THE USE OF SATELLITE DATA TO EVALUATE CLIMATE MODEL SIMULATIONS OF THE RADIATION BUDGET AND CLOUDS

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1. INTRODUCTION

One of the basic features of the Earth's atmosphere which complicates the numerical prediction of weather and climate is the presence of significant internal sources of heating and cooling. These so-called diabatic heating sources are produced by two very different physical mechanisms; the release of latent heat from the changes of phase of water substance during the formation of clouds and precipitation and the transfer of solar and terrestrial radiation. A common element which links these mechanisms is the cloud distribution, which is the visible manifestation of the condensation process and which substantially alters the radiation fields from their clear-sky values. Clouds also have a profound impact on the distribution of radiative fluxes at the Earth's surface, and hence on the energy available for land surface processes and for driving the circulation of the world oceans.

It is therefore clear that climate models need to include formulations of clouds and radiative processes in order to calculate the distributions of radiative and condensational heating within the atmosphere and of radiative fluxes and precipitation at the surface. Detailed calculation of the heating and cooling rates from first principles is not possible, not only because of lack of knowledge of some of the basic physical processes concerned, but also because climate models cannot represent explicitly all the scales of motion which contribute to cloud processes and dynamics. All climate models therefore have to represent processes ocurring on such fine space and time scales through a procedure known as parametrization. Much effort is directed towards developing parametrizations which are as physically realistic as possible and which may be validated through comparisons with measurements from detailed field programmes and other data.

2. VARIABLES REPRESENTED IN CLIMATE MODELS

Cloud parameters which are treated in current climate models include the vertical distribution of areal coverage within a grid-box (together with an assumption about the overlap between cloud layers), water content, condensate phase (liquid or ice) and particle size, as well as precipitation rate. From these, the shortwave and radiative fluxes and heating rates are calculated by the model's radiation code, which provides the radiative contributions to the surface energy balance and to the thermodynamic equation for determining atmospheric temperatures. Some of these parameters, such as the cloud amount and water content, are explicitly modelled through diagnostic or prognostic relationships. Others may be represented very simply, for example the particle sizes are often prescribed to a constant value such as 10 microns for water clouds and a somewhat larger value for ice clouds. However, explicit formulations for cloud microphysical processes are becoming more common in climate models, so that whereas a few years ago the condensate phase would have been parametrized very simply as a function of the local temperature, it is now possible to include some of the methodology previously used only in cloud-resolving models. Thus the mixing ratios of vapour, liquid water and ice may all be held as model variables and parametric equations included to calculate the rates of transfer between these three states. The link between the aerosol concentration and particle size may also be included so that the latter becomes a predicted as opposed to a prescribed variable. The primary motivation for including such additional complexity is the search for greater physical realism, which is required both for improved weather forecasts and for more reliable simulations of the impact of cloud feedbacks on global warming. It is important to appreciate this background of continuous model development, since it continuously stretches the requirements placed on in situ and remote sensing observations and forces a re-assessment of plans for future missions.

Apart from clouds, a complete description of the radiatively active components of the climate system requires additional information on the temperature, albedo and emissivity of the surface, as well as atmospheric temperatures, humidities and aerosol concentrations. It is also necessary to measure the radiative budget itself, which integrates the effect of all these components. The precipitation distribution is obviously also crucial, since this provides the only non-radiative contribution to diabatic heating.

3. SCIENCE ISSUES TO BE ADDRESSED

The most common application for satellite data in global modelling is in the assessment of the overall simulation of the model. This typically includes comparing global and zonal means, geographical distributions and their seasonal and inter-annual variations, for as many quantities as possible. There are countless examples of such comparisons in the literature, which address the basic question; is the model's overall climate reasonable? Unfortunately, all modellers know that, even if the answer to this question is yes, a reasonable simulation can still come about through unphysical interactions between the components of the model, whether by accident or design. A more searching use of observational data is therefore to ask the question; do the components of the model and the various model variables interact in a physically realistic way? Some examples of how satellite data can be used in this manner are discussed in Section 5. Of particular importance in climate models are the various radiative feedbacks involving water vapour and clouds. These are most commonly considered in the context of global change over extended periods, for which satellite data may not be available. However, the feedbacks should also be operating in the current climate and may well be important in determing the system's response to such natural phenomena as the intra-seasonal oscillation and ENSO. Satellite data could play a key role in such studies.

