INTERNATIONAL ASSOCIATION OF
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CLOUD-RADIATION INTERACTIONS AND THEIR PARAMETERIZATION IN CLIMATE MODELS

(Report of international workshop,
National Oceanic and Atmospheric Administration
Science Center,
Camp Springs, Maryland, U.S.A.
18-20 October 1993)

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Technical Editor: Marie Boyko

PREFACE

The scientific community has identified the role of clouds in climate as one of the highest priorities of global-change research. The reason for this is quite clear: the potential feedback effect of clouds is a great cause of uncertainty in current predictions of greenhouse warming. This uncertainty arises because of lack of knowledge on how to generate clouds and their radiative properties in climate models.

Recognizing the need to advance the state of the art of cloud parameterization in climate models, the Joint Working Group on Clouds and Radiation of the International Association of Meteorology and Atmospheric Sciences (IAMAS) took the initiative to bring together an international group of scientists working on various aspects of the problem. The workshop was developed in association with the World Climate Research Program's (WCRP) Working Group on Radiative Fluxes, Working Group on Numerical Experimentation, and GEWEX (Global Energy and Water Cycle Experiment) Cloud Systems Science Panel.

The objectives of the workshop were to:

(1)   Review the problems associated with the generation of clouds and their radiative properties in climate models.

(2)   Assess recent research results bearing on the cloud-radiation interaction problem.

(3)   Develop research strategies aimed at advancing the state of the art of cloud parameterization in the short term and our fundamental understanding of cloud-radiation interaction in the long term.

In a sense, the workshop was quite similar to one held 15 years ago in Oxford, England, on Parameterization of Extended Cloudiness and Radiation for Climate Models. That meeting was organized by the Global Atmospheric Research Program Climate Dynamics Sub-Programme, which shortly thereafter evolved into the WCRP.

The Oxford workshop had a major impact on climate-related cloud-radiation research. Its recommendations led to: the initiation of the International Satellite Cloud Climatology Program, observational and modeling studies of the dependence of climate on cloudiness, and a number of regional field programs to study particular cloud types and their microphysical and radiative properties.

The present workshop was hosted by the U.S. National Oceanic and Atmospheric Administration at its Science Center in Camp Springs, Maryland, on 18-20 October 1993. Fifty international experts in climate modeling, cloud radiative processes, and cloud physics participated (see the list in Section 3 of this volume). After one and a half days of invited and contributed papers (see

Extended Abstracts for summaries), the participants divided into three panels: General Circulation Models, chaired by J.F. Geleyn; Satellite Observations, chaired by G. Stephens; and Process Studies, cochaired by H. Sundqvist and D. Starr.

The workshop's success was due in large part to the efforts of a number of groups:

- The sponsoring organizations, which provided the funding necessary to conduct the workshop:

    U.S. National Oceanic and Atmospheric Administration
    U.S. National Aeronautics and Space Administration
    U.S. Department of Energy
    World Climate Research Program

- The Organizing Committee:

    Leo Donner, Organizing Committee Chair, IAMAS Joint Working Group on Clouds and Radiation
    Anthony Slingo, WCRP Working Group on Radiative Fluxes
    Jean-François Geleyn, WCRP Working Group on Numerical Experimentation
    Peter Jonas, WCRP GEWEX Cloud System Science
    George Ohring, Chair, IAMAS Joint Working Group on Clouds and Radiation

- The University Corporation for Atmospheric Research (UCAR) staff who provided support services before, during, and after the workshop:

    Meg Austin
    Barb Appelhans
    Ellen Martinez

- And last, but not least, the participants, who took time off from their busy, productive scientific lives to help review, assess, and develop research strategies for this critical scientific problem.
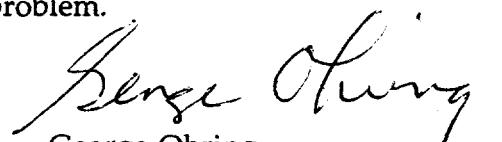
George Ohring
Chair, IAMAS Joint Working
Group on Clouds and Radiation

EXECUTIVE SUMMARY

The International Workshop on Cloud-Radiation Interactions and Their Parameterization in Climate Models met on 18-20 October 1993 in Camp Springs, Maryland, U.S.A. It was organized by the Joint Working Group on Clouds and Radiation of the International Association of Meteorology and Atmospheric Sciences. Recommendations were grouped into three broad areas: (1) general circulation models (GCMs), (2) satellite studies, and (3) process studies. Each of the panels developed recommendations on the themes of the workshop.

Explicitly or implicitly, each panel independently recommended observations of basic cloud microphysical properties (water content, phase, size) on the scales resolved by GCMs. Such observations are necessary to validate cloud parameterizations in GCMs, to use satellite data to infer radiative forcing in the atmosphere and at the earth's surface, and to refine the process models which are used to develop advanced cloud parameterizations.

With respect to GCMs, recent research has demonstrated that model climate and climate sensitivity both depend fairly strongly on the methods used to parameterize clouds. Regarding cloud parameterization, there are experimental efforts under way to use prognostic methods for cloud microphysical properties in GCMs. The workshop recommended:

- A continuation of studies using prognostic methods for cloud microphysical properties in GCMs.

- Increased use of high-resolution, process-resolving models to improve basic understanding of the cloud systems undergoing parameterization, and testing of parameterizations by using observations and models with four-dimensional variational data-assimilation methods.

Successful satellite programs have enabled the assessment of cloud radiative forcing at the top of the atmosphere. Satellite retrievals of global cloud distribution are under way.

With respect to satellite observations the workshop recommended:

- The development of strategies to determine the four-dimensional distribution of cloud properties. This information is necessary if observations of the disposition of radiant energy are to advance from the important, but limited, achievement of the past decade—the determination of the energy balance and cloud forcing at the top of the atmosphere—to the determination of the energy balance within the atmosphere and at the earth's surface.

- Achieving the goal of inferring the four-dimensional cloud distribution will require the deployment of both active and passive satellite sensors. The calibration of these sensors will require field studies using aircraft.

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With respect to field programs, several major experiments, dealing with various types of cloud systems in different geographical regions, have been completed in recent years.

On process studies, the workshop recommended:

- Additional field studies of cloud systems not covered by earlier experimental programs.

- More probing analysis of the results of completed field programs.

- Instrumentation development to permit measurement of some microphysical and radiative properties of clouds, which are presently known poorly.

- The development of retrieval algorithms (using the results of field and process studies) to enable global observations of important cloud properties.

The recommendations of the various workshop panels were in many cases mutually reinforcing or, in some cases, even identical. The detailed panel reports compose the first portion of this report. Brief research summaries from the workshop speakers follow.

1. REPORTS OF WORKING GROUPS
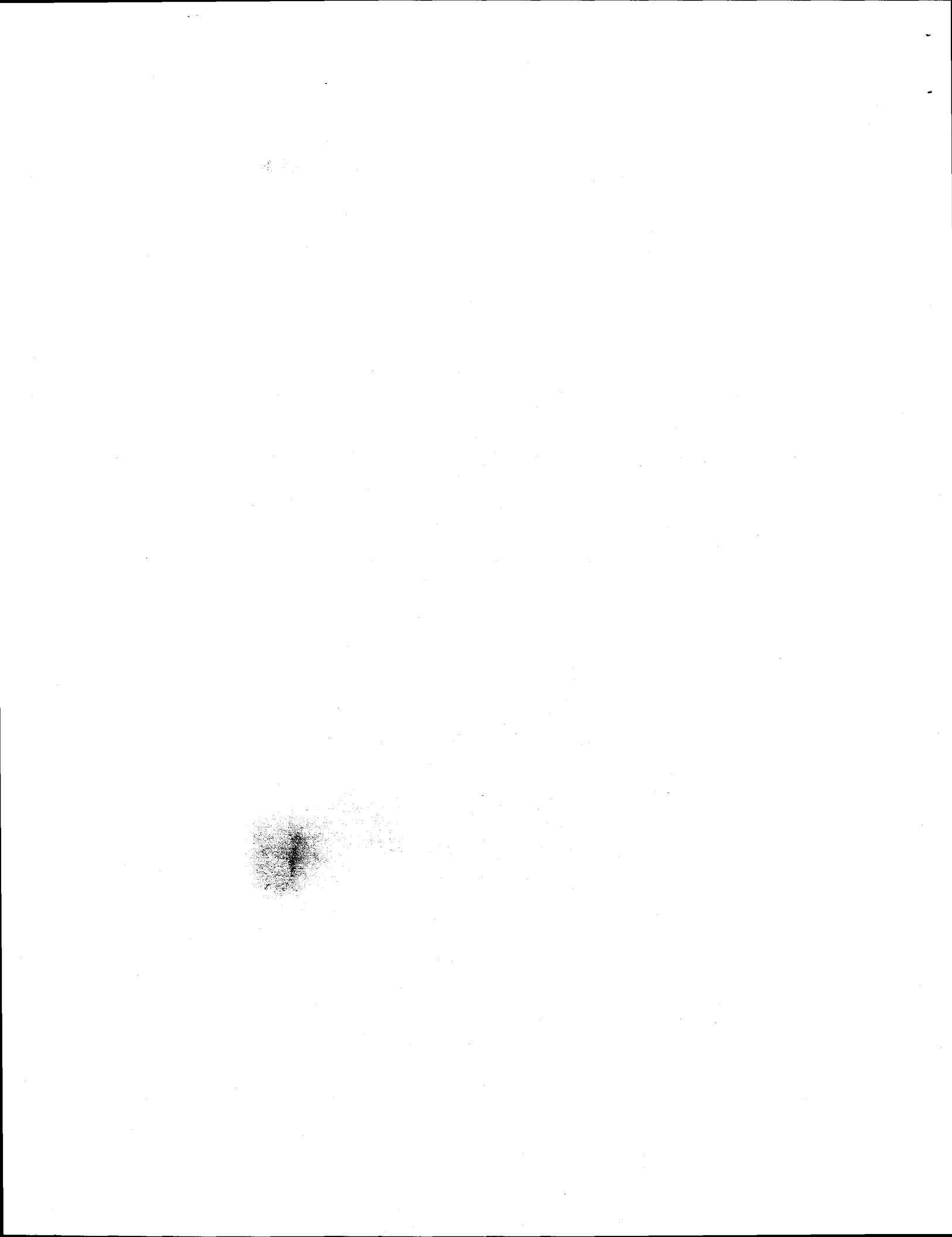
General Circulation Models Final Report

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Centre National de Recherches Météorologiques, France

1. Key Issues and Recent Progress

Clouds exert major influences on both the earth's radiation budget and the hydrologic cycle, but almost all clouds are too small in the horizontal and/or vertical scale to be resolved by climate models. It is therefore necessary to parameterize the effects of unresolved clouds on the global climate system. This is essentially a problem of scale interactions.

Studies over the past decade have shown that climate sensitivity in GCMs strongly depends upon the technique used to parameterize clouds (e.g., Mitchell et al., 1989).

ISCCP offered the first opportunity to compare results of such cloud schemes with observed data at roughly the correct scale. This helped mainly to define the deficiencies of existing schemes and to propose model improvement strategies. ERBE data and the concept of cloud radiative forcing helped to shed a first light on the quality of GCM cloud parameterizations with respect to their effect on the seasonal variation of radiation at the top of the atmosphere.

Meanwhile, GCMs have continuously improved their overall ability to simulate characteristics of the present climate. The hydrologic cycle and the derived cloud representation remain the main obstacles to progress. The cloud inhomogeneity within the large GCM grid boxes also remains a very important issue for the definition of cloud radiative properties.

Progress in parameterizing interactions among scales in cloud systems has been unfortunately very slow. The last ten years have seen some movement towards consensus on some of the key issues in the area of cumulus parameterization. Mass flux schemes are proliferating (Bougeault, 1985; Tiedtke, 1989; Gregory and Rowntree, 1990), moisture-convergence closure is undergoing a critical reexamination, and "relaxed" schemes are replacing "hard" adjustments (Betts, 1986). On the other hand, there has been little progress on the cloud-fraction problem, or on the important issue of mesoscale organization of cloud structures.

During the same period, some progress has been made in recognizing the multiple scales of motion involved in cloud parameterization. Cumulus parameterizations, which in early versions concentrated on updrafts of convective scale, have been extended to include convective-scale downdrafts (Cheng, 1989) and mesoscale up- and downdraft circulations (Donner, 1993). High-resolution cumulus-resolving models have been used to validate basic

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parameterization assumptions (Xu and Arakawa, 1992). All this resulted in some slow progress in the specification of model-computed partial cloud amounts.

In terms of cloud parameterization schemes, significant progress has been made for prognostic schemes where cloud water and cloud ice have their own memory in the GCMs. Improvements include: (i) the use of a prognostic equation for the cloud fraction, based on statistical methods to relate the cloud water and cloud ice distributions to the cloud amount (e.g., Smith, 1990), and to the rate of change of the saturation specific humidity (e.g., Tiedtke, 1993); (ii) the introduction of bulk microphysics equations to simulate the formation/dissipation processes of cloud water and cloud ice (Ose, 1993; Fowler and Randall, 1994); and (iii) the coupling between convective and large-scale cloud processes through the detrainment of cloud water and cloud ice at the tops of cumulus towers. In diagnostic schemes, the use of moist-thermodynamic-based assumptions (Somerville and Remer, 1984; Betts and Harshvardhan, 1987) have also led to a better description of the cloud water/ice contents.

There have been major developments towards the introduction of biophysical processes in the representation of the land-surface processes. Sensitivity studies conducted at different institutions have shown the impact of these improved parameterizations, particularly large on the summer "climate" of mid-latitude continents as well as the strong feedbacks among the soil moisture, the planetary-boundary-layer (PBL) structure, and rainfall—all parameters of paramount importance for the correct representation of cloudiness over those areas.

The availability of reference radiative-transfer profiles provided by the ICRCCM program has created an impetus for major improvements in both longwave and shortwave parameterization schemes for GCMs. This has resulted in an evolution towards more detailed models with a better ability to account for spectral variation of cloud and aerosol optical properties. It should be noted that most of the improvements came to the clear-sky case. There are still, however, outstanding problems regarding intercomparisons for cloudy atmospheres.

Substantial developments in radiation-transfer theory have recently taken place but have not yet been implemented in GCMs. This is due to computational restrictions and the difficulty of providing meaningful input parameters.

2. Outstanding Problems

2.a. Cloud Representation in GCMs

2.a.1. Influence of Cloud Microphysics

The importance of including prognostic cloud water/ice equations in conjunction with cloud microphysics processes in GCMs is widely acknowledged.

Several questions remain on how to best "explore" this kind of parameterization. First, one needs to select the most important cloud microphysical processes that are relevant on GCM spatial and temporal scales. For instance, Ghan and Easter (1991) show, using the cloud microphysics package of the Colorado State University Regional Atmospheric Modeling System (Cotton et al., 1982), that the inclusion of a diagnostic versus a prognostic equation for the precipitation species allows the use of longer time steps without significantly affecting the model performance to simulate the temporal evolution of the cloud water and ice variables. Second, help and collaboration should be sought in the cloud microphysics community for providing some guidance concerning the choice (or tuning limits) of microphysics "constants" that are needed in bulk parameterized equations of the relevant processes. For instance, results from Ose (1993) highlight the very strong sensitivity of the life cycles and radiative properties of tropical cirrus clouds to the parameterized cloud microphysics, especially in terms of the autoconversion process of cloud water and cloud ice into rain and snow.

2.a.2. Scale-Selection Problem

Since the above-mentioned microphysical parameterizations are constructed for spatial and temporal scales characteristic of processes such as coalescence or collision of hydrometeors (i.e., subcloud scale), they should be used in GCMs with an acute awareness of the discrepancy in scales. Microphysical parameterizations are highly nonlinear functions of dynamic quantities such as vertical velocity, and, at GCM resolution, these quantities are subject to substantial spatial averaging. The consideration of subgrid variations is therefore important to deal successfully with this scale problem.

More generally, there are two broad approaches to parameterizing subgrid cloudiness and/or cloud formation. One is to predict or assume probability distribution functions for relevant variables, e.g., water-vapor mixing ratio, temperature, and vertical velocity. The second is to explicitly parameterize specific subgrid processes that can produce partial cloud cover, e.g., convection and orographic gravity waves. Both approaches have their own merits and should be further investigated, bearing in mind all the other uncertainties when one tries to verify their results, especially in terms of induced radiative forcings.

2.a.3. Explicit Dynamic and Subgrid-Scale Issues

There is some suspicion that not enough consideration has been given to the issue of numerical schemes in cloud-radiation parameterization studies. Indeed, spectral vs. finite differences, Eulerian vs. semi-Lagrangian, and even the question of vertical differencing/integrating techniques ought to be considered in detail, owing to their paramount importance in parts of the modeled hydrology cycle.

Ideally higher resolution, especially in the vertical, should help to diminish the importance of these issues, but the benefit of an increase in resolution should primarily be the partial solution of some outstanding physical

issues, in contrast to any parameterization strategy (stratocumulus cloud-cover determination, life cycle of cirrus clouds, broad organization of the transport of mesoscale convective systems, etc.). Thus, climate-oriented parameterization schemes ought to be tested for their robustness to changes in the resolution, or their resolution dependencies should be explicitly identified.

In parameterizing cloud cover and liquid/ice-water content, prognostic methods will eventually supersede diagnostic methods but the new degrees of freedom will bring some difficulties with them and progress may be slow.

In general, parameterizing cloud formation, dissipation, fractional cover, spatial properties, etc., should be facilitated as problems related to errors in the large-scale environment for clouds are reduced.

Note that one should not isolate cloud parameterization from other GCM physics work, and the emphasis should be put not only on the cloud description but also on getting a better modeled hydrologic cycle. In addition, the "prognostic" solution will surely not solve all outstanding problems, especially those associated with the resolved/unresolved scale dilemma and with the links between microscale and macroscale cloud properties.

2.a.4. Influence of Land-Surface Processes

Improvements in the atmospheric hydrology (i.e., the vertical transports of all water phases) and its links to land-surface hydrology are necessary for climate modeling. The continental planetary-boundary-layer (PBL) clouds and the underlying surface form a tightly coupled system with a strong diurnal cycle which modulates the surface radiative budget. The PBL diurnal cycle of moist enthalpy influences precipitating convection. On large scales, these mechanisms influence the balance of convectively linked cloud cover and precipitation over continents.

The soil moisture can therefore provide a long-time-scale memory (from month to season) for the atmosphere over land, analogous to the role of sea surface temperature over the oceans. All these hydrologic interactions deserve further study. Indeed, on long time scales, errors in the surface radiation budget can introduce climate drifts over land; e.g., too much incoming net radiation will lock the surface in a too-warm-and-dry state without precipitation (or inversely).

2.b. Radiative Computations in GCMs

2.b.1. Atmospheric Absorption of Shortwave Radiation

Preliminary results of satellite-derived surface radiation budgets suggest that some GCMs overestimate shortwave radiation at the surface and underestimate shortwave absorption by the atmosphere even in the absence of clouds. However, discrepancies between the results of the different surface-radiation-budget algorithms and a lack of comparison with or the nonavailability of "reference" computations have yet to allow quantitative estimates of these

biases. Likely sources of the problem are the broad-band parameterization of water-vapor transmittance, uncertainties concerning the corresponding basic spectroscopic properties, and/or the neglect of aerosols' radiative effects.

