions, atmospheric sulphur and climatic warming at the K/T boundary. Nature, 332, 63-65.

Raschke, E., and K. Ya. Kondratiev, 1982 : Radiation budget of the Earth and its atmosphere. WCP-40, 31 pp.

Raschke, E., T.H. Vonder Haar, W.R. Bandeen, and M. Pasternak, 1973 : The annual radiation balance of the earth-atmosphere system during 1969-70 from Nimbus-3 measurements. J. Atmos. Sci., 30, 341-364.

Roeckner, E., 1988 : Cloud-radiation feedbacks in a climate model. Atmosph. Res., 21, 293-303.

Schlesinger, M.E., and J.F.B. Mitchell, 1987 : Climate model simulations of the equilibrium climatic response to increased carbon dioxide. Rev. Geophys., 25, 760-798.

Schmetz, P., J. Schmetz, and E. Raschke, 1986 : Downward longwave radiation at the surface from satellite and grid point data. Theoret. Appl. Climatol., 37, 136-149.

Schneider, S.H., 1972 : Cloudiness as a global climatic feedback mechanism : the effects on the radiation balance and surface temperature of variations in cloudiness. J. Atmos. Sci., 29, 1413-1422.

Slingo, J.M., 1982 : As study of the earth's radiation budget using a general circulation model. Quart. J. Roy. Meteor. Soc., 108, 379-405.

Slingo, A., R.C. Wilderspin, and S.J. Brentnall, 1987 : Simulation of the diurnal cycle of outgoing longwave radiation with an atmospheric GCM. Mon. Wea. Rev., 115, 1451-1457.

Smith, E.A., and M.R. Smith, 1987a : Atlas of Earth Radiation Budget Measurements from Nimbus 7 ERB (1979-1983).Florida State Univ., Tallahassee, 254 pp.

Smith, E.A., and M.R. Smith, 1987b : Interannual variability of the tropical radiation blance and the role of extended cloud systems. J. Atmos. Sci., 21, 3210-3234.

Somerville, R.C., and L.A. Remer, 1984 : Cloud optical thickness feedbacks in the CO_2 climate problem. J. Geophys. Res., 89, 9668-9672.

Stephens, G.L., G.G. Campbell, and T.H. Vonder Haar, 1981 : Earth radiation budgets. J. Geophys. Res., 86, 9739-9760.

Suttles, J.T., and G. Ohring (eds.), 1986 : Report of the Workshop on Surface Radiation Budget for Climate Applications. WCP-115, 139 pp.

Vonder Haar, T.H., and A.H. Oort, 1973 : New estimate of annual poleward energy transport by Northern hemisphere oceans. J. Phys. Oceanogr., 3, 169-172.

WCP-6, 1981 : The International Satellite Cloud Climatology Project. WMO, Geneva, 62 pp.

WCP-70, 1984 : Report on Satellite Systems to Measure the Earth's Radiation Budget Parameters and Climate Change Signals. (Igls, 29/8-2/9/83) WMO, Geneva, 36 pp.

Wetherald, R.T., and S. Manabe, 1986 : An investigation of cloud cover change in response to thermal forcing. Climatic Change, 8, 5-23.

Wilson, C.A. and J.F.B. Mitchell, 1986 : Diurnal variation and cloud in a general circulation model. Quart. J. Roy. Meteor. Soc., 112, 347-369.