There are several more specific questions which remain open in the area of clouds and radiation. Research is active in determining what controls the cloud physical and radiative properties, including the fraction of the incident solar radiation absorbed by clouds. The physics of the formation and persistence of cirrus, including the ice water content, crystal habit and size are all uncertain, yet need to be represented in large scale models in some way. For all clouds, the role of the cloud macro- and micro-structure (e.g cloud overlaps and smaller scale inhomogeneities) in determing cloud radiative properties are not fully understood. Much of the work in these areas is motivated by the need to make the best use of the wide range of satellite data now available, and it is likely that some of the new techniques developed in that field will have applications in large-scale modelling.

4. SATELLITE DATA CURRENTLY AVAILABLE

Satellite data play a vital role in evaluating climate models and assisting in their development. The data may come from either operational weather satellites or from dedicated research satellites. It is important to remember that the only quantities actually measured by Earth observation instruments are currents and voltages (Level 0). Through modelling of the instrument and calibration, these are converted into radiances (Level 1) and the latter may be used directly (e.g. in NWP systems) or may be converted further into derived geophysical products (Level 2). At each stage, a priori assumptions and external data are used, often accompanied by significant amounts of modelling. The growing use of radiances to perform more direct comparisons between satellite data and global models is partly motivated by the desire to minimise the errors introduced by such assumptions and modelling.

Many of the model variables mentioned in Section 2 can be compared with satellite products, although there are important gaps (see Section 6). Variables which may be compared include the radiation budget, cloud amounts and properties, water vapour fields and precipitation. Table 1 lists several useful Web sites which provide an entry into the various datasets available. Many of the initiatives have been sponsored by the World Climate Research Programmme (WCRP) Global Energy and Water Cycle Experiment (GEWEX). The GEWEX website is particularly useful and includes many links to other sites for specific projects and products.

Early work on the use of satellite data to determine the radiation budget and cloud cover is reviewed by Hartmann (1993). The research satellite Nimbus 7 provided an important milestone, since it carried both radiation budget sensors and narrow band instruments from which cloud amounts could be retrieved. Unfortunately, the scanning radiation budget sensors lasted for only about 18 months, but the low resolution sensors lasted very much longer and the data have been used in studies of the radiation budget and clouds (e.g. Kyle et al. 1995).

Two satellite datasets which have most commonly been used in comparisons with climate models are radiation budget data from the Earth Radiation Budget Experiment (ERBE, Harrison et al. 1990) and cloud retrievals from the International Satellite Cloud Climatology Project (ISCCP, Rossow and Schiffer 1991). ERBE used specially designed broad-band radiation budget instruments mounted on the operational weather satellites NOAA-9 and NOAA-10, as well as on the dedicated Earth Radiation Budget Satellite (ERBS). No other information was used from other instruments on these missions (e.g. on cloud amounts and properties), since ERBE was very much a stand-alone experiment. Despite this, much valuable information was obtained on the relationship between clouds and the Earth's radiation budget, since considerable efforts were directed towards producing an estimate of the clear-sky radiation budget, from which the effect of clouds could be obtained by differencing this product from the all-sky radiation budget to produce the cloud radiative forcing diagnostic (Harrison et al. 1990). In sharp contrast, ISCCP had no dedicated instruments and instead consisted of re-processing a sampled sub-set of narrow band visible and thermal infrared radiances from existing operational geostationary and polar orbiting satellite imagery through a cloud detection and characterisation algorithm, to produce retrievals of cloud amounts and optical depths covering the period 1983 onwards. Comparisons between ISCCP and ERBE have shown that the cloud and radiation budget products are broadly consistent, although since they were obtained from different platforms some of the differences may be related to sampling.