Uncertainties still also exist regarding absorption of shorwave radiation by all clouds. Areas of special concern are the interaction of gaseous and particle absorption and single-scattering properties of cloud particles. These issues of uncertainty are particularly relevant since even numerical weather prediction (NWP) simulations show a strong impact on the atmospheric vertical structure of temperature. As noted in Section 2.a.1, the problem of parameterizing the mixing ratio, phase, shape, and sizes of cloud particles is immense and must also be overcome if new information on the preceding issues is to be useful.

2.b.2. Problems Related to "Cloud Geometry"

There are several aspects of "cloud geometry" governing radiative transfer that ought to be seriously addressed.

Cloud overlap is an especially difficult problem for shortwave radiative-transfer codes (e.g., Ritter and Geleyn, 1992). Since several competing solutions can be easily incorporated in the same codes, comparison of correctly tuned versions of these options should be encouraged.

Beyond this problem of layered structures comes the question of the horizontal variation of cloud optical properties and shapes. The nonlinearity of radiative-transfer computations indicates that grid-averaged micro/macrophysical cloud properties, possibly obtained from GCM parameterizations, may be unsuitable for a direct calculation of grid-averaged fluxes. Conversely, the translation in cloud parameterizations of what leads to the "best" radiative fluxes might create heavy biases in the hydrologic cycle of the GCM.

The determination of "effective," adjusted cloud properties is therefore urgently required to solve this double problem. There is special concern about the balance between macro- (i.e., cloud cover/shape) and microphysical (i.e., "inside cloud" liquid/ice-water content) properties that can be very difficult to validate.

2.c. Process Studies' Related GCM Problems

2.c.1. Acceptable "Scale Jumps"

Referring to the problems of nonlinearity and of scale selection addressed above, one of the objectives of process studies should be to quantify the upper limit of the "scale jump" that the parameterization of a given process is likely to support without losing its relevance.

2.c.2. Feedback Accuracy vs. Process Accuracy in Modeling

It is obvious that GCM modeling is more concerned with accurate descriptions of overall effects, including all interactions between processes, and relatively less concerned with the absolute accuracy to which a given separate process has to be reproduced, while the reverse can be said of modeling for process studies (i.e., fine-scale models, or even high-resolution NWP models). Some effort is necessary to bridge this "cultural" gap as much as possible.

2.c.3. Radiation Observations' Link to Relevant Process Studies

It is important to validate as far as possible the results from radiation parameterizations used in GCMs. Field studies that simultaneously measure the profiles of the radiatively active atmospheric constituents and radiances/fluxes would be useful to accomplish this task.

3. Recommendations

The outstanding problems documented above will require broad-based efforts by modeling groups and individual investigators for their solution. In addition to research focused on those problems, some specific recommendations follow:

3.a. GCM Studies

3.a.1. Validation Strategies

In order to validate new prognostic cloud parameterizations, global measurements of the atmospheric cloud water amount and especially cloud ice amount are desperately needed. For instance, at present the best way to validate the global distribution of the vertically integrated cloud ice mass is using satellite observations of the cloud radiative forcing of upper-tropospheric ice clouds. Also, statistics on the subgrid-scale variability of clouds and particle size distributions are needed. In addition, we need better measurements of the upper-tropospheric water vapor.

Several centers are using the same model for NWP and climate research. Clouds generated in numerical forecasts should be assessed against cloud distributions derived from contemporaneous satellite data. This will allow identification of systematic errors in specific synoptic situations, in the absence of problems associated with climate drift.

The comparison of model simulations to nonsatellite data, e.g., near-surface data from conventional observing systems, should be considered as a potentially useful tool for the validation of the models and deficiencies in the simulation of cloud-radiation interactions.

3.a.2. Model Developments

High-resolution models of cloud systems, which are essential for process studies (see the Process Studies Final Report), should also be used to assess cloud parameterizations and the assumptions which underlie these parameterizations. Several groups have been testing newly developed prognostic microphysics parameterizations for climate models, and it has been demonstrated that the simulated climate sensitivity depends strongly on the details of such formulations. We see a need for a small, focused workshop specifically addressing this important development, perhaps organized in terms of intercomparisons of model formulations and results from simple test cases.

3.b. Observations' Use

3.b.1. Comparison of Modeled and Satellite Radiances

Satellites are currently measuring radiances for a number of wavelengths (e.g., AVHRR). Current efforts are focused on using these radiances to retrieve a range of cloud properties (e.g., cloud optical depths, particle size). In conjunction with these efforts by the satellite community, models should generate their equivalent to those radiances. Comparison of modeled with measured radiances at a number of wavelengths should aid in the validation of cloud-climate simulation and improvements of physical parameterizations.

3.b.2. Atmospheric and Ocean/Atmospheric NWP-Type Data Assimilation

Four-dimensional variational data-assimilation methods are likely to become operational NWP tools within the next ten years, and they are the only serious hope to solve (even partially) the oceanic data-assimilation problem. The power of these methods lies in their capacity to fully use the model physics/dynamics to extend consistently in space and time the influence of the information contained in any observation (provided the model can simulate the observation "forward" process; see above). We support the forthcoming reanalyses with these new methods of long sets of data, including as much as possible cloud-related radiation measurements. Furthermore, once these methods have become stabilized, we encourage a new type of GCM validation by running them in such data-assimilation procedures at their usual resolution, since the fit to the observations, especially to those related to clouds, is the most comprehensive possible test of the model's physics.

3.c. General Recommendation

We endorse the continuation of the ongoing radiation and GCM intercomparison projects, specifically ICRCCM, FANGIO, and AMIP.

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Satellite Observations Final Report

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1. Key Issues and Recent Progress

As a result of the major role that clouds and precipitation play in the climate system, it is generally recognized (e.g., Intergovernmental Panel on Climate Change, 1992) that the lack of understanding of clouds represents one of the main uncertainties in the modeling and prediction of climate. Thus, clouds have been put at the top of the priorities for research by, as an example, the U.S. Global Change Research Program.

Several space programs address the problem of observing clouds and the associated precipitation. For instance, TRMM, due to be launched in 1997, addresses the latent heating associated with tropical precipitation. Meanwhile several programs are addressing the distribution of clouds and how they interact with radiation. These include ISCCP, now part of GEWEX, and measurements of the Earth's radiation budget under the auspices of ERBE, SCARAB, and CERES (Rossow et al., 1985; Barkstrom et al., 1989).

Despite the apparent abundance of space observations of clouds, our understanding derived from them is severely limited by our inability to resolve the vertical structure of clouds worldwide. Well-designed programs that define the effects of clouds on radiation at the top of the atmosphere already exist, including TRMM-1 to give us the vertical distribution of latent heating.

The influence of clouds and cloud systems on the vertical distribution of radiative heating in the atmosphere and the distribution of radiative fluxes at the surface are crucial areas that need further study. Of equal importance is the need to understand how the other variables of the climate system influence the formation of clouds, their structure, and dissipation. We believe the current and planned systems will not adequately represent the vertical distribution of clouds on the global scale. To achieve this goal, we need to:

(1)   Determine the four-dimensional distribution of cloud optical properties and those aerosol properties that affect cloud microphysics.

(2)   Determine quantitative information on the global distribution of cloud liquid water, water vapor, and ice, in particular, as well as the partition between ice and water in the atmosphere and aerosol properties.

(3)   Understand the links between the cloud properties determined in (1) and (2) and their radiative effects and, ultimately, establish their relationship to the large-scale variables of the climate system.

2. Outstanding Problems

2.a. Science Rationale

The global climate system cannot be adequately modeled without understanding the role of ice and water clouds and their effects on the vertical distribution of heating and cooling in the atmosphere. On a global, annual scale, the radiative heating of the atmosphere is approximately balanced by latent heating associated with precipitation. Clouds significantly affect the radiative heating of the atmosphere.

The four-dimensional distribution of heating and cooling—modified slightly by adiabatic processes tightly coupled to vertical motions—manifests itself in changes of atmospheric wind fields and kinetic energy by directly affecting the generation of eddy potential energy, which, in turn, is converted to kinetic energy. This generation of atmospheric energy occurs at a greater rate when warm layers are warmed or cool layers are cooled. Persistent effects of radiation in a cloudy atmosphere often lead to very efficient generation of regional atmospheric energy anomalies. These features directly change the wind fields (potential vorticity) and significantly influence seasonal, interannual, and long-term climate variations over widespread areas.

Based upon our knowledge of the relative magnitudes of specific and net radiative processes, water phase-change processes, and the vertical and horizontal transport of heat in and out of atmospheric regions, we may state that the cloud radiative heating/cooling variations must be determined to ±0.2°C/day/200 hPa.

2.a.1. The Effects of Clouds on the Radiation Budget

The effects of clouds on the Earth's radiation budget are studied in terms of the differences between the net flux leaving the top of the atmosphere (TOA) in the presence of clouds and the net flux leaving the top of a clear-sky atmosphere. An example of this TOA flux difference (referred to as the cloud radiative forcing), derived from July 1988 ERBE data, is presented in Figure 1a.

A comparative distribution obtained using simulations from a climate GCM is presented in Figure 1b. Two relevant features of these distributions are the dominance of summertime mid- to high-latitude clouds in creating large negative flux differences which dominate the global mean values, and the smallness of the net flux differences at low latitudes, despite the fact that the individual contributions by both longwave and shortwave fluxes in these regions are large (Ramanathan et al., 1989).

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From the point of view of understanding the effects of clouds on the radiation budget, and to test how well these effects are treated in models, it is important to provide cloud-profile information that covers those latitudes where the radiative forcing is significant.

JULY 1988 NET CLOUD FORCING (W m^{-2})
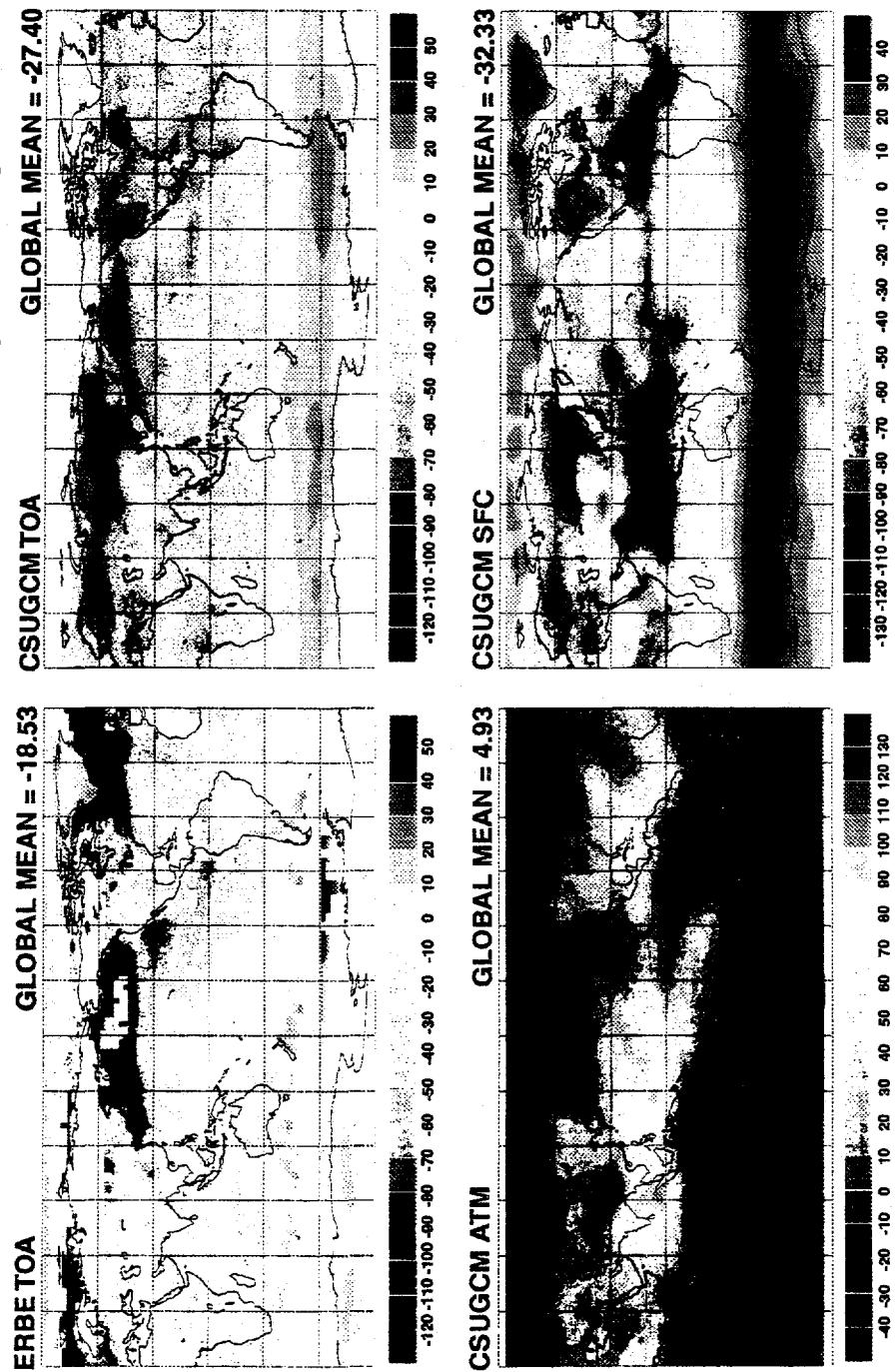
Figure 1—The difference between cloudy and clear-sky net radiative fluxes (a) at the top of the atmosphere from ERBE, (b) at the top of the atmosphere from simulations using the Colorado State University (CSU) GCM, (c) within the atmosphere from the CSU GCM, and (d) at the surface from the CSU GCM (Randall, personal communication).

Although the net radiative effect of clouds at the top of the atmosphere is small throughout most of the low latitudes, the partitioning of this effect between the atmosphere and the surface is both large in magnitude and of opposite sign. This is evident in the results presented in Figures 1c and d, which show the distributions of the net flux differences within the atmosphere (this will be referred to as the atmospheric cloud radiative forcing) and at the surface (the surface cloud radiative forcing), respectively, for the same GCM climate simulations used to produce TOA distributions presented in Figure 1b. These simulations show how clouds radiatively heat the atmospheric column (relative to the clear sky) and how this heating is largely compensated for by a cooling at the surface (e.g., Slingo and Slingo, 1988). The heating of the atmosphere by clouds is important for a number of reasons. The location of the maximum value of the atmospheric cloud radiative forcing coincides with the maximum of deep convection and convective heating. The coupling of these different forms of heating and feedbacks between them are mentioned in more detail below.

Estimating the effect of clouds on the radiative balance of the atmosphere and surface is crucial for understanding links between clouds and other components of the climate system. For instance, both the heating of the atmosphere and the cooling at the Earth's surface (specifically the ocean) by clouds are key elements of hypothesized cloud-climate feedback mechanisms (Randall et al., 1989; Ramanathan and Collins, 1991). Unfortunately, there are no measurements to confirm model simulations of the partitioning of the cloud radiative forcing between the atmosphere and the surface, and it is clear that more detailed information about the surface radiation budget is required to do this.

2.a.2. Cloud Overlap

The introduction of different overlap assumptions using the same satellite data has a substantial effect on both the vertical distribution of radiative heating in the atmosphere and the horizontal distribution of radiative fluxes at the surface. Examples of these effects are shown in Figures 2a, b, and c. Figure 2a illustrates four different overlap assumptions used in radiative-transfer calculations of longwave cooling-rate calculations and surface-flux calculations. The four different overlap assumptions correspond to the same total cloud fraction as observed from a satellite. Figure 2b is the vertical distribution of radiative heating, and Figure 2c is the horizontal distribution of longwave flux for each of these overlap assumptions.

2.b. Status and Existing Observations

A synergistic approach involving modeling and observations will be required to adequately represent the vertical distribution of clouds on a global scale. Unfortunately the current satellite observations, such as are available from ERBE, ISCCP, TOVS, and SSM/I among others, have insufficient vertical and horizontal resolution of cloud physical and radiative properties. In the short term, we expect some advances in the reprocessing of ISCCP data to provide

improved information on cirrus and polar clouds under the auspices of ISCCP-2 (Stowe et al., 1991).

INDEPENDENT OVERLAP

MODEL LEVELS

20%
30%
15%
5%
30% clear

MAXIMUM OVERLAP

MODEL LEVELS

20%
50%
65%
70%
30% clear

RANDOM OVERLAP

MODEL LEVELS

20%
37%
30%
14%
30% clear

MIXED OVERLAP

MODEL LEVELS

20%
37%
52%
14%
30% clear
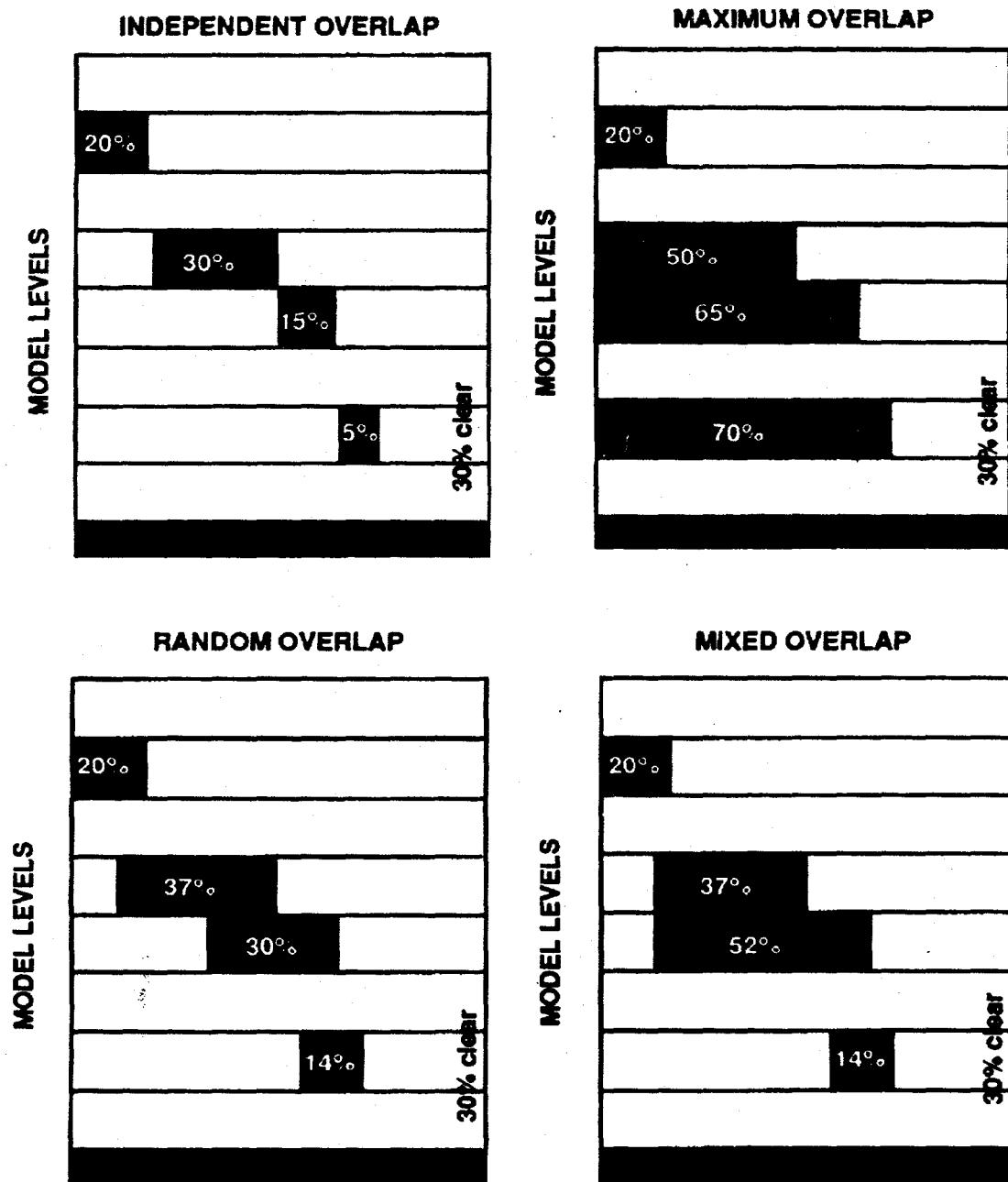
Figure 2a—Four different cloud overlap assumptions producing the same total cloud amount from space.
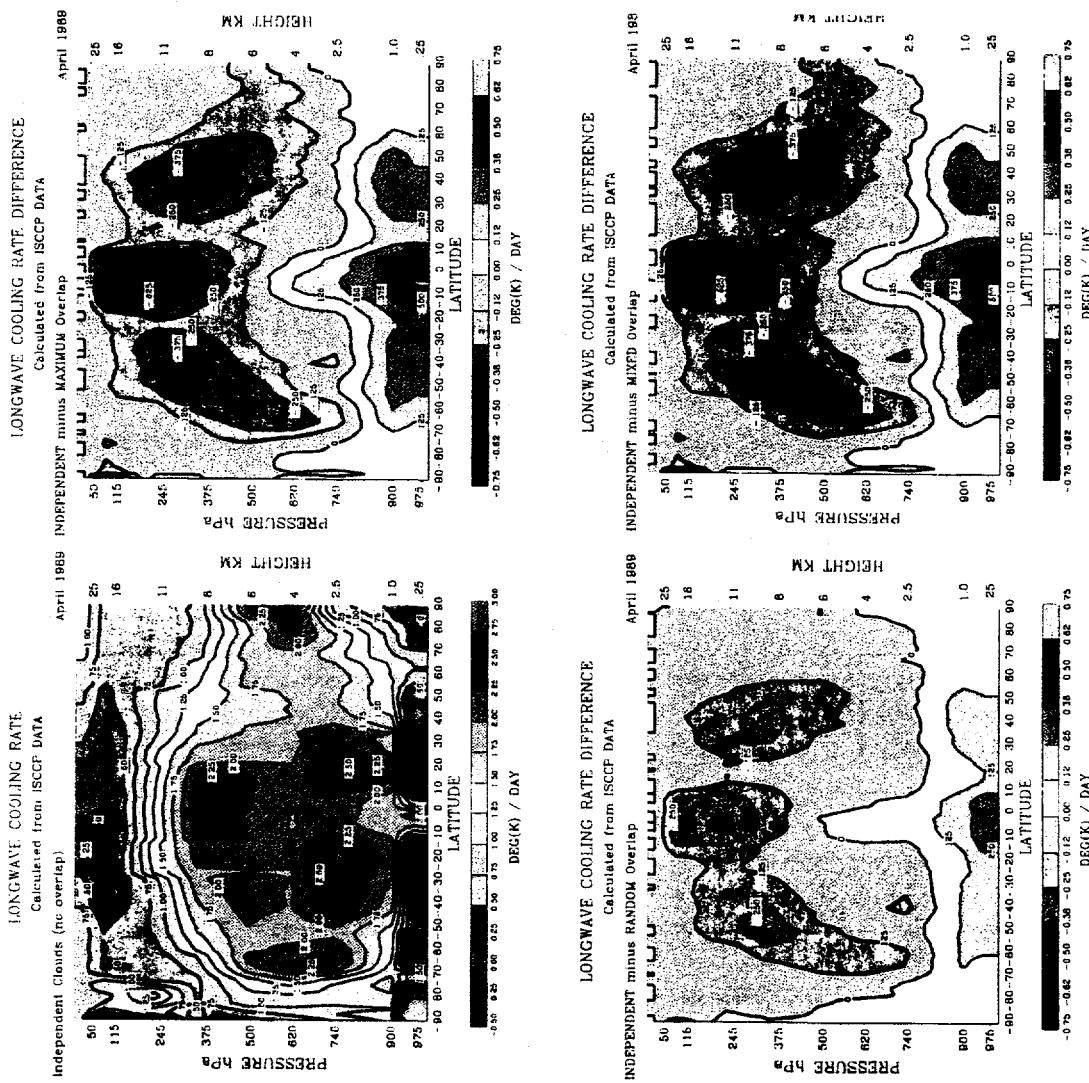
Figure 2b—The vertical cross section of radiative heating corresponding to the different overlap assumptions illustrated in Figure 2a. Monthly mean for April 1989, calculated with three-hourly ISCCP infrared-only data for clouds and TOVS for temperature and humidity.

Downward Longwave Flux
INDEPENDENT - RANDOM Overlap

April 1989   Full Sky   100% Layer Thickness

WATTS/METER²

DOMAIN AVG = 5.61

Downward Longwave Flux
INDEPENDENT - MAXIMUM Overlap

April 1989   Full Sky   100% Layer Thickness

WATTS/METER²

DOMAIN AVG = 9.22
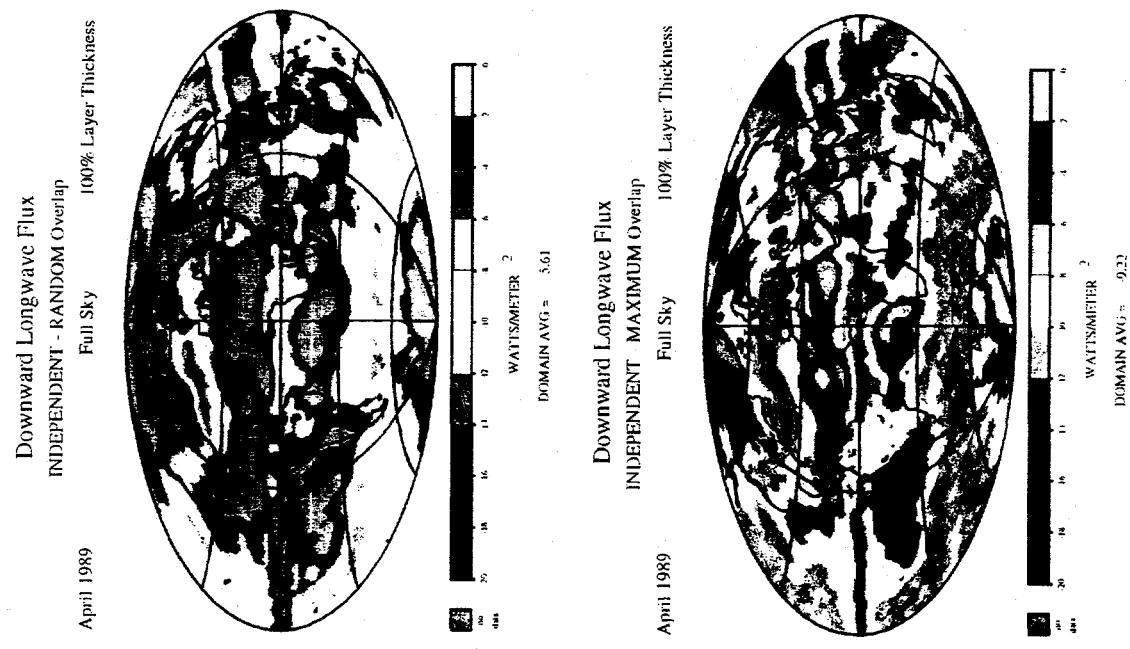
Figure 2c

Future sensors on TRMM and EOS will improve measurements of cloud-particle size, cloud fraction, cloud optical depth, and cloud liquid-water path. In particular, improvements will be made for cases of thin cirrus and boundary-layer cloud. Unfortunately, even these systems will not be able to measure the full three-dimensional structure of cloud fields, in particular cloud thickness and cloud-base altitude for single-layered clouds, and cloud overlap for multilayered clouds. While new methodologies hold hope for deriving cloud overlap for low clouds covered by optically thin cirrus (Baum et al., 1994), there is no clear way to handle cloud systems with optically thick high clouds. Such systems include critical tropical convection as well as mid-latitude storm systems. Only active lidar and radar systems can be expected to handle the complex vertical cloud structure common to these systems. Similar difficulties are likely for polar cloud fields, where detection against bright cold backgrounds is difficult.

2.c. Observations Unavailable from Existing and Planned Satellite Programs

Cloud process experiments, such as FIRE and ICE, together with surface and observing programs like ARM, are providing valuable experience in learning how to use both passive and active sensors in a synergistic approach to the remote sensing of clouds (Ackerman et al., 1990; Starr, 1987). Thus, combinations of sensors are vital for interpreting satellite data in terms of optical properties of clouds. For example, the combination of an active system with a spectral radiometer can unambiguously identify cloudy scenes from clear scenes, especially for those regions of low contrast that currently cannot be detected with passive systems alone. Active systems also provide the much-needed capability to detail the vertical structure of clouds, both day and night. A combination of sensors, both active and passive, provides for the possibility of determining the much-needed information on the vertical distribution of clouds.

2.d. Supporting Observations and Programs

The efficient utilization of information from a combination of active and passive sensors should be guided by experience gained from field experiments. For example, the merging of radar measurements that would distinguish ice from water particles with passive microwave observations of total water and visible near-infrared measurements of brightness needs to be tested. To test such concepts there needs to be a continuing program of field experiments where these sensors can be deployed in various combinations to develop an optimal remote-sensing strategy.

Parallel with testing sensors in varying combinations is the need to develop remote-sensing techniques that will optimally process the measurements from various sensors in individual channels to maximize the information that can be extracted. These studies will involve numerical simulations using radiative-transfer models to simulate observations as well as actual data from satellite and field experiments.

3. Recommendations

The global-climate problem cannot be solved without a better understanding of the role of clouds. We not only need to study the effects of clouds on the radiation budget measured at the top of the atmosphere, but we also need to establish how these effects are partitioned between the atmosphere and surface and within the atmosphere in order to validate models and understand various cloud-induced feedbacks. Of parallel importance is the need to determine how the variables of the climate system influence the generation of clouds, their spatial structure, and their temporal evolution. The main deficiency is our lack of knowledge on the vertical distribution of cloud (including cloud-base altitude and ice content), which cannot be estimated reliably using data from instruments that are presently flying on satellites or proposed for future missions.

Existing and planned measurements, while providing TOA radiation information, do not provide the essential vertical profiles of cloud and the resultant heating. Only with the prospect of flying an active system, such as with a radar and lidar, is it realistic to expect to begin to document the vertical structure of clouds, including cloud-base altitude, and thus the radiative heating distribution (Spinhirne and Hart, 1990; Intrieri et al., 1993; Stackhouse and Stephens, 1993; Kropfli et al., 1994). This information should greatly aid in the parameterization of cloud radiative processes and cloud-evolution mechanisms in climate models.

An important but poorly understood link between radiative heating and hydrology lies in the connection between water vapor, ice mass, and radiative transfer. A major deficiency that needs urgent attention is that there is not yet a viable method to measure the mass of ice in the atmosphere, either from existing satellites or from sensors to be flown on future satellite missions. This deficiency is expected to become even more acute as climate models evolve in the coming years requiring validation of ice distributions (e.g., Fowler and Randall, 1994).

The principal recommendations are:

(1)   We believe that with a combination of active and passive systems flown on satellites, we can expect to make significant progress on determining the four-dimensional distribution of cloud optical properties and the relationships between these properties and cloud liquid water, ice mass, and water vapor.

(2)   The synergistic approach recommended above should be explored with the goal of developing a prototype global measuring system. This must address the expected issues of limited space/time sampling associated with active sensors and the calibration of these sensors.

(3)   A clearly defined validation strategy for this global cloud-measuring system needs to be established. As part of this effort, the global

measurements within the atmosphere and at the surface need to be supported by detailed measurements of the microphysical, radiative, and thermodynamic properties of individual cloud systems, including the use of airborne sensors, together with cloud-resolving models as part of the GEWEX Cloud-System Study (GCSS).

(4) In parallel with the above activities, intensification of studies using airborne and ground-based active and passive sensors is needed, together with in-situ observations and supporting theoretical and laboratory work:

- To develop, refine and validate retrieval algorithms for the spaceborne measurements.

- To pursue detailed cloud-related process studies to determine the influence of clouds on the large-scale variables of the climate system and vice versa.

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Process Studies Final Report

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1. Key Issues and Recent Progress

Cloud process studies consider the processes governing the formation, maintenance, and dissipation of clouds, with particular emphasis on the morphology of clouds on scales that are generally not resolved by climate models (ranging from the microscale through the mesoscale), and that largely govern the radiative properties and effects of the cloud fields as well as playing a significant role in determining the associated transports of heat, moisture, and momentum. Cloud-radiation interaction is a fundamental concern.

The key issue is to quantify the factors controlling cloud type, phase, size, evolution, lifetime, and cloud radiative properties for prescribed large-scale thermodynamic and dynamical conditions. Cloud type and size depend on many factors including stratification and mean rate of uplift, while cloud evolution depends on the conversion of water to precipitation and the interaction between cloud, radiation, diabatic heating, and circulation. Such effects have not been well quantified, making it difficult to prescribe relationships between large-scale dynamical parameters and cloud optical properties or the heat, moisture, and momentum transports associated with cloud processes.

Many highly successful cloud-radiation process studies have been conducted in the past decade. Some of these have been international in scope and participation, while others have been national programs. These process studies ;have included theoretical components, numerical modeling components, and field campaigns. They have yielded significant advances in our understanding of climatically important cloud systems and in our ability to make critical observations from the surface, in situ, and from satellites.

1.a. Clouds and Cloud Systems

Our understanding of the macroscopic physics of marine stratocumulus cloud systems has advanced in three main areas over the past decade. First, the stratocumulus breakup process has been intensively studied and debated. Several studies have produced evidence that cloud-top entrainment instability is a real process that can reduce cloud amount, and new criteria for the onset of cloud-top entrainment instability have been proposed and tested. Solar warming has been shown to be capable of producing decoupling. One consequence of

decoupling is a transition from stratiform to cumuliform cloudiness, at least in the lower portion of the cloud layer. A second consequence is a departure from a well-mixed vertical structure.

The importance of aerosols for marine stratocumulus microphysics and radiative transfer has become widely recognized during the past ten years, largely as a result of data collected as part of the FIRE process studies. For example, ship emissions can lead to strong and physically interesting perturbations in the cloud structure. In addition, observations yielded important measurements of cloud properties, including solar absorptance, albedo, and infrared emittance.

Significant progress has also been made toward including marine stratocumulus clouds in climate models. The basic climatological distributions of these clouds have now been simulated, although there are still important deficiencies in the results. Attempts have also been made to simulate interannual variations in marine stratocumulus cloud amount in response to the annual variations of sea surface temperature, with very modest success.

Understanding and quantitative knowledge of the physical properties of cirrus clouds and the processes governing cloud formation, maintenance, and dissipation have greatly increased over the last decade as a result of a strong program of field observations coupled to efforts to model fundamental processes. Modeling efforts have helped identify key parameters and processes and have greatly influenced the design of field experiments and the development and utilization of new instrumentation. Observations have confirmed the importance of synoptic-scale forcing and identified mesoscale dynamical processes as a key element determining observed structure. Model predictions of the importance of small-scale convective and wave dynamics have also been confirmed and recent improvements in observing capability (e.g., shortwave-length Doppler radar and replicators) have enabled collection of essential data sets on cloud-scale processes. Another important finding is that cirrus-generating layers are often fairly shallow, apparently reflecting a basic aspect of large-scale processes, even though cirrus often evolve to encompass appreciable depth. This finding has significant implications for efforts to model cirrus cloud systems on the large scale.

Knowledge of cirrus cloud microphysical properties has also been dramatically increased. The pervasive presence of large (> 100 μm) ice crystals, which dominate the cloud water budget and strongly regulate the upper-tropospheric water budget as a consequence of their appreciable fall speeds, has been further documented. Moreover, recent advances in instrumentation have led to improved knowledge of the habits of cirrus ice crystals and have confirmed the presence of appreciable numbers of smaller (< 50 μm) ice crystals that dominate the radiative interactions. Observations and modeling studies have indicated the possibility that variations in natural aerosol in the upper troposphere, specifically stratospheric aerosols of volcanic origin, may significantly impact microphysical processes in cirrus. Although significant issues remain to be resolved, knowledge of cirrus cloud radiative properties has

greatly increased, and, in particular, much progress has been made in relating these properties to the cloud microphysical properties.

Models of cirrus clouds have evolved significantly in response to knowledge gained through observations. Microphysical models have been used to investigate the role of cloud condensation nuclei (CCN) and haze particles in cirrus development and have increased our understanding of certain anomalous signals detected by remote-sensing systems. Cloud-scale models have been able to achieve fairly realistic simulations and indicated the likely importance of microphysical-radiative-dynamical interactions in determining bulk cloud properties. Cloud-system (regional) models have successfully simulated mesoscale features of cirrus cloud fields. Such models now include fairly detailed microphysical treatments that have been shown to be a key element determing the quality of the simulations in terms of cloud ice-water content and cloud radiative properties. These efforts are just at the initial stages; however, significant progress is expected as a direct result of the availability of fairly comprehensive multiscale and multiparameter data sets from recent field experiments. Cloud-system models are viewed as the most appropriate test-bed for development and validation of improved cirrus cloud parameterizations for large-scale climate models.

As to precipitating cloud-system processes, there have been significant advances in the understanding of precipitating convection, spanning observational, numerical modeling, and theoretical approaches. In particular, there has been substantial progress in understanding convective downdrafts, which have been identified as an important process over the tropical oceans, as well as improved understanding of important effects of mean-flow shear and mesoscale circulation in the development of convective systems. Field experiments have been conducted in many parts of the world. Modeling has become increasingly sophisticated, now being fully three-dimensional and time-dependent. Moreover, models are now capable of including most physical processes in a fairly sophisticated way.

Advances have been made in several areas, for example, in understanding the interaction between cloud physics and dynamics, the structure and transport properties of various types of convection, the development of mesoscale circulations and their role in initiation and maintenance of convective systems, and mesoscale cirrus anvils from convective outflows. Recently the development and application of explicit cloud-resolving models with large domains are starting to address the cumulus cloud-system parameterization problem in an explicit way. In terms of the potential for improving parameterizations, the last development used in conjunction with field experiments has much promise.

It is also pertinent to observe that very little attention has been paid to modeling of the dynamics and microphysics of stratiform, multilayer frontal clouds, which also are of mixed phase (liquid-ice).

1.b. Radiation Modeling for Clouds

The climatically important cloud types that have been specially identified for radiation modeling are lower-tropospheric stratocumulus and stratus clouds and upper cirrus clouds. To this point, little attention has been paid to the more complicated mixed-phase clouds whose climatic importance from a radiative point of view has not been established.

Stratocumulus are generally broken clouds for which the assumption of plane-parallel radiative transfer is not valid. Observations of the drop size distribution and liquid-water content reveal that even stratus clouds are frequently horizontally inhomogeneous. In the last ten years or so, methods have been developed to treat the transfer of solar radiation in a broken cloud field that include fully three-dimensional Monte Carlo methods and laboratory simulations. Fractal concepts have been developed as a useful tool for characterizing the inhomogenous structure of clouds for radiative applications.