Comparisons of radiation budget simulations with the 5-year record from ERBE are now a standard tool for evaluating the overall performance of these models (e.g. Kiehl et al. 1998). Comparisons with ISCCP require care, since the definition of what constitutes a cloud may not be consistent between the satellite data and the model (Yu et al. 1996). Cloud comparisons with several models which took part in the Atmospheric Model Intercomparison Project (AMIP) are shown by Weare et al. (1996). ISCCP data have been particularly valuable in process studies, for example of the temperature dependence of cloud optical depth (Tselioudis et al. 1993) and of the relationship between cloud cover and dynamical variables (Lau and Crane 1995). ISCCP and ERBE data have also been used to infer the surface radiation budget (Li et al. 1995) as well as atmospheric heating rates.

As with Nimbus 7, the ERBE Wide Field Of View (WFOV) sensors have continued to operate for many years after the demise of the higher resolution scanners, the final observations from which were made in 1990. Since then, scanner measurements of the radiation budget have been made from the ScaRaB instrument (Kandel et al. 1998). The radiation budget record is currently being continued with the CERES scanners on the TRMM satellite, to be followed by the CERES instruments on Eos-AM and the Geostationary Earth Radiation Budget (GERB) instrument on Meteosat Second Generation. With the ERBE WFOV sensors still producing data, a cross calibration is possible of at least ERBE, ScaRaB and CERES on TRMM and hopefully the later instruments as well. All of these measurements will be used extensively in evaluating climate models.

Although ISCCP data have found many applications, they suffer from problems resulting from the use of only one visible and one infrared channel, in both cases from the operational imagers. Wylie et al. (1994) showed that additional sensitivity to high clouds could be obtained by the use of the 15 micron CO_2 sounding channels, through a technique known as "CO_2 slicing". A comparison of these data with ISCCP is shown by Jin et al. (1996) and Wylie and Menzel (1999) shows results from 8 years of data.

With the growing sophistication of climate models, validation data are needed for cloud microphysical properties in addition to the information available from ERBE and ISCCP. The first such quantity to be retrieved reliably from satellite data was the liquid water path, notably from the Special Sensor Microwave/Imager (SSM/I) instruments on the U.S. Defense Meteorological Satellite Program (DMSP) (e.g. see Greenwald et al. 1993). The algorithms have undergone frequent revisions; recent results are shown by Weng et al. (1997).

A parameter of particular importance in studies of global warming is the mean droplet size for water clouds, also known as the effective radius, because in conjunction with the water path this controls the cloud optical thickness and hence the shortwave albedo of water clouds. The effective radius is known to be sensitive to the presence of hygrospcopic aerosols, so that pollution can increase cloud albedo and exert a cooling effect on climate. Estimates were derived from ISCCP data by Han et al. (1994) and it is surprising that few other attempts have been made to derive global climatologies of this parameter, given its importance.

Apart from the impact of aerosols on the effective radius of clouds, there are a variety of aerosol species which have a significant influence on the radiation balance in clear conditions, such as sea salt, anthropogenic and naturally occurring sulphate as well as products from biomass burning and wind-blown dust. Limited information on the aerosol loading is available from retrievals based on the narrow band visible channels on the NOAA polar orbiters (AVHRR) and Meteosat. Comparisons between ERBE data and climate models also provide a direct measure of the effect of aerosols on the clear-sky radiation budget (Haywood et al. 1999). The most reliable data came from the French POLDER instrument on the ADEOS satellite. POLDER had a multi-angle viewing capability which provides additional information on the scattering properties of aerosols and clouds.

Some climate and numerical weather prediction (NWP) models now include explicit formulations of cloud microphysical processes, including the phase of the condensate. The need to match this simulation capability with satellite retrievals of the ice water path and mean crystal size is providing a considerable challenge to remote sensing, although techniques are being developed, particularly in the sub-millimetre region of the spectrum (Stephens et al. 1998). The area of ice clouds and ice water contents provides the most glaring example of a gap between the capabilities of climate models and the variables which can be retrieved reliably from satellite data.