For both stratocumulus and stratus-type clouds, the single-scattering parameters and phase functions can be computed once the water-droplet size distributions are known. Field experiments have produced observations of solar reflection (albedo) and transmission for stratocumulus and stratus cloud fields along with quantitative description of cloud water structure from aircraft and ground-based measurements. However, it appears that comparisons between observed values and theoretical results have not been carried out to actually verify the theoretical calculations for broken and inhomogeneous cloud fields. Moreover, the source of the observed anomalous solar absorption within stratus clouds has not been resolved at this point. Possible sources of the anomalous absorption include in-cloud aerosols, the treatment of water-vapor absorption, and cloud inhomogeneity.

For cirrus clouds, methods have been developed for calculation of the absorption, scattering, and polarization properties of hexagonal ice crystals with a variety of shapes, including columns, plates, simple bullet rosettes, and hollow columns, and with size parameters (product of 2π and effective radius, divided by wavelength of incident radiation) greater than about 30, based on geometric ray tracing principles. These have led to significant improvements in remote sensing of cirrus clouds from satellites. However, calculations have not been made for the more complex shapes that commonly occur in cirrus clouds. Moreover, methods are not available to calculate scattering and absorption for small ice crystals with size parameters less than about 30. Such a capability is particularly important for consideration of thermal infrared radiative transfer. It has been noted from FIRE II replicator data that there often are a significant number of small ice crystals (< 30 μm) present in mid-latitude cirrus clouds, and the proper analysis of them requires knowledge of the scattering properties of small ice crystals. The recently developed finite-difference numerical technique and discrete-dipole method appear to offer computational advantage in the calculations of scattering phase functions for ice crystals with small size parameters. In all cases, the theoretical calculations of the fundamental

scattering, absorption, and polarization properties of ice crystals require verification either from laboratory or from field measurements.

On the basis of radiative-transfer calculations, the radiation field involving solar reflection and infrared emittance depends on both particle-size distribution and ice/liquid-water path. Particle habit and orientation may also be important factors. Greater consideration of polarization characteristics may prove fruitful in developing methods to observe crystal shapes, sizes, and orientation.

However, cirrus clouds are frequently observed to be highly inhomogeneous, and little attempt has been made to investigate the effects of horizontal and vertical inhomogeneity. The uncertain effects of cloud inhomogeneity are likely comparable to any of the other present uncertainties in treating radiative transfer in cirrus.

1.c. Measurements, Observations, and Instrumentation

Process studies have stimulated the development and application of many state-of-the-art instrumentation and observation systems. These systems have enabled us to observe clouds in ways that were unachievable in the past. Current systems enable us to make reliable in-situ observations of ice-crystal habits and resolve small ice crystals. Internal structures of cloud water/ice and motion may now be observed with high-resolution millimeter radars. Advances in radiometery and interferometry have yielded high-spectral-resolution observations of the radiative properties of clouds and inferences of microphysical cloud properties and thermodynamic structure of clear air. These capabilities and others spawned by process studies of the past have greatly enhanced our understanding of cloud systems and will play important roles in future process studies.

Process studies performed during the last decade have provided many new remote and in-situ measurement systems to obtain a better understanding of cloud and radiative processes. Many of these systems were deployed from the ground and/or aircraft. High-resolution lidar systems have enabled us to observe the structure of clouds on scales as small as a few meters. Raman lidar has enabled us to observe high-resolution water-vapor structures that are precursors to actual cloud formation. Millimeter cloud radars have been employed to map cloud boundaries and to provide quantitative observations of internal cloud structure; a Doppler version of the millimeter cloud radar has been developed and applied to observe cloud-scale velocity patterns. Infrared interferometry with high spectral resolution (1 cm^{-1}) in the spectral band 5 to 20 μm has been applied to infer emittance properties of cloud systems and to infer lower-troposphere temperatures.

A number of remote-sensing applications spawned from cloud-radiation process studies have been applied both from the earth's surface and from satellites. Passive microwave radiometry has been refined and applied to the continuous observation of total column liquid water. Water-vapor overburden

has similarly been inferred from ground-based applications of microwave radiometry. A variety of remote-sensing applications using passive solar and infrared observations to infer droplet/particle size distribution properties of clouds have also been developed and applied from both the surface and satellites.

Observations of the dynamic structure of cloud layers were first performed by wind profilers during process-study campaigns in the past decade. These systems provided high-temporal-resolution wind structure in both the lower and the upper troposphere; the successful development and application of radio-acoustic sounding systems also enabled the continuous monitoring of lower-tropospheric temperature profiles.

Process experiments have produced a number of high-precision, broad-band and spectral radiometers; cloud-particle replicators; video cloud-particle imagers; and a cryogenic frost-point device to measure upper-tropospheric moisture. A unique balloon-borne replicator was also developed specifically to support investigations of cirrus cloud-particle size and shape.

Another extremely significant accomplishment of process studies has been to support the evaluation and verification of cloud-field-property remote sensing performed by ISCCP. Significant improvements in ISCCP algorithms and evaluation of confidence limits of ISCCP data have been provided by process-study campaigns and investigations.

In summary, process studies of the past decade have produced a large number of innovative instruments and techniques which have greatly improved our present knowledge of cloud-climate-radiation interactions and will continue to provide additional insights in the decades ahead.

2. Outstanding Problems

The roles of clouds in the climate system are determined by a complex combination of many factors spanning a great range of spatial and temporal scales and physical processes. Therefore, it is essential to aim at integrated programs of modeling and field studies of cloud processes. Recommendations are made in the three areas: (a) cloud systems, (b) cloud-radiation interactions, and (c) cloud-aerosol interactions. It is emphasized that the field experiments should be carried out in several geographical locations to achieve insight into continental-maritime differences and latitudinal dependencies.

2.a. Cloud Systems

The basic assumption in parameterization is that all aspects of subgrid-scale cloud systems can be represented in terms of resolved or grid-scale variables. However, this may not be a valid assumption. In particular, the nonlinear processes taking place within cloud systems—such as microphysical-dynamical interactions; multi-phase cloud physics; the interaction among dynamics, radiation, and cloud physics; and the interactions among the subgrid-

scale processes themselves—need to be better understood. Studies to achieve a better understanding of the complex interaction among physical processes on the fundamental scales at which they act need to be conducted in order to test the basic assumptions behind parameterization. While studies using a hierarchy of models are most appropriate, it is crucial that these efforts be coupled to focused field campaigns that provide measures of fundamental properties required by the models and for validation of model results.

Specific attention should be given to process studies of:

- Cirrus
- Stratocumulus
- Precipitating mixed-phase clouds,

where the latter include both deep convective cloud systems and frontal cloud systems that often exhibit a multilayered stratiform character. It is particularly important to determine the impact of diurnal changes in radiative forcing, the effects of dynamical forcing, and the effects of microphysical processes in determining the cloud structure and to assess the impact of cloud structure on radiative processes. Further studies of cirrus cloud systems are a high priority. Differences between anvil and frontal cirrus need to be determined and the relationship between deep convective systems and anvil cirrus needs to be established. However, studies of medium-level frontal clouds (mixed-phase) should be initiated, as these clouds have not been the focus of major field experiments.

An important characteristic of clouds is the phase of the contained hydrometeors. This fundamental property has a pronounced effect on the microphysical mechanisms for release of precipitation and consequently the vertical distribution of cloud water. The cloud radiative properties are substantially modulated through the presence of ice, with regard to both reflectance and emittance. The albedo of land surfaces differs strongly depending on whether precipitation is liquid or snow/ice. The factors controlling glaciation of hydrometeors and especially the partitioning between water and ice mass are not well understood. Field studies on distribution of liquid and ice in clouds indicate that temperature may not even be the primary control factor, but that size and particle composition near the cloud top, as well as cloud-base temperature, are strongly influential in this context. Furthermore, the interaction of nucleation with processes including entrainment and glaciation is not sufficiently quantified to enable the processes to be adequately represented in GCMs. Improved knowledge of the distribution of liquid and ice in cloud systems is sorely needed.

Process studies must be designed to investigate specific components of these complicated cloud systems. High-resolution, limited-area (regional) models will be an essential tool in such studies. Field campaigns will also be an important element. The application of high-resolution, regional models will be required in the design, implementation, and analysis of the field experiments, and the assessment of model performance should be an important component of

the field experiment objectives. Process studies should take full advantage of data collected in prior field campaigns as well as identify new experimental thrusts which will yield further insight into the factors governing the characteristics and effects of cloud fields. One important focus of these process studies should be to identify which of the cloud-field properties are governed by GCM-resolvable scales and which are governed by subgrid-scale motions/processes.

2.b. Cloud-Radiation Interactions

Two aspects of clouds that play a strong role in governing cloud-radiation interaction and deserve high priority at the present time are:

- Cloud heterogeneity
- Scattering and absorption properties of ice crystals.

The spatial and temporal variability (including internal inhomogeneity) of different types of cloud systems should be determined by a combination of field experiments and cloud-system-scale numerical modeling. Field experiments using airborne and satellite observing platforms can provide confidence in the numerical studies, but the latter are essential if a broad range of cloud-system types and conditions are to be studied.

The impact of inhomogeneities on the cloud radiative properties, especially in the shortwave, should be systematically studied using detailed radiation transfer models such as fully three-dimensional Monte Carlo techniques. The results of such calculations, which should include the range of cloud physical structures identified from field observations and dynamical modeling studies, should be verified using radiative observations from field studies and compared to calculations using simplified radiation codes with the aim of providing empirical corrections which might be applied for different cloud types.

It has been shown that the use of the equivalent-spheres approximation provides a significant underestimate of the observed albedo of cirrus clouds. Equivalent spheres absorb more and scatter more in the forward directions as compared with hexagonal ice crystals. The use of appropriate phase functions is important in the interpretation of remote-sensing data, obtained from satellites or lidars. Moreover, it is necessary to construct appropriate parameterizations of the single-scattering properties of hexagonal ice particles for inclusion in cloud-system models.

For clouds containing spherical water droplets, the scattering and absorption properties can be calculated by Mie theory once the droplet size distributions are known. However, for clouds containing nonspherical ice crystals, the scattering and absorption properties require specific light-scattering programs to treat the complex structure of ice particles. Although single-scattering parameters have been generated for simple ice-crystal shapes with size parameters larger than about 30, the scattering properties of more complex ice-

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crystal shapes that occur in ice clouds still require in-depth research efforts. In addition, methods need to be developed and/or applied to calculate the scattering properties of the smaller ice crystals that are also observed. The fundamental scattering and absorption properties determined from theory for ice crystals should be verified by laboratory and/or field measurements. Laboratory experiments and aircraft measurements of the scattering phase functions for ice crystals in all clouds should be encouraged.

2.c. Cloud-Aerosol Interactions

The demonstrated impact of aerosols on the radiative properties of stratus and stratocumulus clouds and the present indications of a possible significant impact of aerosols on cirrus cloud microphysics and radiative properties strongly suggest that process studies focused on cloud-aerosol interaction be initiated. Issues of particular concern include:

- CCN and cloud microphysical and radiative properties
- Solar absorption by aerosols in clouds
- Cloud generation of aerosols

The first two factors are inherently bound to the study of cloud-radiation and cloud-system studies, as discussed previously. Specific questions in this context are: Are the effects of CCN on cloud-droplet size distributions at cloud base propagated upward in a cloud? At what depth of cloud is the CCN memory effect lost, and what role do cloud interstitial aerosols play in the radiative properties of clouds?

The latter factor arises from the fact that clouds produce aerosols by chemical reactions both within the cloud and in the surrounding clear air. Indeed, this may be a major source of atmospheric aerosols worldwide. There are also indications that aerosols may have an important radiative cooling effect on climate. Therefore, to evaluate the effects of clouds on the radiative balance of the Earth, it is necessary to determine the contribution of cloud processes to the global aerosol budget and to assess the radiative effects of aerosols.

3. Recommendations

To acquire a much-needed enhanced understanding of the complex interplay between the wide range of spatial and temporal scales of various cloud processes, well-concerted modeling studies and measurement campaigns are required. It appears that data already collected contain a substantial amount of valuable, but incompletely utilized, information. Yet it is also necessary to design and perform new field campaigns and to improve and develop new instruments, which will enable measurement or more accurate measurement of various essential parameters at improved resolution. This will facilitate more accurate calibration of retrieval algorithms and provide a means for verification of new hypotheses and of model simulations.

The principal recommendations are:

(1)   Model studies:

- Utilize high-resolution limited-area models to develop suitable cloud parameterizations for typical GCM scales.

- Determine the impact of radiative forcing, including diurnal changes, and effects of microphysical processes, including the roles of aerosols, in determining cloud properties and structure.

- Develop/improve algorithms for retrieval of cloud and precipitation parameters from remote-sensing data.

(2)   Field campaigns:

- Fully utilize data collected in prior field campaigns to characterize cloud properties and associated environmental conditions.

- Plan and carry through new campaigns at different geographical locations (climate zones) in order to acquire data on the distribution of liquid and ice-phase hydrometeors, and on macro (cloud) -scale parameters.

(3)   Instruments:

- Develop/improve surface-based as well as aircraft and satellite-borne instruments that allow measurements of the vertical distribution of liquid and ice in clouds and precipitation.

- Develop/improve instruments that allow characterization of cloud and aerosol particles, especially the sizes and shapes of ice particles, including small (less than 20 μm) particles, for deployment on aircraft and satellites.

- Develop/improve instruments that allow direct measurement of the fundamental radiative properties of clouds and cloud particles.
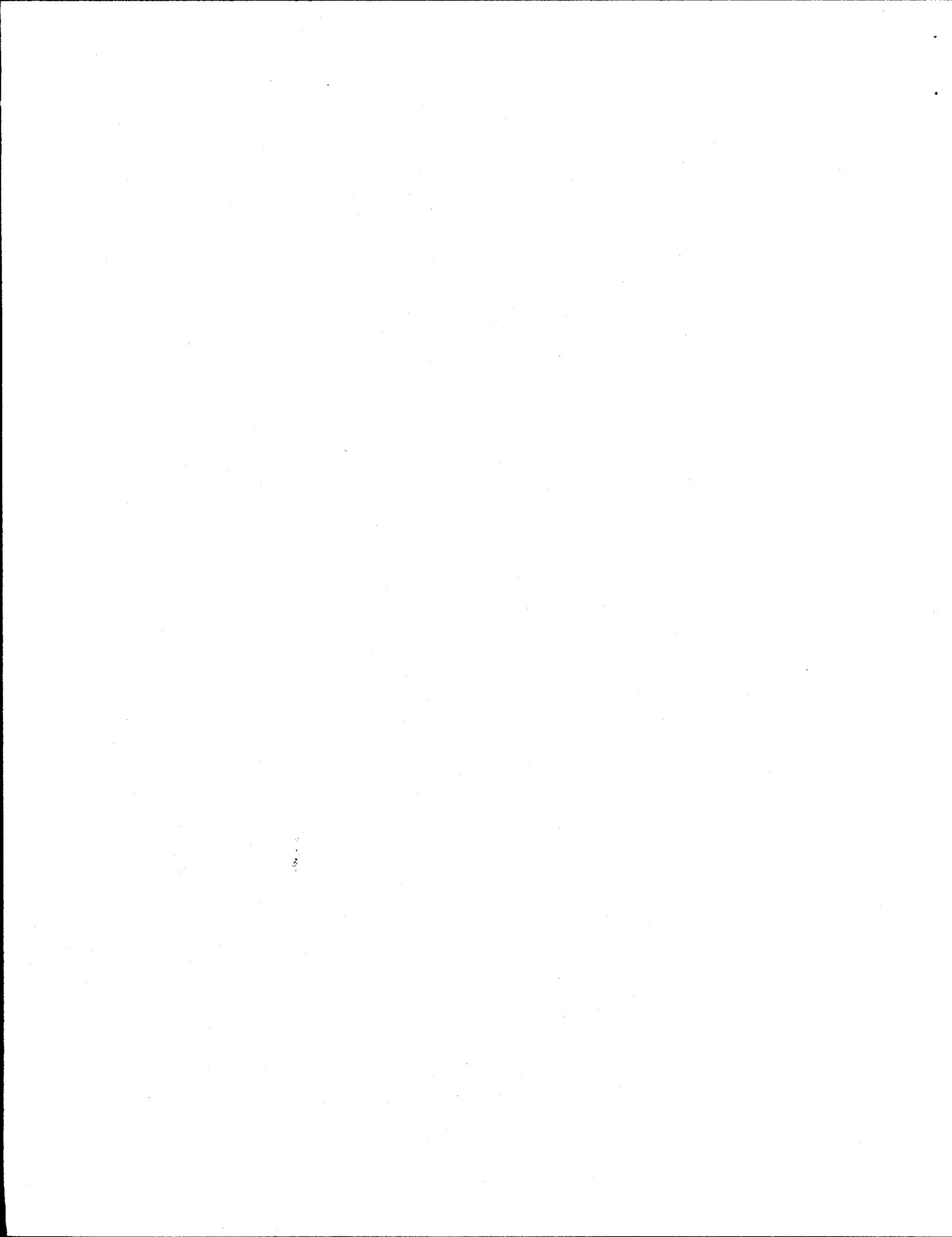
2.   EXTENDED ABSTRACTS

Session 1: Introductory Session
T. VonderHaar, Chair
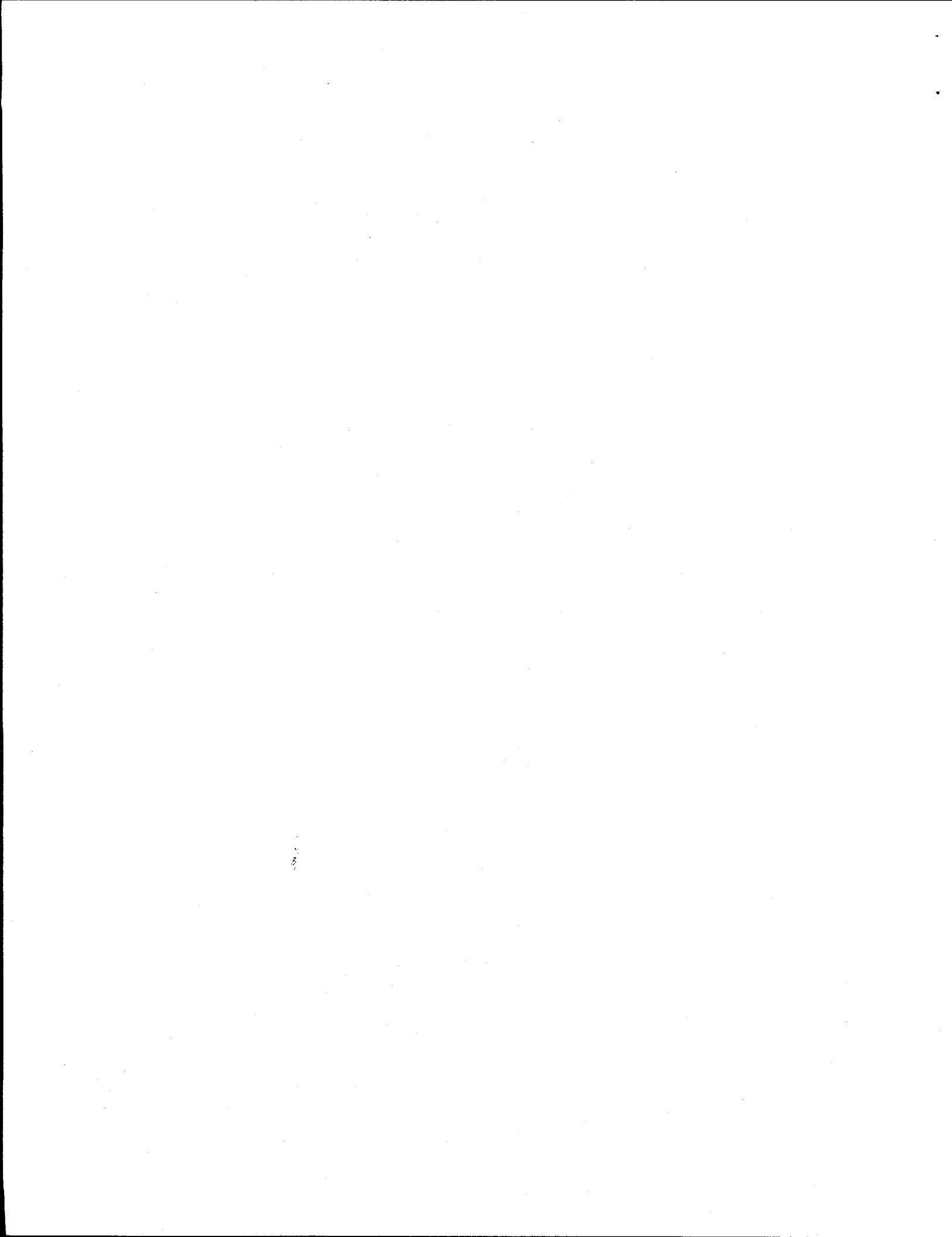
Cloud Radiative Feedback in GCMs

Robert D. Cess

State University of New York at Stony Brook, U.S.A.