One of the most basic quantities to be evaluated in a climate simulation is the precipitation distribution. Unfortunately, the heterogeneous nature of precipitation in space and its intermittency in time poses severe sampling problems for any observing system, whether based on conventional instruments such as rain guages, weather radars or satellite instruments. As a result, global climatologies are subject to significant errors, but efforts to reduce these problems have been a focus of the GEWEX Global Precipitation Climatology Project (GPCP). For further information, follow the link from the GEWEX website (Table 1).

The re-analysis projects run by the major weather prediction centres provide an important new source of data for evaluating models. The advantage of using re-analyses as opposed to the high level products such as those discussed above is that the analysis system produces the optimum fit to all the assimilated conventional and satellite radiance data, so that the analyses provide a self-consistent set of a wide range of variables, including dynamical and thermodynamic as well as water vapour, cloud and radiation fields. This consistency may be exploited to study some of the basic factors which control the radiation budget (Slingo et al. 1998). In contrast, data gathered from separate satellite observing systems, each with their own processing and retrieval algorithms, may have inconsistencies which make it impossible to obtain such a coherent picture. Analyses can suffer from undue influence from the underlying forecast model, with its attendant systematic errors, but the availability of two or more analyses for the same period is helpful to estimate this effect. See the websites in Table 1 for links to the NCEP (Kalnay et al. 1996) and ECMWF (Gibson et al. 1997) re-analysis web pages.

5. USING SATELLITE DATA TO EVALUATE MODELS

Satellite data can be used in many ways to evaluate climate and numerical weather prediction models, as can the data from other sources. In this section, we consider three particular methods. We first consider the most common application, in which global, zonal and geographical averages and their seasonal variations are compared. This may be summarised as checking the overall climate of the model (5.1). The second involves a more searching examination of the relationships between variables, to test the physical basis of the model and of its internal interactions and processes (5.2). Finally, we consider the use of the "raw" satellite radiances, free from the uncertainties and errors introduced by the retrieval process (5.3). These categories are somewhat arbitrary, because some studies fit all three criteria simultaneously, but they are helpful nevertheless.

5.1 Checking the overall climate of the model

The data can be used to evaluate the overall simulation of clouds and radiation, with the data providing a climatological record of the geographical distributions and their seasonal and inter-annual variability. There are many examples in the literature of such comparisons, which form the foundation of any evaluation of a new version of a model. Models which have recently been tested in this way include the Hamburg model ECHAM4 (Chen and Roeckner 1997), the NCAR CCM3 (Kiehl et al. 1998) and the Hadley Centre model HadAM3 (Pope et al. 1999).

The more variables that are examined the more likely it is that any anomalies in the performance of a model will be picked up. However, one problem with this method of comparison is that it is often difficult to separate the strengths and weaknesses of particular parametrizations from the performance of the model as a whole, although it does provide a final check on the overall simulation. It is also common experience that a good simulation of climatological means provides a poor guide to the reliability of the physical basis of the model; many problems may be obscured by what appears to be a satisfactory "climatology".

5.2 Physical basis and processes

A further use of the satellite data is to examine the relationships between variables and to verify that these relationships are also satisfied in the models. These may be termed process studies, since their primary aim is to study the physical interactions between processes in the real world and in the models. There is an analogy with process studies using aircraft and surface-based data and indeed some of the larger field programmes (e.g. TOGA-COARE, ACE etc) include a substantial satellite data component for this reason). The satellite data can then be used to examine the global applicability of the relationships found in the field programmes, which can only cover a limited number of locations. The FIRE programme (First ISCCP Regional Experiment) is a good example of this paradigm.

An important result from ERBE is that the shortwave and longwave cloud radiation forcing at the top of the atmosphere tend to cancel over regions of deep, tropical convection. Kiehl (1994) suggested that this was a result of the fact that such cloud systems tend to consist of deep, optically thick clouds with their tops near the tropical tropopause. This result thus provides a useful check on the cloud structure and radiative properties in these regions.

In mid-latitudes, it is common experience that the nature of the cloud fields is strongly influenced by the dynamical regime. For example, warm sectors of depressions contain much low cloud, frontal clouds are usually deep and often multi layered and the cold air behind cold fronts has a mixture of shallow and deep convection. Lau and Crane (1995, 1997) showed that such relationships between the cloud and dynamical regimes can be extracted from ISCCP data. Klein and Jakob (1998) have applied the Lau and Crane compositing technique to evaluate the cloud simulated by the ECMWF forecast model. Mark Webb (personal communication) has performed a similar analysis with the Met. Office Unified Model.

An important and related application for satellite data is to check on hypothesized links between variables which may contribute to cloud feedbacks in climate change. Tselioudis et al. (1993) used ISCCP data to study the global distribution of the relationship between cloud optical thickness and temperature. A simple thermodynamic argument suggests that cloud optical thickness should increase with temperature, leading to a negative cloud optical property feedback on global warming. Tselioudis et al. (1993) found that the satellite data showed such a relationship over land, but elsewhere there were decreases in optical thickness with temperature, implying a positive feedback. Tselioudis et al. (1998) extended this analysis through comparisons with simulations by the Goddard Institute for Space Studies (GISS) climate model.

It has also been hypothesized that, since the mean size of water droplets in warm clouds depends on the sub-cloud aerosol distribution, there is potential for increases in pollution to lead to smaller drops, brighter clouds and hence global cooling, through the "Twomey effect". The distributions of effective radius derived by Han et al. (1994) from ISCCP data were used by Jones and Slingo (1997), among others, to validate their climate model simulations of this effect. Some of the underlying assumptions in such modelling studies have been challenged by Han et al. (1998), using ISCCP retrievals of effective radius and liquid water paths.

A challenging application of satellite data is to study cloud and radiation feedbacks in the coupled ocean-atmosphere system and to provide a means of evaluating these feedbacks in climate models (Karl 1995). It is well established that uncertainty as to the magnitude of cloud feedbacks constitutes one of the major limitations on climate model predictions of global warming (Kattenberg et al. 1996). If satellite data can be used to reduce this uncertainty then a major step forward will have been taken. The study by Klein et al. (1999) of possible tele-connections between sea surface temperature anomalies in different ocean basins provided by coherent changes in cloudiness represents a step in this direction.

5.3 Direct radiance comparisons

In all of the above examples, the satellite data are processed through a variety of retrieval schemes to produce high level products. Such schemes require a significant amount of a priori information to convert the satellite radiances into geophysical quantities. It is now common practice in NWP applications to avoid such retrievals and assimilate the radiances directly into the forecast model. This requires a forward radiative transfer code to simulate the observed radiances from the variables available in the forecast model. Various methods are then used to adjust the model variables to give the optimum fit of the simulated radiances to the observed, taking into account the error characteristics of both the forecast model and the satellite instrumentation. This is a fairly straightforward procedure for extracting information on atmospheric temperature and water vapour in cloud-free regions from the thermal and microwave sounding channels. In the future, the technique will be extended to include clouds. Before such techniques can be made operational, experience needs to be gained with simulating cloudy radiances. Even without the simulation of cloudy radiances, however, there is already significant skill in the simulation of cloud fields by NWP models, as has been shown recently for the ECMWF Re-Analyses by Jakob (1999).

There are also arguments in favour of using such techniques in diagnostic studies of climate models. This is particularly valuable where the radiances contain information on, for example, the diurnal cycle of surface temperature and cloudiness which can be studied without the need to perform a cloud retrieval. An example of the information content of radiances in such applications are shown for data from Meteosat by Duvel and Kandel (1985) and Duvel et al. (1996). Such studies are usually confined to the area covered by a single geostationary satellite, but the EU-funded CLAUS project (Cloud Archive User Service) has produced a global archive of infrared window channel radiances every 3 hours, by re-processing the raw data on which ISCCP is based. Initial comparisons with the Unified Model have shown that the CLAUS data can be very helpful in revealing model problems (Yang and Slingo 1998).