To better understand cloud-climate interactions in GCMs, ERBE data have been used to test the seasonal change in cloud radiative forcing (CRF) as produced by 12 GCMs. This comparison utilizes four-year means (1985-1988) of ERBE data together with comparable results from the 12 GCMs. To both maximize the signal and minimize interannual variability, a seasonal ΔCRF has been defined as the difference in CRF between the extreme months (January minus July) and the hemispheres (Southern Hemisphere minus Northern Hemisphere). Figure 1 shows the comparison of both longwave and shortwave components of ΔCRF. Interpretation of the reasons for the model differences should lead to improvements in our understanding of cloud radiative feedback as it relates to climate change.

Figure 1

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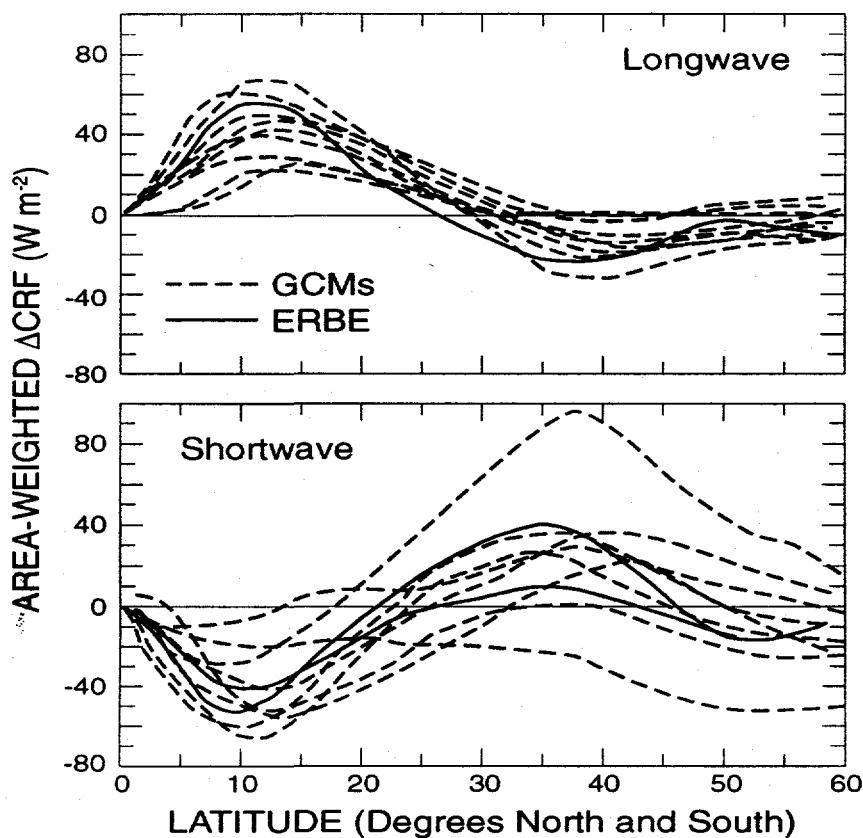
Modelling Clouds in GCMs for Climate Change Studies

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Clouds cool the Earth by reflecting solar radiation and warm it through the emission of longwave radiation. At present, it is estimated that clouds cool the Earth by about 20 W m^{-2} in the mean.

In current coupled ocean-atmosphere models, a failure to predict enough subtropical stratocumulus clouds off the eastern coasts of continents contributes to the simulation of anomalously warm surface temperatures there. There are other comparable errors in such models, not associated with deficiencies in the simulation of clouds.

In sensitivity studies of the effect of doubling atmospheric carbon dioxide, models with simple relative-humidity clouds show increases in high clouds near the tropopause, with decreases below. Increased carbon dioxide (and water vapour) cool near the troposphere and warm lower levels and the surface, tending to destabilize the atmosphere and produce changes in vertical circulation and therefore temperature, moisture, and cloud (Mitchell and Ingram, 1992). Hence an accurate representation of all physical processes, particularly those concerned with the transport of moisture, is necessary for an accurate simulation of cloud changes.

Studies with more elaborate cloud schemes indicate that changes in cloud phase (ice/water), cloud water content, and effective radius can contribute substantially to simulated climate change—see Figure 1, taken from Senior and Mitchell (1993).

Clouds are subgrid-scale vertically, horizontally, and temporally. Furthermore, even the most "uniform" clouds can display an alarming heterogeneity in physical properties. It is not obvious that we can represent the large-scale effects of clouds accurately in global models. In attempting to do so, we will require a better understanding of cloud processes, and will need to parameterize clouds in terms of GCM grid-scale parameters. This will require close collaboration between modellers and observational scientists.

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WARMING DUE TO DOUBLING CARBON DIOXIDE

Cloud Scheme	Change in temperature
Relative Humidity	5.4
Cloud water	2.8
Cloud water/variable radiative properties	1.9

The Met. Office

Figure 1—from Senior and Mitchell (1993).

The Natural Variability of Cloud Forcing in Space and Time

Thomas H. VonderHaar
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- Background: Our goal and objectives
- Cloud variability in (x, y, t)
- Variability of top-of-atmosphere (TOA) cloud forcing and principal mechanisms
- Vertical variation of cloud forcing

Long-Term goal:
Link vertical variation of cloud forcing (radiative heating and cooling) to regional and large-scale dynamics.

Questions today:
(1)   Where are the cloud forcing max/min variations at TOA located in (x, y, t)?

(2)   What are the principal causes of each observed TOA max/min?

- Cloud amount?
- Cloud height?
- Cloud physical/radiative properties?

(3)   What large vertical variations of cloud forcing exist under the observed TOA max/mins—or under "unremarkable" TOA cloud forcing?

The Natural Variability of Cloud Forcing in Space and Time—The Approach:

(1)   The ~7-year climatology of ISCCP observations of cloud amount (total, high, middle, low, and "cirrus") are analyzed for the mean and standard deviation of monthly means for the entire period (~90 months) and for seasonal cases. Significant regional capabilities are observed and discussed.

(2)   An ~6-year climatology of ERBE monthly values of net, longwave, and shortwave cloud forcing maps for the approximate same period are analyzed. Total-variability and special-variability maps with the annual cycle removed are also analyzed. Several regions of high (and low) interannual variability are identified (e.g., over China, Pacific area west of Mexico).

The regions of maximum variability are cross-analyzed using *both* ISCCP and ERBE data to infer the probable *reasons* for major changes (e.g., for China, apparently most variation of cloud-radiation effects occurs due to summer/fall, bright, high cloud occurrences in some years).

Finally, the need to quantify the vertical variation of cloud forcing is noted, and a five-layer atmospheric analysis is proposed with the goal of obtaining the net radiative flux divergence to ± 5 W m^{-2} ($\sim\pm 0.2°$ C/day/ 200 hPa).
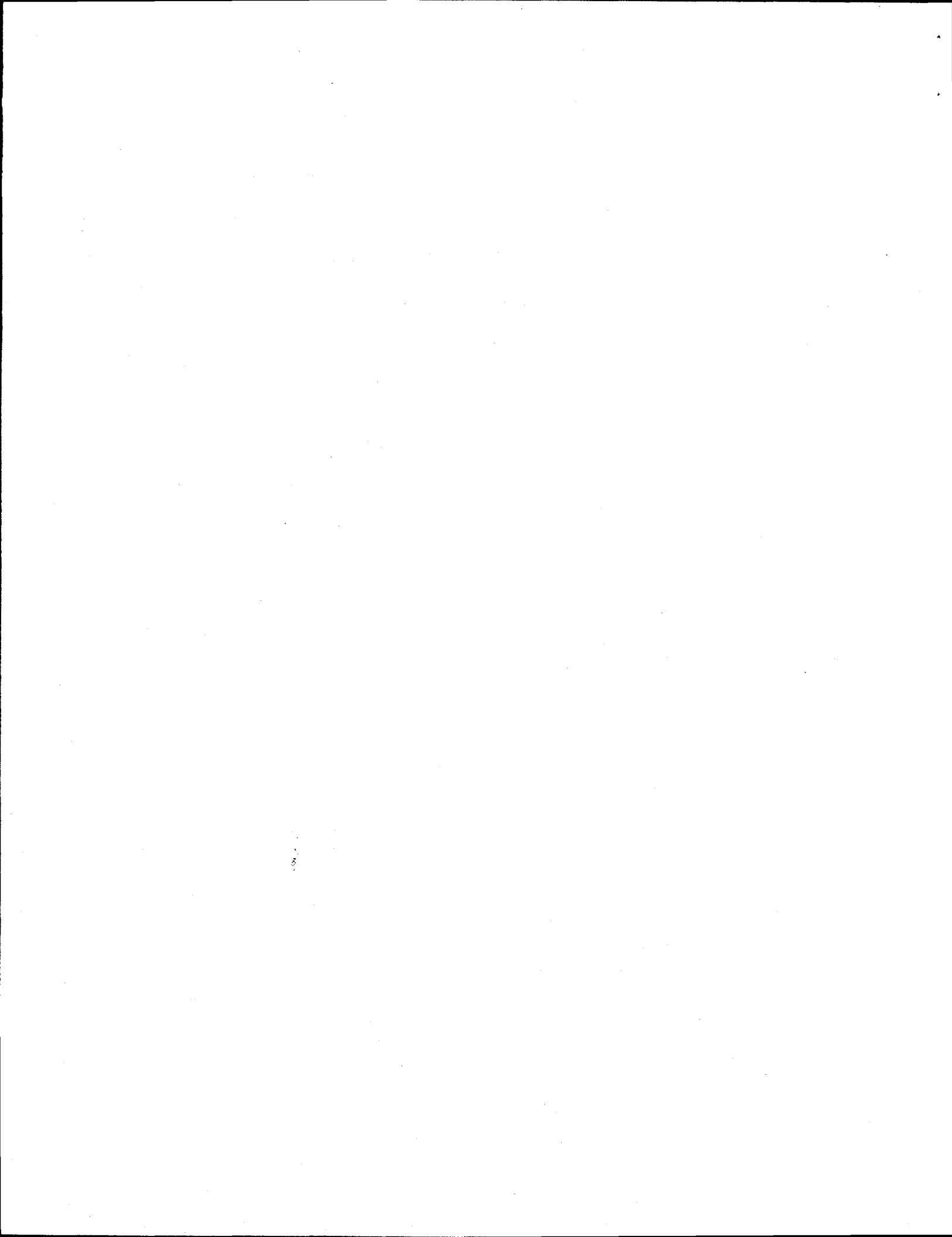
Session 2: Current Status of Cloud Formation and Radiative Modeling in GCMs
J.J. Morcrette, Chair
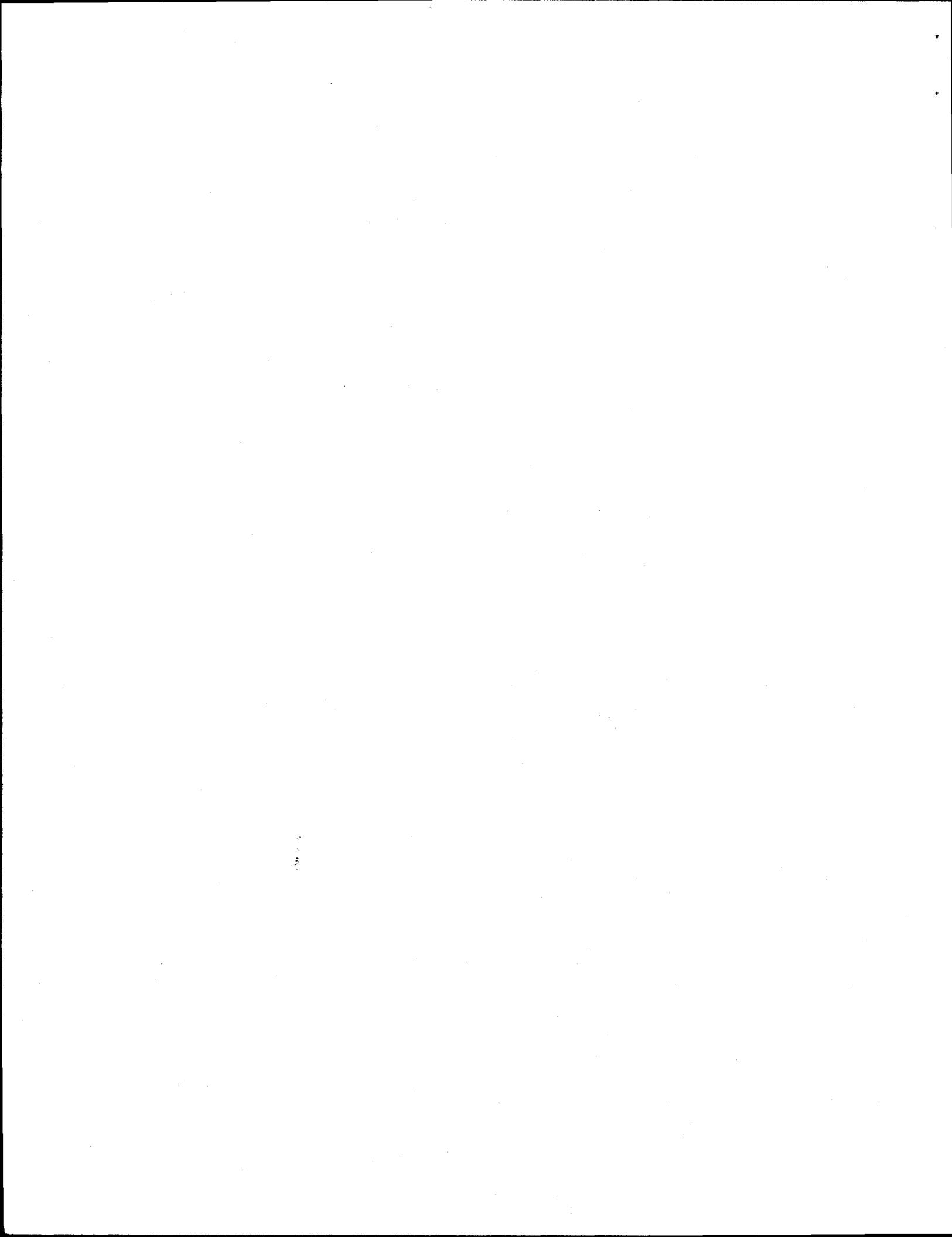
Cloud Formation and Radiative Modeling in the NCAR CCM2:
The Present and Future

J.T. Kiehl
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The most recent version of the NCAR Community Climate Model (CCM2) was released in the fall of 1992. CCM2 is in most respects a completely new version of the CCM (Hack et al., 1993). The dynamical transport of moisture and other tracers is represented with a shape-preserving semi-Lagrangian method (Williamson and Rasch, 1994). The convection scheme in CCM2 is based on a mass flux approach (Hack, 1994); the model includes a diurnal cycle and four-layer soil layer. The solar radiation scheme is an 18-spectral-interval delta-Eddington model (Briegleb, 1992). The cloud formation scheme is an extension of the Slingo approach (Kiehl et al., 1994). The climate simulation from the model is a significant improvement over previous versions of the CCM (Hack et al., 1994).

Although the CCM2 is generally an improvement over CCM1, there are still biases in CCM2. These are: (1) northern summer continents that are too warm, (2) excessive precipitation over land, and (3) a weak Northern Hemisphere winter stationary wave pattern in the Pacific Northwest. It is believed that to a large degree these biases are related to cloud properties.

Observations indicate that over continents the warm cloud-drop effective radius is approximately 5 μm, while over oceans the drop size is more like 10 μm. A sensitivity study has been carried out (Kiehl, 1994) where the distinction is made between continental and maritime drop size. This simulation was compared to a control where the effective drop size was set to 10 μm everywhere. The smaller drop size over continents led to higher cloud albedos over land regions. This, in turn, led to less solar radiation absorbed at the surface, which led to a reduction of surface temperature (maximum reduction of around 5 K). Furthermore, the latent heat flux over land decreased, which led to a decrease in local precipitation. Thus, adopting a more realistic cloud-drop size for land and ocean led to an improved climate simulation. In January, there was an improvement in the Australian monsoon simulation, with a displacement of the maximum precipitation in the northeast. This shift in tropical heating led to a shift in the Northern Hemisphere planetary wave structure, which again decreased the known bias in the control model.

CCM2 employs a prescribed zonally symmetric in-cloud liquid-water path (Kiehl et al., 1994). Hack and Kiehl (1994) have recently replaced this with a local diagnostic for in-cloud liquid water. This new approach to in-cloud liquid water leads to further improvements in the summer land-surface temperature bias. This approach also vastly improves the shortwave cloud forcing over the North Atlantic storm track region.

The conclusion of these studies is that improvements in the diagnosis of cloud microphysical properties (drop size and liquid water content) leads to a significant improvement in the simulated climate of CCM2. Future research in the area will focus on implementation of a prognostic formulation for cloud water and ice concentration.

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Modeling of Solar Radiative Transfer in Overcast Atmospheres

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The interaction of the near-infrared solar radiation with water vapor and water drops in vertically inhomogeneous overcast atmospheres is discussed in this study. Two specific issues are addressed in the sections that follow.

1. Factors Governing the Solar Absorption Process

Line-by-line plus doubling-adding calculations are performed over the entire spectral range of overlap between vapor absorption and drop extinction. The solar interactions in this spectral range involve the convolution of the spectral variations in the solar irradiance at the top of the atmosphere, drop single-scattering properties, and the much finer spectral variation of the vapor absorption characteristics. The results, performed for a variety of cloud cases (including different optical depths, locations, and geometric thicknesses) and solar zenith angles, demonstrate that the location of the cloud and the amount of vapor above it influence the absorption in the cloud layer and, more particularly, the solar absorption in the overcast atmosphere. The vapor inside the cloud also contributes in a significant manner to the absorption within the cloud layer.