Table 1 shows several web sites and projects devoted to water vapour. Some of the products (notably NVAP and GVaP) make use of radiances from the water vapour channels on the operational weather satellites. These data are of course also routinely assimilated into weather forecast models and re-analyses. The water vapour radiances can also be studied in their own right and are particularly valuable in revealing the dynamical re-distribution of water vapour associated with ENSO events and other circulation anomalies (Bates et al. 1996). Comparisons with climate model simulations of these radiances are in progress in several centres. More conventional comparisons between water vapour retrievals and climate models are reported by Bates and Jackson (1997).

6. LIMITATIONS, GAPS AND FUTURE NEEDS

From the discussion in the previous sections, it is possible to identify some gaps in the satellite observing system which need to be filled. There is a well-known lack of reliable information on the vertical structure of clouds and on the overlaps between clouds in different layers. This problem is likely to be addressed by plans to fly active instruments, such as cloud profiling radars and lidars, in process-oriented missions (see the CLOUDSAT web page in Table 1). Temporal sampling is always poor from low earth polar orbits and the only practical solution is to use geostationary satellites (e.g. as in ISCCP). The next opportunity for an advance in this area will come with the launch of Meteosat Second Generation (MSG) in 2000, which will include the SEVIRI visible/infrared imager and the Geostationary Earth Radiation Budget (GERB) broad-band instrument (see http://www.ssd.rl.ac.uk/gerb/). MSG provides an example of the importance of mounting broad and narrow band instruments on the same platform, so as to relate the cloud products to the observed radiation budget. This will also be achieved by the CERES and MODIS instruments on Eos-AM. However, every opportunity should also be taken for exploiting the substantial quantity of instrumentation which is being developed for operational meteorological purposes and which, as in ISCCP, can also be used for climate studies. This includes visible, infrared and microwave imagers following the heritage of instruments such as AVHRR and SSM/I.

One of the most important gaps is in the area of ice clouds, where there is little reliable information on ice water paths and on the crystal habit and size (Stephens et al. 1998), although the ice water path has been inferred indirectly from a combination of ISCCP and SSM/I data (Lin and Rossow (1996). Long-term monitoring to ensure that inter-annual and longer period variability are sampled properly with instrumentation which is not changing continually is also not a focus of many planned missions, which either concentrate on NWP applications or on short-term process studies. A satellite which concentrated on the long-term monitoring of cloud properties and their impact on broad-band fluxes, could discriminate between liquid water and ice and retrieve the liquid water and ice water paths together with the mean droplet and ice crystal size, would make a substantial contribution to closing the significant gaps in the observing system. However, long-term monitoring requires proven and reliable instrumentation, which may not be available for all of the above quantities.

7. REFERENCES

Bates, J.J., Wu, X. and Jackson, D.L., 1996. Interannual variability of upper troposphere water vapor band brightness temperature. J. Clim., 9, 427-438.

Bates, J.J. and Jackson, D.L., 1997. A comparison of water vapor observations with AMIP I simulations. J. Geophys. Res., 102, 21837-21852.

Chen, C.-T. and Roeckner, E., 1997. Cloud simulations with the Max Planck Institute for Meteorology general circulation model ECHAM4 and comparison with observations. J. Geophys. Res., 102, 9335-9350.

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

Duvel, J.P., Morcrette, J.J. and Klinker, E., 1996. Evaluation of the spatio-temporal variability of tropical convection in GCMs by using geostationary satellite data. In: Climate sensitivity to radiative perturbations: physical mechanisms and their validation. NATO ASI Series I, 34, 43-50.

Gibson, J.K., Kallberg, P., Uppala, S., Hernandez, A., Nomura, A. and Serrano, E. 1997. ERA description. ECMWF Re-Analysis Project Report no. 1, ECMWF, 72pp.