2. Broad-Band Cloud Radiative Parameterizations in GCMs

With the help of the "reference" calculations, the accuracy of the broad-band parameterizations employed in several climate GCMs has been investigated. For the case of clear skies containing water vapor only, a modification of the Lacis and Hansen (1974) parameterization enables an excellent agreement with reference solutions for various atmospheric profiles, zenith angles, and surface albedos. The parameterizations of the near-infrared radiative transfer in overcast atmospheres in GCMs involve either the prescription of solar "mean" drop single-scattering properties (including the single-scattering albedo) or the prescription (or computation using an approximation such as the delta-Eddington method) of drop reflection and transmission. The first type of treatment could result in large inaccuracies in the cloud solar absorption and, in general, it is not possible to prescribe solar "mean" drop single-scattering properties. In the second type of treatment, the broad-band absorption by the drops in the cloud depends crucially on the spectral attenuation by the vapor above it. Because the latter information is not available in the broad-band radiative transfer framework, the effect results in an overestimate of absorption within the cloud layer, particularly for clouds in the lower troposphere.

Further, in the broad-band framework, the details of the interaction with drops and vapor inside the cloud are not accounted for adequately. This effect

results in an underestimate of the solar flux absorbed by the cloud, particularly for geometrically thick clouds. Under some conditions, a parameterization that does not account for both the effects mentioned above can have compensations in the errors and can actually yield a good but fortuitous agreement with the reference values. While it is possible to refine the broad-band treatments and correct the shortcomings for some overcast sky cases using the reference solutions, it may be impossible to achieve accuracies of better than 10% in cloud layer heating rates using such formulations. It is suggested that, for higher accuracies, GCMs employ a narrow-band approach, with the number of bands to be used depending on the practical issue of the tradeoff between the accuracy desired and the computational burden associated with it.

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Cloud Formation Modeling for GCMs

David A. Randall
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Early climate models prescribed both the distribution of clouds and cloud optical properties. Interactive clouds were introduced around 1970, but still with prescribed optical properties. The dependence of cloud optical properties on temperature has been the subject of research since about 1980. Today, GCMs are introducing prognostic variables for cloud water and ice, and the cloud optical properties are being computed from the predicted cloud-mass distributions. Such models should, in principle, be able to reproduce observed dependencies of cloud optical properties on temperature.

Prognostic cloud water variables provide the key physical link between condensation and radiative effects. They do not automatically solve such problems as determining cloud amount, but they may be needed in order to make these problems solvable.

Recently, L. Fowler, D. Randall, and S. Rutledge (Fowler et al., 1994) have incorporated the Rutledge-Hobbs bulk microphysics parameterization into the CSU GCM. This parameterization was originally designed for use in mesoscale models. Cumulus detrainment was added as a source of cloud water and cloud ice. Prognostic variables are carried for cloud water, cloud ice, rainwater, and snow, as well as water vapor.

In order to obtain a realistic simulation of the Earth's radiation budget, it was necessary to drastically reduce the threshold for autoconversion of cloud ice to snow. With this change, the simulated Earth radiation budget is considerably more realistic then the "control" run without the microphysics. The simulated precipitation fields were not greatly affected by the introduction of the microphysics, except that the cumulus precipitation in the tropical western Pacific was significantly reduced and became more realistic; this change appears to be a byproduct off the different radiative effects of the new scheme and their impact on the convective parameterization and large-scale dynamics.

When the original Rutledge-Hobbs autoconversion threshold is used, the model produces too much cloud ice, and this has the effect of drastically reducing the rate at which the atmosphere cools radiatively. It also radiatively warms the upper troposphere, increasing the static stability so much that cumulus convection practically stops. These very unrealistic results do suggest a real feedback loop that presumably operates, less vigorously, to regulate the intensity of the hydrologic cycle in nature.

The tuning of the autoconversion threshold is unfortunately necessary at this stage of our knowledge. When our understanding improves in the future, we should be able to avoid such tuning.

We are currently working on a parameterization of fractional cloudiness in which the predicted cloud water and cloud ice mass are input variables. A high-resolution cloud model is being used as a tool in this work.

A key problem for comparison of the model results with observations is that we currently have no measurements of the large-scale distribution of cloud ice in the atmosphere.

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Parameterization of Clouds and Radiative Transfer at DWD

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Atmospheric modeling at DWD concentrates on applications in the field of numerical weather forecasting. For this purpose, a model chain consisting of a global model and two nested regional models (Europa-Modell and Deutschland-Modell) produces, twice daily, operational forecasts over various forecast ranges and domains.

The importance of the interaction between clouds, radiation, and the rest of the model increases in parallel with the continuous development of the models and the extension of the range of model products and their applications. In particular, the general tendency to base even forecasts of local weather elements to some extent on direct model output enhances the role of all components of the model parameterization schemes. Clouds and their microphysical properties are key elements in the simulation of most processes affecting the evolution of the local weather. Cloud cover is itself an important forecast quantity, but inadequacies in the simulation of clouds, their impact on radiative transfer, and the hydrological cycle also have a strong detrimental effect on the quality of other model products like the near-surface temperature and the precipitation rates. An accurate prediction of these quantities requires a realistic evolution of the simulated cloud field and the associated processes in space *and* time, putting high demands on the quality of the model parameterization schemes. From this point of view the model requirements exceed even those for climate simulations, where minor phase or location errors are of little relevance for the interpretation of the results.

However, in practice it is rather difficult, if not impossible, to satisfy these quality requirements. Figure 1, showing a graphical illustration of a contingency table of collocated observations and simulated total cloud cover, presents an example of a total failure of the operational cloud scheme of the global model's cloud scheme in a wintertime high-pressure situation. The model underpredicts the cloud cover at most observing stations, where large cloud amounts occurred, and exhibits a tendency to simulate total cloudiness in locations where no clouds are observed. These deficiencies are related to specific properties of the operational cloud scheme, which is based on the parameterization scheme of Slingo (1987). The problem can be substantially alleviated by a simple revision of the cloud scheme, but model-simulated cloudiness remains far from perfect for the foreseeable future.

The simulation and validation of cloud microphysical properties (liquid- and ice-water content, size distributions, etc.) are even more difficult tasks in the context of numerical weather prediction and climate simulations. At the same time, these cloud properties have a strong impact on radiative fluxes and heating rates and are therefore influential in the evolution of the atmospheric state at all temporal and spatial scales. The possible impact of uncertainties in cloud

microphysical properties is illustrated in Figure 2. After only five days of integration, the zonal mean temperatures exhibit significant differences between two forecasts, using the same model physics, but assuming different levels of ice-water content for cold clouds.

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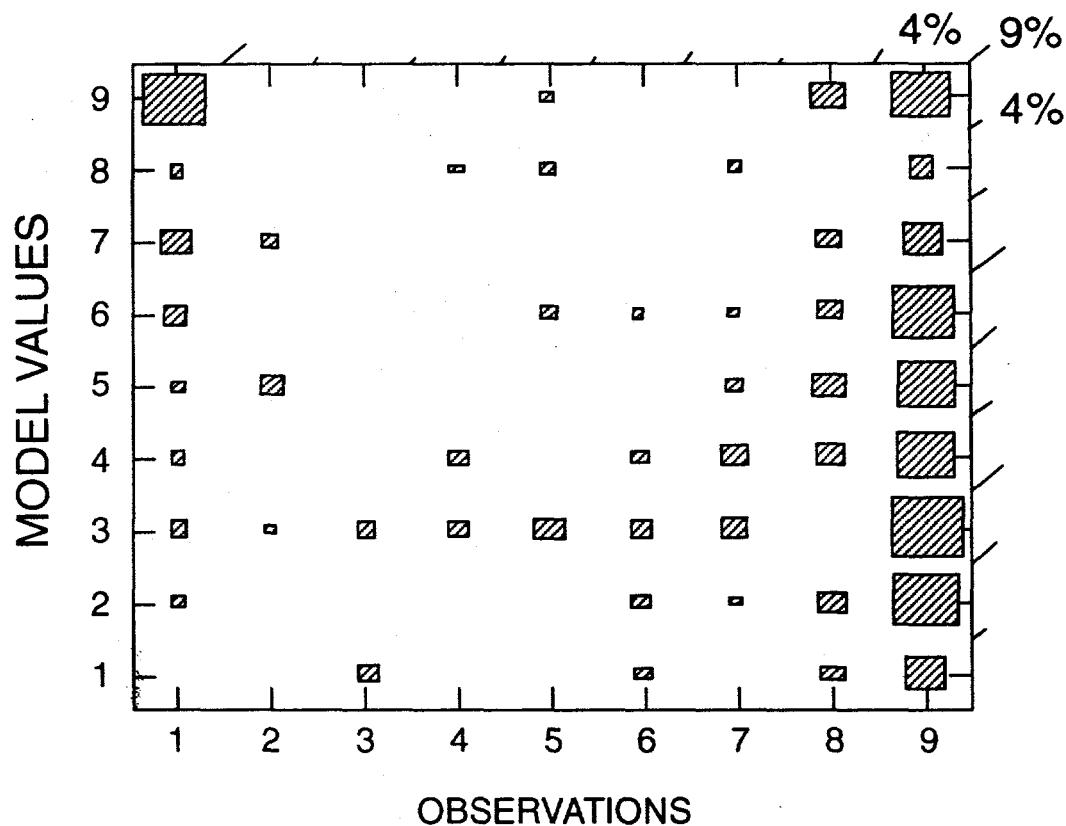
Figure 1—Comparison of collocated observations and model simulations of total cloud cover for central and northern Europe in February 1993 0000 UTC. Model values correspond to the initial date of the forecast. Class width for the illustrated contingency table is one octa. The size of the squares is proportional to the number of cases in each category; the length of the small diagonal bars is proportional to the sum over all categories in the corresponding diagonal.

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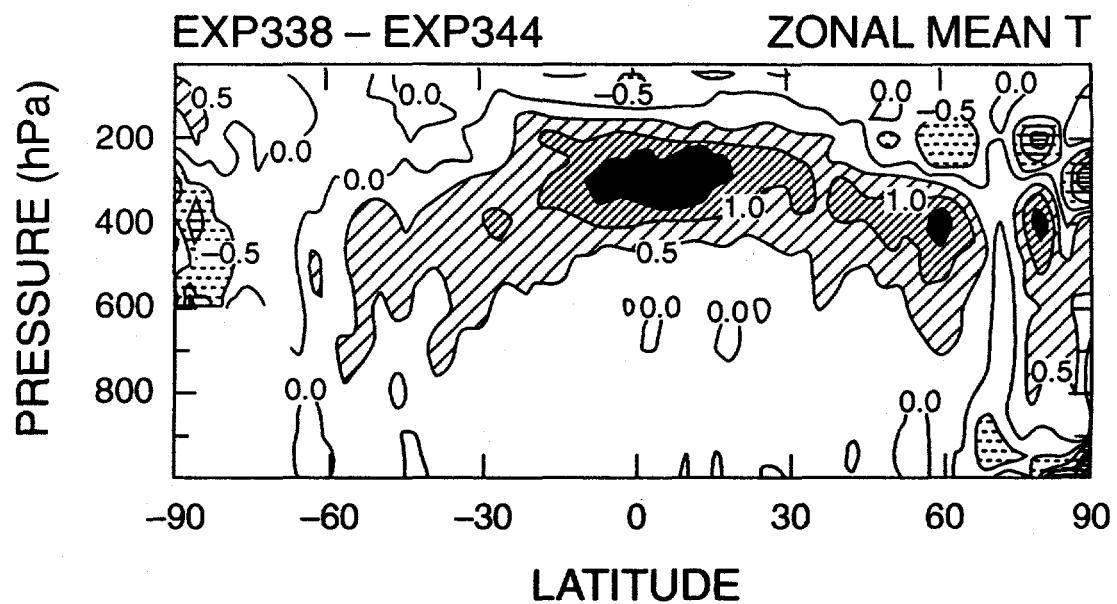
Figure 2—Zonal mean temperature differences for two five-day forecasts with the DWD global model. Initial date: 930815 1200 UTC. Exp 344 employs the empirical relation of Heymsfield (1997) for the determination of cloud ice-water contents; Exp 338 uses a diagnostic approach, which yields somewhat higher values.

Towards a More Unified Representation of the Cloud-Radiation Interactions in the ECMWF Model

Michael Tiedtke and Jean-Jacques Morcrette
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A prognostic scheme for stratiform and convective clouds is developed for large-scale models (Tiedtke, 1993). The time evolution of clouds is defined through the large-scale budget equations for cloud water content and cloud air (which is converted into a prognostic equation for fractional cloud cover). The scheme considers the formation of clouds in connection with large-scale ascent, diabatic cooling, boundary-layer turbulence, and horizontal transport of cloud water from convective updrafts. Clouds dissipate through adiabatic and diabatic heating, turbulent mixing of cloud air with unsaturated environmental air, and depletion of cloud water with precipitation.

The scheme differs from conventional schemes in its approach, which is fully prognostic and model-consistent, and in the larger degree of complexity as the formation of anvil and cirrus clouds originating by cumulus updrafts and of boundary-layer clouds is included.

The scheme has been tested in the ECMWF global forecast model and compared with the operational diagnostic cloud scheme. The results show that realistic cloud fields are produced when compared to observed values of cloud cover (AVHRR-derived, ISCCP-C1 cloud products) and cloud water content (SSM/I). Radiation fields at the top of the atmosphere produced by the new scheme are in better agreement with observations (ERBE, HIRS/2 radiances) than those produced by the operational diagnostic cloud scheme.

The representation of cloud processes in connection with anvil clouds is shown to have a strong effect on the hydrological cycle and the maintenance of the tropospheric water-vapour content. A strong sensitivity is found to the representation of the precipitation of ice crystals and to the details of the inclusion of the radiative effects of clouds.

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Session 3: Relevant Satellite Data Studies
B. Wielicki, Chair
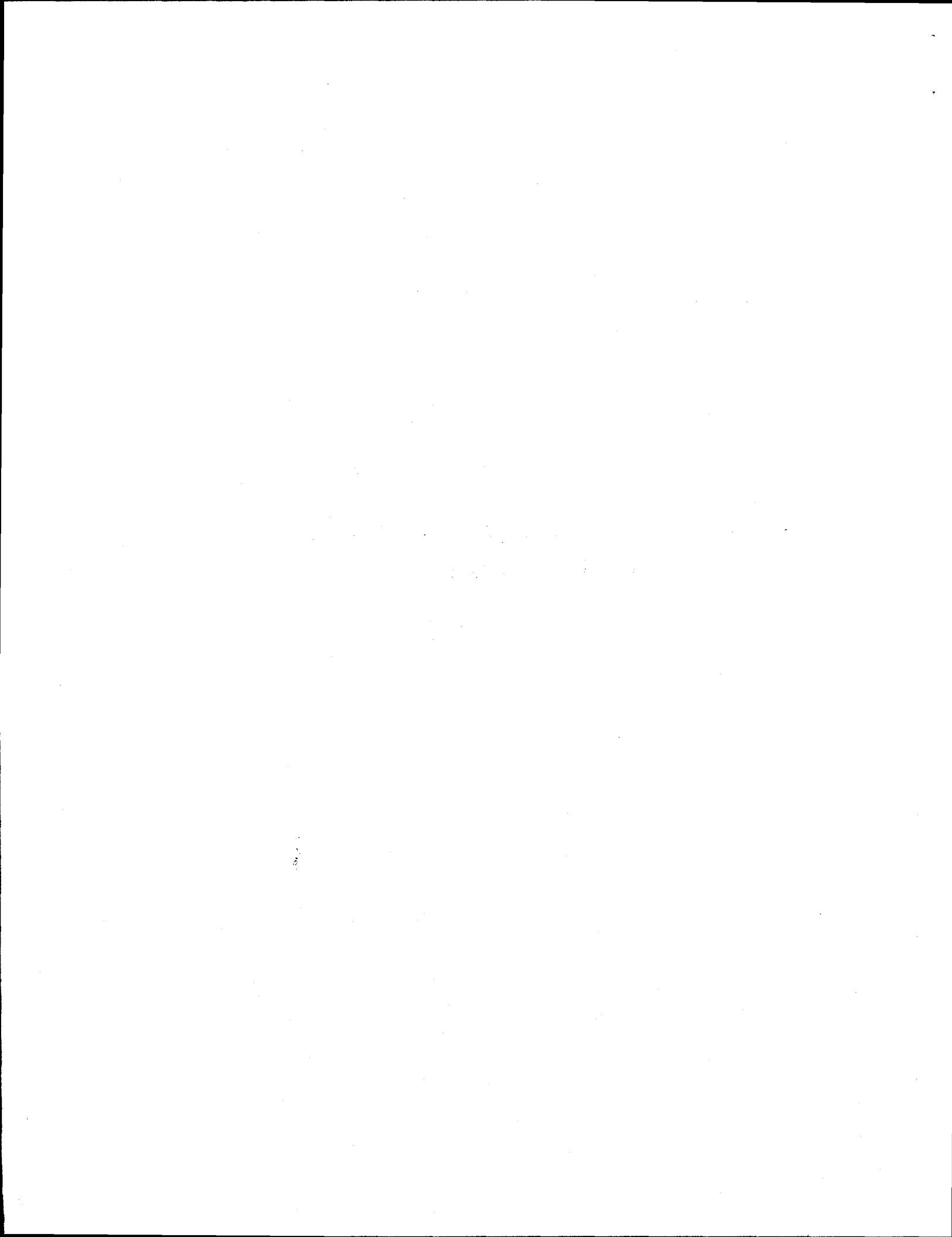
Relationship between Clouds and Sea Surface Temperatures in the Tropical Pacific

Albert Arking and Daniel Ziskin
Johns Hopkins University, U.S.A.

1. Cloud and Water-Vapor Feedback

The feedback effects of clouds and water vapor on the Earth radiation budget in response to changes in sea surface temperature are determined from a statistical analysis of four years of observations over the tropical Pacific. The data utilized include the Earth radiation budget parameters from ERBE, cloud parameters from ISCCP, total column water vapor from NOAA TOVS, and sea surface temperatures from NOAA based on blended AVHRR and in-situ measurements. The data used are monthly averages on a 2.5° latitude by 2.5° longitude grid, extending from 150°E to 90° W and 25°S to 25°N for the period February 1985 through January 1989.

The feedback effects are defined by means of a linear expansion of the sensitivity of the net incoming radiative flux at the top of the atmosphere (N) to changes in sea surface temperature (T_s):

$$\frac{dN}{dT_s} = \frac{\partial N}{\partial T_s} + \frac{\partial N}{\partial w}\frac{dw}{dT_s} + \sum_i \frac{\partial N}{\partial x_i}\frac{dx_i}{dT_s}$$

where w is total column water vapor and the x_i represents the three cloud variables: fractional cloud cover, cloud temperature, and optical thickness. The first term on the right-hand side is called the *direct effect* (although here it also includes the feedback effects of all variables other than w and the x_i), the second term is the *water-vapor feedback effect*, and the third term is the *cloud feedback effect*. The derivatives are determined by multiple linear regression.

Contour plots of the water-vapor and cloud feedback effects are presented in Figure 1. The feedbacks show considerable variability over the domain. Water-vapor feedback is generally positive throughout, and is particularly strong in the central tropical Pacific. Cloud feedback appears strong in two separate areas: in the western tropical Pacific and in the northern subtropics of the eastern Pacific. In the central tropical Pacific, where water-vapor feedback is strong, cloud feedback is negative, partially offsetting the water-vapor effect.

Table 1 shows the average cloud feedback, net and separated into a longwave and shortwave effect, in 12 subdivisions of the domain. It reveals significant differences between the two areas of strong cloud feedback. In both areas the feedback is positive, but the signs of the longwave and shortwave effects and their relative magnitudes are reversed—indicating that the feedback is dominated by low-level clouds in the eastern region and high-level clouds in the west. (Details appear in Ziskin, 1993.)

Table 1—Cloud longwave, shortwave, and net feedback contributions to sensitivity (W m^{-2} K^{-1})

|					
					—25°N
Longwave	0.3	−2.9	−3.2	−1.1	
Shortwave	1.4	3.0	7.1	3.6	
Net	1.8	0.1	3.9	2.4	
					—10°N
Longwave	12.8	11.5	3.4	2.1	
Shortwave	−9.9	−12.6	−2.6	−0.5	
Net	2.9	−1.1	0.8	1.5	
					—10°S
Longwave	8.5	4.2	0.2	−2.0	
Shortwave	−6.3	−4.6	−0.2	2.6	
Net	2.3	−0.4	0.0	0.6	
	150°E	180°	150°W	120°W	90°W —25°S
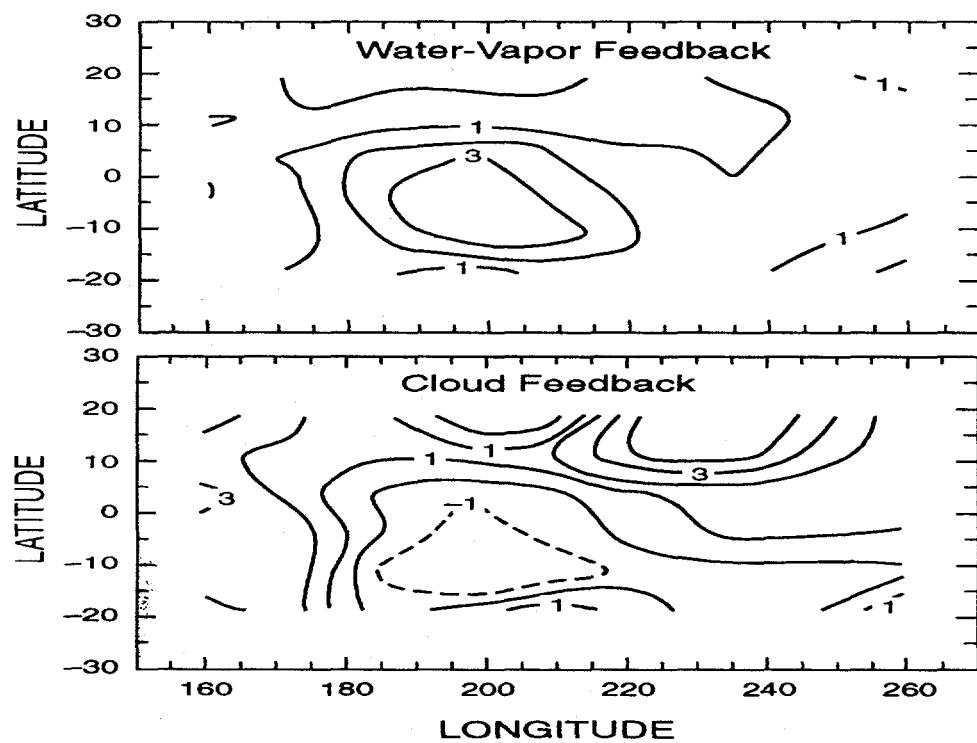
Figure 1—Contour plots of water-vapor and cloud feedback effects in W/m^2/K as defined in the text.

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2. Test of the Ramanathan-Collins "Thermostat"

Further analysis of the observations in the western tropical Pacific was done to determine the relationship between clouds and T_S and to test the thermostat hypothesis of Ramanathan and Collins (1991): that solar radiation causes T_S to rise, the rise in T_S produces an increase in high-level clouds, and the clouds, in turn, reduce the solar radiation at the surface and arrest further warming. If this hypothesis were correct, one would expect (1) a positive correlation between clouds and T_S at the time that high T_S causes a growth in high-level clouds, and (2) a negative correlation when the clouds reduce available solar radiation. An expected time lag between cloud development and a reduction in T_S, due to the ocean's heat capacity, would allow one to distinguish between the two correlations.

The correlation of four cloud variables (cloud fraction, cloud temperature, and the longwave and shortwave cloud radiative effects) with respect to T_S, as a function of the lag of T_S, are plotted in Figure 2 for the region 10°S-10°N and 150°E-180°E. (The seasonal cycle has been removed.) They show that the correlation is positive at all lags, with a peak at -1 month. There is an indication of a small negative correlation superimposed on the distribution of the broad positive correlation, with a negative peak at a lag of 2-3 months, accounting for the skewness in the distribution, but if so, it is small. We conclude that any influence that high-level clouds have on T_S is weak, and that if clouds have a regulating effect on sea surface temperatures it is not by means of their radiative effect on sea surface. (Details appear in Arking and Ziskin, 1994.)

3. Upper-Tropospheric Moisture and a Runaway Greenhouse Effect

Total column water vapor is also highly correlated with sea surface temperature. This is revealed in Figure 3, where total column water vapor within equal intervals of sea surface temperature (open circles) is binned against sea surface temperature. To see how this relationship is affected by the high-level clouds that develop when sea surface temperatures exceed ~300 K, we form two subsets of the data: a "high-cloud" regime, which represents the cloud conditions that obtain after the sea-surface-temperature-induced clouds are near maximum development (defined to be grid points where mean cloud fraction is ≥0.72 and mean cloud temperature is ≤256 K), and a "normal-cloud" regime (mean cloud fraction is <0.72 and mean cloud temperature is >256). For each regime, the equatorial region (12.5°S-12.5°N) and the subtropics (25°S-12.5°S and 12.5°N-25°N) are plotted separately.

The water-vapor curves in Figure 3 reveal that for the "normal-cloud" regime the slope is nearly constant, with $d\ln W/dT_S = 0.05$ K^{-1}, about the value that maintains constant relative humidity in a tropical atmosphere. For the "high-cloud" regime the slope is less, by a factor of two, indicating that relative humidity decreases with increasing temperature. Our interpretation of this result is that low-level convergence, which supplies most of the moisture in the upward branch of the Hadley/Walker circulations, is weakened when the high-level clouds reach maximum development.
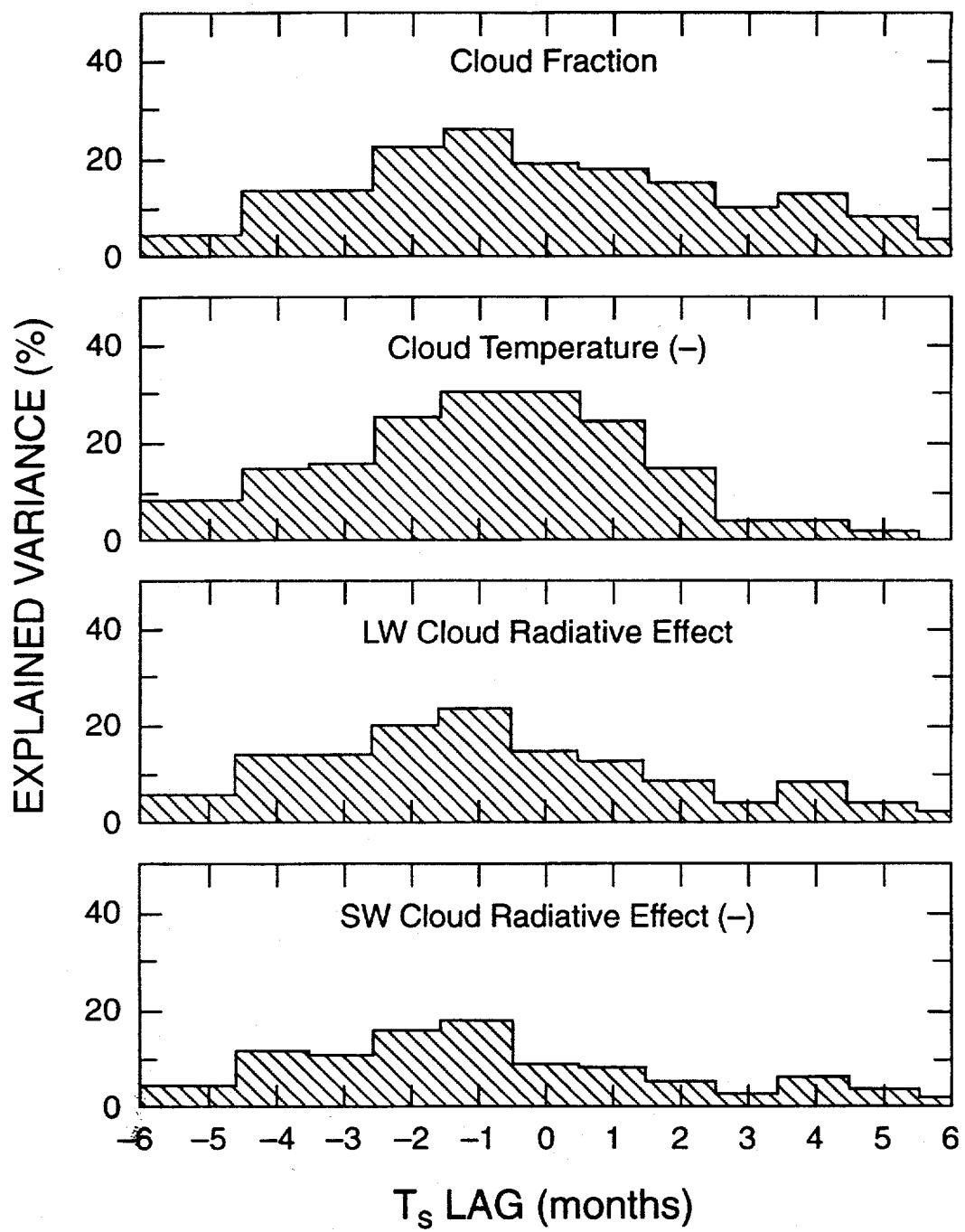
Figure 2—The explained variance (%) obtained by linear regression of four cloud parameters against sea surface temperature (T_s), with the seasonal cycle removed, as a function of the lag of T_s for the region 10°S-10°N, 150°E-180°E. [-] indicates a reversal of sign.
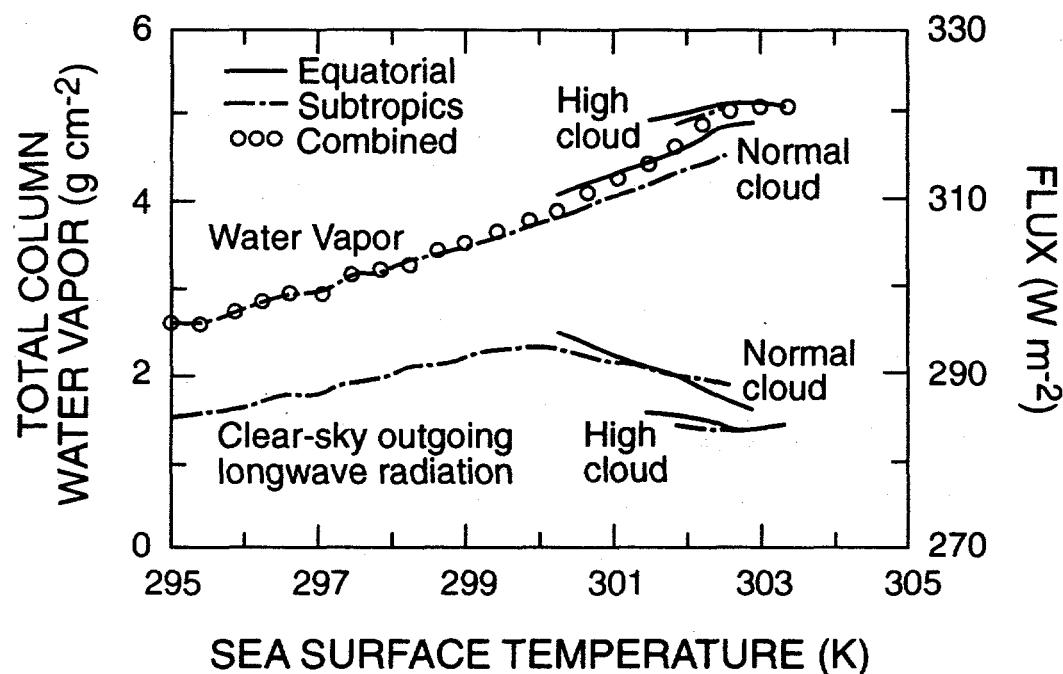
Figure 3—Total column water vapor and clear-sky outgoing longwave radiation, averaged within equal intervals of sea surface temperature, versus sea surface temperature. Open circles show mean values for water vapor for the entire domain. Curves labeled "high cloud" are restricted to grid points where mean cloud fraction ≥0.72 and mean cloud temperature is ≤256 K; "normal cloud" refers to cloud fraction <0.72 and cloud temperature >256 K. Solid lines are for the equatorial region (12.5°S-12.5°N) and dash-dot lines are for the subtropics (25°S-12.5°S and 12.5°N-25°N).

Figure 3 also shows the clear-sky outgoing longwave flux. Here we have the unusual situation that in the "normal-cloud" regime the slope is *negative* at sea surface temperatures above ~300 K. It is unusual because in a clear atmosphere rising temperatures will cause the outgoing radiation to *increase*, if relative humidity remains constant.

The most likely explanation for the downturn in the slope is the greenhouse effect of a large increase in upper-tropospheric moisture that occurs when sea surface temperatures increase beyond ~300 K (Hallberg and Inamdar, 1993). Numerical experiments with a radiation model show that the relative increase in moisture near the top of the troposphere would have to be as much as 50 times larger than near the surface to account for the observed downward slope. Such a large increase in upper-tropospheric moisture is made possible by a strong circulation, including strong low-level convergence, which brings moisture into the region, and strong convection, which carries the moisture to the upper troposphere; this is the situation in the "normal-cloud" regime. In the "high-cloud" regime, however, the slope is flatter, indicating a weakening of the large-scale circulation, associated low-level convergence, and convection.

The negative slope is indicative of an unstable situation, where rising sea surface temperatures bring more heat into the vertical column, which could contribute to further heating of the surface and a continuing rise in sea surface temperatures. This instability, associated with the greenhouse effect of increasing water vapor, is not unlike the runaway greenhouse effect that occurs on a planetary scale on Venus, which accounts for its very high surface temperatures. In the present case it is a regional effect, and stability is quickly restored by the high-level clouds that develop in response to high sea surface temperatures.

4. An Explanation of the "Warm Pool"

If, indeed, there is a greenhouse stability as described above, which can be quenched by high-level clouds, then there is a simple explanation for the "warm pool" character of the western tropical Pacific: low-level convergence, coupled to increasing upper-tropospheric moisture and a water-vapor greenhouse effect, leads to an uncontrolled rise in sea surface temperature; this leads to a growth in high-level clouds, bringing back stability and a halt to the sea surface temperature rise. In this picture the western tropical Pacific is self-regulating, with the key process being a coupling between the radiative effects of clouds and atmospheric dynamics. This mechanism behaves like the "thermostat" of Ramanathan and Collins (1991), in that it stops the rise of sea surface temperatures beyond a certain point, but it does not require that clouds exercise radiative control over sea surface temperatures, a mechanism that is not supported by the observations.

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GLAS Cloud and Aerosol Sensing

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A principal goal of satellite cloud remote sensing is to define heating and cooling rates in the atmosphere. The vertical cloud structure must be known in order to derive the height profile of cloud radiative heating. Although estimates can be made to a degree by passive remote-sensing techniques, the application of direct active sensing of the vertical atmospheric structure provides the necessary acuracy and nonambiguity of results (Spinhirne and Hart, 1990). Both from laser profiling through cirrus and other optically thin clouds and from the very accurate laser cloud edge height of more dense clouds, a height distribution of cloud radiative effects can be obtained from combined laser altimetery and passive radiometric measurements. The accuracy of laser-based measurements is complementary to the much larger coverage possible from retrievals based on passive data.

A laser altimetry sounding system is currently planned for the EOS program. GLAS as currently designed has both atmospheric and solid-earth applications. The cloud science issues addressed by GLAS are the vertical distribution and coverage of optically thin, multilayered clouds and Arctic clouds. Atmospheric aerosol structure will be profiled and the associated planetary-boundary-layer height will also be measured by the GLAS instrument. The principal solid-earth application of GLAS is to observe the height and thickness change of the polar ice sheets as they relate to climate change.

Laser atmospheric measurements are especially important in Arctic regions, where very cold temperatures, long periods of darkness, and high-albedo backgrounds inhibit passive observations. From current satellite data there are significant obstacles for observing polar cloudiness (Curry et al., 1990). The polar regions have the lowest solar illumination and lowest temperatures of any terrestrial area. Satellite radiometers thus operate at or beyond the limit of their response. In the cold half of the year in Arctic regions, hazes of small ice crystals are thought to be an important factor in the radiation transfer which determines the vertical temperature and humidity structure of the winter Arctic atmosphere. Polar stratospheric clouds are known to play a major role in the chemistry of the Arctic upper atmosphere and ozone depletion.

The laser profiling and identification of aerosol-layer height will support estimates of surface haze derived from satellite imagery. The identification of elevated aerosol layering will also support the interpretation of aerosol radiative effects when aerosol optical thickness becomes appreciable.

The GLAS instrument is designed as a basic altimeter and lidar that utilizes elastic scattering from atmospheric particulates and surface topography. The along-track spatial resolution would be 175 m for dense clouds and would be expected to be 1 to 5 km in most cases for thin clouds and aerosol profiling. The vertical resolution for atmospheric measurements would be 75 m. Currently it is expected that the GLAS instrument would be in operation from a 92°

inclination polar orbit in the early part of the next decade. It is expected that active profiling of the atmosphere from space will fill important gaps in cloud measurements from satellites.

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Cloud and Radiation Measurements from
TRMM and EOS: CERES, VIRS/MODIS, and TMI/MIMR

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Planned satellite observations for the mid to late 1990s and beyond promise substantial improvements in our capabilities to remotely sense clouds and radiation over the entire Earth. Improvements will include the following. The list contains approved U.S., Japanese, and European instruments. Instrument launch dates are given in brackets.

- Greatly improved calibration for cloud imagers (OCTS [1996], VIRS [1997], MODIS [1998], GLI [1999]).

- Improved spectral resolution and coverage to allow measurement of *new* physical variables, as well as improve the accuracy of others. (OCTS [1996], IMG [1998], MODIS [1998], GLI [1999], AIRS [2000]).

- Improved spatial resolution to minimize ambiguities caused by observation of several physical processes in the same measurement (OCTS [1996], CERES [1997], MODIS [1998], MIMR [1998], GLI [1999], AMSR [1999]).

- New multiple-angle-of-view sampling to detect atmospheric properties using variable path lengths through the atmosphere and to determine radiation budget anisotropy (ATSR [1991], POLDER [1996], CERES [1997], MISR [1998]).

- New measurements of polarization to examine aerosols and cloud microphysics (POLDER [1996], EOSP [2002]).

- Active lidar system to improve cloud-height measurement (GLAS [2002]).

- Increased computational power to allow more physically based retrievals as well as new capabilities such as the use of cloud and surface textures in neural networks to improve classification of polar clouds.

While these new measurements become available, ISCCP will continue the current record of cloud observations. For radiation budget at the top of the atmosphere, the ERBE nonscanners are still operative, and the SCARAB scanning broad-band radiometer launched successfully in December 1993 to continue this critical climate record.