Greenwald, T.J., Stephens, G.L. and Vonder Haar, T.H., 1993. A physical retrieval of cloud liquid water over the global oceans using special sensor microwave/imager (SSM/I) observations. J. Geophys. Res., 98, 18471-18488.

Han, Q., Rossow, W.B. and Lacis, A.A., 1994. Near-global survey of effective droplet radii in liquid water clouds using ISCCP data. J. Clim., 7, 475-497.

Han, Q., Rossow, W.B., Chou, J. and Welch, R.M., 1998. Global survey of the relationships of cloud albedo and liquid water path with droplet size using ISCCP. J. Clim., 11, 1516-1528.

Harrison, E.F., Minnis, P., Barkstrom, B.R., Ramanathan, V., Cess, R.D. Gibson, G.G., 1990. Seasonal variation of cloud radiative forcing derived from the Earth Radiation Budget Experiment. J. Geophys. Res., 95, 18687-18703.

Hartmann, D.L., 1993. Radiative effects of clouds on earth's climate. Pp 151-173 in: Aerosol-Cloud-Climate Interactions. Ed. P. V. Hobbs, Academic Press.

Haywood, J.M., Ramaswamy, V. and Soden, B.J., 1999. Tropospheric aerosol climate forcing in clear-sky satellite observations over the oceans. Science, 283, 1299-1303.

Jakob, C., 1999. Cloud cover in the ECMWF reanalysis. J. Clim., 12, 947-959.

Jin, Y., Rossow, W.B. and Wylie, D.P., 1996. Comparison of the climatologies of high-level clouds from HIRS and ISCCP. J. Clim., 9, 2850-2879.

Jones, A. and Slingo, A., 1997. Climate model studies of sulphate aerosols and clouds. Phil. Trans. R. Soc. Lond., B, 352, 221-229.

Kalnay, E. and others, 1996. The NCEP/NCAR 40-year reanalysis project. Bull. Am. Meteorol. Soc., 77, 437-471.

Kandel, R. and others, 1998. The ScaRaB earth radiation budget dataset. Bull. Am. Meteorol. Soc., 79, 765-783.

Karl, T.R. (Editor), 1995. Long-term climate monitoring by the global climate observing system. Climatic Change, 31, December 1995 special issue.

Kattenberg, A. and others, 1996. Climate models - projections of future climate. Pp 285-357 in: Climate Change 1995. The science of climate change. Cambridge University Press.

Kiehl, J.T., 1994. On the observed near cancellation between longwave and shortwave cloud forcing in tropical regions. J. Clim., 7, 559-565.

Kiehl, J.T., Hack, J.J., Hurrel, J.W., 1998. The energy budget of the NCAR Community Climate Model: CCM3. J. Clim., 11, 1151-1178.

Klein, S.A. and Jakob, C., 1998. Validation and sensitivities of frontal clouds simulated by the ECMWF model. Mon. Wea. Rev., submitted for publication.

Klein, S.A., Soden, B.J. and Lau, N.-C., 1999. Remote sea surface temperature variations during ENSO: evidence for a tropical atmospheric bridge. J. Clim., 12, 917-932.

Kyle, H.L., Weiss, M. and Ardanuy, P. 1995. Cloud, surface temperature and outgoing longwave radiation for the period from 1979 to 1990. J. Clim., 8, 2644-2658.

Lau, N.-C. and Crane, M.W., 1995. A satellite view of the synoptic-scale organization of cloud properties in midlatitude and tropical circulation systems. Mon. Wea. Rev., 123, 1984-2006.

Lau, N.-C. and Crane, M.W., 1997. Comparing satellite and surface observations of cloud patterns in synoptic-scale circulation systems. Mon. Wea. Rev., 125, 3172-3189.

Li, Z., Whitlock, C.H., Charlock, T.P, 1995. Assessment of the global monthly mean surface insolation estimated from satellite measurements using global energy balance archive data. J. Clim., 8, 315-328.

Lin, B. and Rossow, W.B., 1996. Seasonal variation of liquid and ice water path in nonprecipitating clouds over oceans. J. Clim., 9, 2890-2902.

Pope, V.D., Gallani, M.L., Rowntree, P.R. and Stratton, R.A., 1999. The impact of new physical parametrizations in the Hadley Centre climate model - HadAM3. Clim. Dynam., in press.

Rossow, W.B. and Schiffer, R.A., 1991. ISCCP Cloud Data Products. Bull Am. Meteorol. Soc., 72, 2-20.

Slingo, A., Pamment, J.A. and Webb, M.J., 1998. A 15-year simulation of the clear-sky greenhouse effect using the ECMWF reanalyses: fluxes and comparisons with ERBE. J. Clim., 11, 690-708.

Stephens, G.L., Jakob, C. and Miller, M., 1998. Atmospheric ice - a major gap in understanding the effects of clouds on climate. GEWEX News, February 1998.

Tselioudis, G., Lacis, A.A., Rind, D. and Rossow, W.B., 1993. Potential effects of cloud optical thickness on climate warming. Nature, 366, 670-672.

Tselioudis, G., Del Genio, A.D., Kovari, W. and Yao, M.-S., 1998. Temperature dependence of low cloud optical thickness in the GISS GCM: contributing mechanisms and climate implications. J. Clim., 11, 3268-3281.

Weare, B.C. and others, 1996. Evaluation of the vertical structure of zonally averaged cloudiness and its variability in the Atmospheric Model Intercomparison Project. J. Clim., 9, 3419-3431.

Weng, F., Grody, N.C., Ferraro, R.,Basist, A., Forsyth, D., 1997. Cloud liquid water climatology from the Special Sensor Microwave/Imager. J. Clim., 10, 1086-1098.

Wylie, D.P. and Menzel, W.P., 1999. Eight years of high cloud statistics using HIRS. J. Clim., 12, 170-184.

Wylie, D.P., Menzel, W.P., Woolf, H.M. and Strabala, K.I., 1994. Four years of global cirrus cloud statistics using HIRS. J. Clim., 7, 1972-1986.

Yang, G. and Slingo, J.M., 1998. The seasonal mean and diurnal cycle of tropical convection as inferred from CLAUS data and the Unified Model. UGAMP Technical Report No. 47. Universities Global Atmospheric Modelling Programme, Reading University.

Yu, W., Doutriaux, M., Seze, G., Le Treut, H., Desbois, M., 1996. A methodology study of the validation of clouds in GCMs using ISCCP satellite observations. Clim. Dynam., 12, 389-401.

Table 1. Websites with satellite data related to radiation and clouds

GEWEX:	http://www.cais.com/gewex/gewex.html (useful information plus links)
Water vapour	
NVAP:	http://www.stcnet.com/projects/nvap.html
GVaP:	http://www.cais.com/gewex/gvap.html
HALOE:	http://haloedata.larc.nasa.gov/haloe.html
MLS:	http://uarsfot08.gsfc.nasa.gov/
Earth Radiation Budget	
CERES:	http://asd-www.larc.nasa.gov/ceres/trmm/ceres_trmm.html
Clouds	
ISCCP:	http://isccp.giss.nasa.gov
HIRS (Wylie):	http://www.ssec.wisc.edu/~donw/
Precipitation	
GPCP:	http://orbit-net.nesdis.noaa.gov/arad/gpcp
TRMM:	http://trmm.gsfc.nasa.gov/
Aerosols	
GACP:	http://gacp.giss.nasa.gov/
POLDER:	http://polder.www-projet.cnes.fr:8060/
Re-Analyses	
ERA:	http://www.ecmwf.int/html/ERA/index.html
NCEP:	http://wesley.wwb.noaa.gov/reanalysis2/index.html
New Satellite Initiatives	
GERB:	http://www.ssd.rl.ac.uk/gerb/
CloudSat	http://cloudsat.atmos.colostate.edu