The next major step in capability will occur in 1997, with the launch of the joint U.S./Japanese TRMM. TRMM will examine the tropics with simultaneous cloud-radiation (VIRS, TMI) budget (CERES), and precipitation (TMI, PR) measurements. This combination will allow the first combined estimation of both radiative and latent heating for the tropics.

Finally, in 2000 we will have available combined simultaneous cloud and radiation data including: cloud properties from advanced cloud imagers, cloud liquid-water path from advanced passive microwave imagers, and radiation budget from advanced broad-band scanning radiometers:

Satellite	Cloud Instrument	Cloud Liquid-Water Path Instrument	Radiation Instrument	Orbit
TRMM	VIRS	TMI	CERES	35°
EOS-AM	MODIS		CERES	10:30 a.m.
METOP-1		MIMR		10:30 a.m.
EOS-PM	MODIS	MIMR	CERES	1:30 p.m.

Using this combination, we expect to improve the accuracy of cloud and radiation measurements by a factor of 4 over current capabilities. In addition, new estimates of radiative fluxes within the atmosphere and at the surface will be possible, as well as new estimates of cloud-particle size.

Because of the critical need for high accuracy and stability of measurements in studies of global change, the current international system is particularly robust because of the ability to intercompare independent instruments for each of the critical measurements shown in the table. In 1998, overlap of CERES and SCARAB will verify the accuracy of radiation budget measurements. In 1999, MODIS and GLI will test the consistency of cloud physical properties derived using cloud imagers. Finally, in 2000, MIMR and AMSR will test the accuracy of passive microwave measurements of cloud liquid-water path. Previous intercomparisons of this type have proven critical to obtaining an accurate understanding of the strengths and weaknesses of the ERBE radiation budget and ISCCP cloud data sets.

Session 4: Relevant Process Studies
D. Starr, Chair

Cloud and Radiation Studies in Japan

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In Japan, a comprehensive and systematic study on cloud-radiation interactions started in the mid-1980s as part of Japanese WCRP activities. The Japanese National Program of WCRP was implemented for the period of four years from FY 1987 to FY 1990. The research project named WENPEX was one of the major projects in the Japanese WCRP. WENPEX has been implemented by the participation of many scientists from universities, including Peking University of China, and national institutes such as the Meteorological Research Institute (MRI) of the Japan Meteorological Agency. WENPEX was directed toward deeper understanding of the climatology, radiative properties, and cloud-radiation interaction processes for clouds in the western north Pacific region. The following four research subjects were principally studied:

(1)   Cloud climatology in the western Pacific region
(2)   Distribution of extended clouds and their bulk radiative properties
(3)   Radiative and physical properties of stratiform clouds
(4)   Formation of marine low-level stratiform clouds.

The WENPEX program contained two kinds of field observational projects. One was the project by the MRI group, which was carried out in the Tsukuba-Hachijojima area. The other was the project by the university group, which was carried out mainly in the southwest islands area in January 1991.

The main purpose of the southwest islands experiment was to study structures of cloud-capped boundary layers under cold-air outbreaks over the warm ocean and to study the relationship between bulk radiative properties and cloud structures. The results of the aircraft observations on cloud-radiation interactions in the southwest islands experiment are summarized as follows:

(1)   Stratocumulus clouds in this area were very convective (thicker and higher) with active entrainment.

(2)   Liquid-water path (LWP) was shown to be a suitable cloud parameter to describe cloud radiative properties. The airborne microwave radiometer of 37 GHz was a useful tool to measure LWP.

(3)   Stratocumulus clouds were highly inhomogeneous, vertically and horizontally. The effect of horizontal inhomogeneity on apparent radiation convergence could be corrected. The so-called anomalous absorption was not recognized.

As part of WENPEX, the MRI group has carried out two types of field observations for radiative properties and cloud microphysical and macrophysical structures. One is the in-situ aircraft observations of stratiform water clouds

over the ocean around Hachijojima. The other type of our field experiments is ground-based observations for high-level ice clouds at the MRI in Tsukuba.

Through the aircraft observations, a new remote-sensing technique has been developed to estimate cloud water microphysical properties from airborne measurement of spectral solar reflectance. Reasonable values of the various cloud physical parameters have been estimated by this retrieval method applied to the aircraft observational data for stratocumulus clouds.

The ground-based observations of high-level ice clouds has been carried out by combining various instruments as well as concurrent satellite data analysis. Results of the ground-based ice-cloud observation are summarized as follows:

(1)   Ice-crystal size distributions were measured by using a special sonde system. The mean size distribution for cirrostratus clouds could be approximated by a power law function with a mean exponent of –3.5.

(2)   Visible optical thicknesses were estimated from sun photometer measurements. A relationship between the visible optical thickness and the broad-band solar flux transmittance was obtained.

3)   Infrared optical thickness and lower-limit size of the power law size distribution were estimated from the spectral zenith radiance measurements in the infrared-window region. The estimated infrared optical thicknesses were about half of the visible optical thicknesses.

4)   Analysis of the brightness temperature differences between the infrared window channels of AVHRR and HIRS of NOAA satellites was consistent with the ground-based observational results.

Following the WENPEX program the MRI group has started another research program, termed JACCS. JACCS is a decade-long (FY 1991–FY 2000) climate research program sponsored by the Science and Technology Agency of the Japanese Government. The objective of the JACCS program is to advance our understanding of cloud-radiation interaction processes, and to develop better parameterization of cloud and radiation processes used in climate models. A secondary objective is to develop advanced uses of satellite data in the cloud-climate study. Research activity involves field observations of clouds and radiation, laboratory experiments, satellite data analyses, and numerical modeling of cloud and radiation processes. Present status and future plans are stated.

Recent Field Studies of Aerosol and Cloud Processes Relevant to Climate

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Aerosols have the potential to change the radiative balance of the earth, both directly, by scattering solar radiation back into space, and indirectly, by acting as cloud condensation nuclei (CCN) and changing the radiative properties of clouds. Although some estimates have been made of the direct and indirect effects of anthropogenic sulfates, more information is needed on their worldwide distribution and properties to determine their effects on climate. Recent measurements on the light-scattering efficiency of sulfate over the northern Atlantic Ocean give lower values than those over land (Hegg et al., 1993a, b), which have been used in previous estimates of the direct effects of anthropogenic sulfates on climate. Also, during the period of measurements over the Atlantic Ocean, sulfate was not the dominant constituent of the aerosols (Hegg et al., 1993a). The geographical variations in the CCN efficiency of sulfate also need to be known in order to estimate the indirect effects of anthropogenic sulfates on climate. Some values of the CCN efficiencies of sulfates over the Atlantic Ocean are presented (Hegg et al., 1993a).

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On the Representation of Mesoscale Convection
in Global Models: A New Challenge

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The term mesoscale convection includes deep precipitating cloud systems with accompanying mesoscale circulations. The scales of motion involved, O (10 - 100 km), are dynamically, thermodynamically, and hydrologically important. However, mesoscale convection is not properly included in global models because it is at best crudely resolved and is not properly parameterized. In moderate to strong shear, mesoscale convection propagates and has diverse effects on the atmosphere as summarized in Figure 1. The extensive cirrus or stratiform decks due to these systems have recently received attention because of their strong radiative feedback. The physics of mesoscale convection has been the subject of much research in the last decade or so, but its global-scale impact has received little attention. As a subgrid-scale process, it questions some of the fundamental assumptions involved with parameterization, especially Reynolds averaging and scale separation.

Mesoscale convection is common in the atmosphere and takes several forms. Cloud clusters in the tropical western Pacific represent mesoscale convection on a grand scale, O (1,000 km), and are associated with the Madden-Julian oscillation. With strong westerly wind episodes or "bursts" providing a large-scale forcing, high-resolution global models may at least crudely resolve mesoscale cloud clusters. The ECMWF T213 operational forecasts and T106 experiments for the TOGA COARE December 1992 westerly burst episode were examined to investigate this possibility. Preliminary analysis shows that traveling cloud clusters are indeed present.

Examination of the physical process in T106 experiments indicates that the transports were largely by resolved scale fluxes rather than parameterized fluxes. The thermodynamical transports are qualitatively consistent with what is expected by mesoscale convection in the sheared environment of westerly bursts, including strong mesoscale descent to the rear of the cloud system. The vertical transport of horizontal momentum is, however, a more subtle problem, especially when convection is part resolved and part parameterized. The momentum flux by the resolved-scale convection and by the parameterized convection are both sufficiently in error to produce wind bias in the western Pacific.

These findings indicate that the scale dependence of the transport in large cloud clusters in the tropical Pacific and the problem of scale separation in subgrid-scale parameterization in high-resolution global models are now issues. The fundamental problem is how to treat organized (coherent) mesoscale structures in a convective parameterization scheme. This aspect is being studied by using a combination of idealized analytical models and nonhydrostatic, cloud-resolving numerical models.
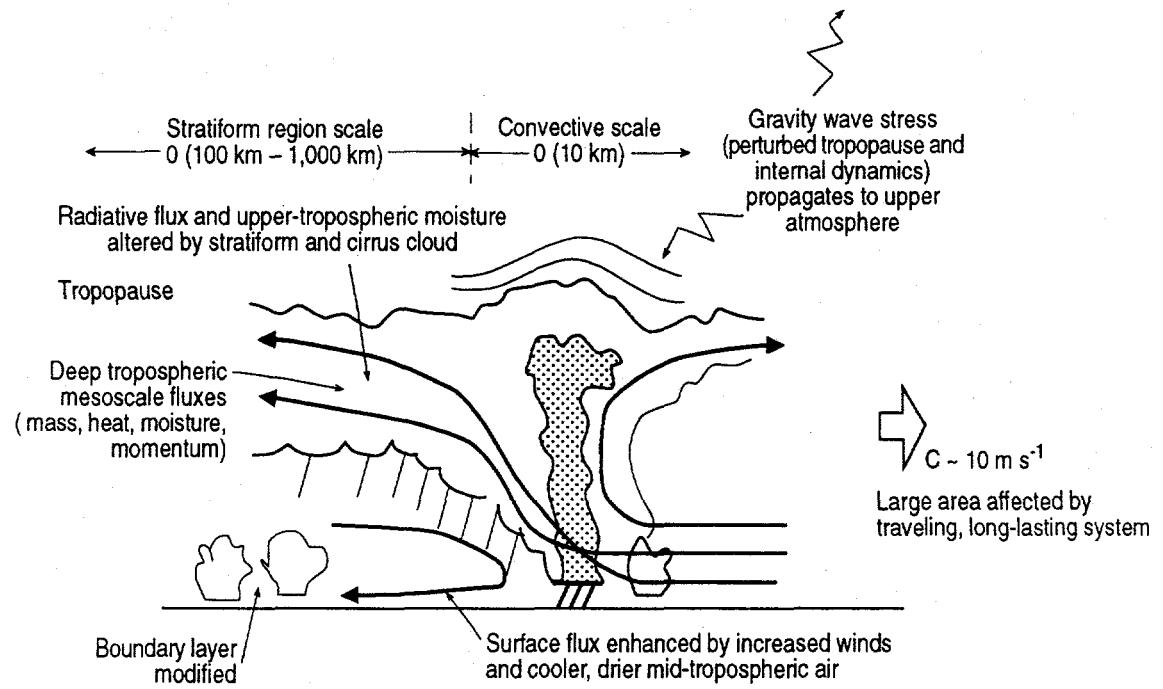
Figure 1

Physical Processes in Cirrus Clouds: Fundamental Scales and Implications

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Important physical processes involved in the formation, maintenance, and dissipation of cirrus clouds encompass microphysical, dynamical, and radiative processes. Cirrus clouds are composed of relatively broad distributions of particle sizes, including significant populations of smaller (10-100 μm) and larger (100 μm to 1 mm) ice crystals. A variety of crystal habits are commonly observed (columns, plates, bullet rosettes, and aggregates). Recent observations indicate that the numbers and characteristics of the ambient aerosols may influence cirrus cloud microphysical composition.

Although cloud ice-water content, particle size distribution, and habit exhibit general tendencies with respect to temperature that have enabled development of new more realistic cirrus parameterizations for climate models, these properties are observed to be highly variable, even within a given cirrus cloud or cloud system. This variability is associated with cloud-scale, mesoscale, and synoptic-scale motions. Small-scale cellular structures (100 m to 1 km), often organized into clusters (10-100 km), are commonly found within larger-scale cirrus cloud systems. Consequently, cirrus cloud radiative properties are also quite variable since cloud radiative properties, and the radiative effects of a cirrus cloud, are governed not only by the mean physical state of the cloud but also to a significant extent by the structural organization of the cloud due to the nonlinear relationship between cloud microphysical and radiative properties, especially when the cloud is optically thin. In turn, radiative processes impact cloud development through their effects on cloud dynamics and microphysical processes. In addition to the direct radiative climatic role of cirrus, these clouds are now recognized as playing a major role in the upper-tropospheric water budget. The downward transport of cloud water, a direct consequence of the prevalence of large ice crystals, redistributes water vapor between the upper and middle troposphere with significant radiative implications, and affects precipitation development via natural cloud seeding. The vertical ice transport also strongly depends on cloud structure due to the nonlinear relation between ice-crystal fall speed and particle size and habit, and also the modulating effect of vertical motion. It should be noted that the cloud radiative properties are more sensitive to the small-particle component of the crystal population while vertical transport is dominated by larger particles.

Recognition of the importance of cloud-scale and mesoscale motions and consequent organization of cloud physical properties represents a key finding of recent cirrus cloud process studies and observations. Another key finding is that cirrus clouds are usually generated in fairly shallow layers (100-500 m), often multiple, with vertical extension and development to depths of 2-5 km initially via vertical ice transport. Although subtle in comparison to what is observed in the lower troposphere, vertical structure in the ambient moisture, thermal, and dynamical fields (lamination) likely plays a key role in determining cloud vertical structure and the cloud-scale and mesoscale motion fields that most

directly govern cloud microphysical and radiative properties. It appears that the pre-existing structure may evolve essentially via large-scale processes—the effects of wind shear and deformation acting on upwind features such as the moisture and heat "shadows" of precipitating convective systems or extratropical cyclones. Radiative processes may also play a role here. One implication is that parameterizations of cirrus clouds in present climate models (GCMs), which typically employ a vertical resolution of about 1.5-2 km in the upper troposphere, must attempt to diagnose not only the response of cloud-scale processes but also the evolution of the unresolved vertical structure that most directly governs this response. This is a very difficult task. Finer vertical resolution (~250 m) must be used in these models to allow resolution of the physical processes forcing the specifics of cloud response separately from the cloud-scale response itself.

Cloud-system (mesoscale) models will be a key element in the process of developing improved physically based cloud parameterizations for climate models over the next decade. Present understanding of the cloud-scale physical processes has advanced appreciably in the last decade and will likely continue to do so given the dramatic gains in observing technology. Integration of this knowledge into cloud-system models is a natural next step that is already under way. The recent improvements in models and observations have been a direct result of strong cooperation and interaction between these communities. Cloud-system models are the most appropriate venue in which to directly apply and test the knowledge of cloud processes and cloud-scale variability, and separately address the issue of mesoscale processes and variability, all of which are subgrid-scale in a GCM. Collection of the first suitable data sets to support the requirements of cloud-system modeling of cirrus clouds during FIRE Cirrus-II was a significant accomplishment and will facilitate the application of the multiscale approach to understanding cirrus and improving present capabilities for representing cirrus clouds in climate models.
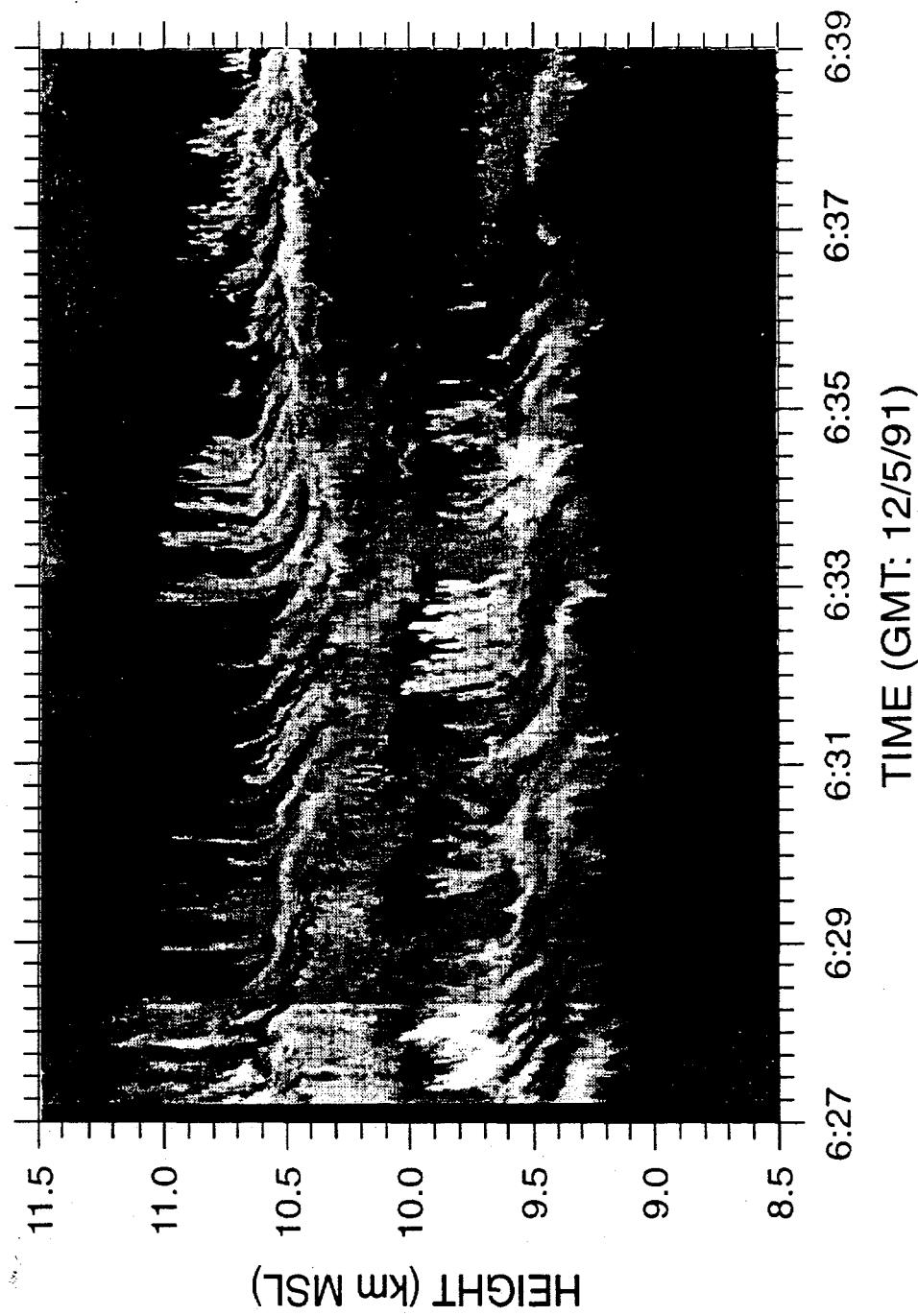
Figure 1—Time-height display of backscattered return signal observed by the University of Utah dual-polarization lidar system depicting the fine-scale cellular convection and associated fall-streaks in optically thin cirrus cloud layers on 5 December 1991 during the FIRE Cirrus-II field experiment (courtesy of K. Sassen). Total time elapsed is 12 minutes, corresponding to a length of about 20 km at the a_ ient wind speed.
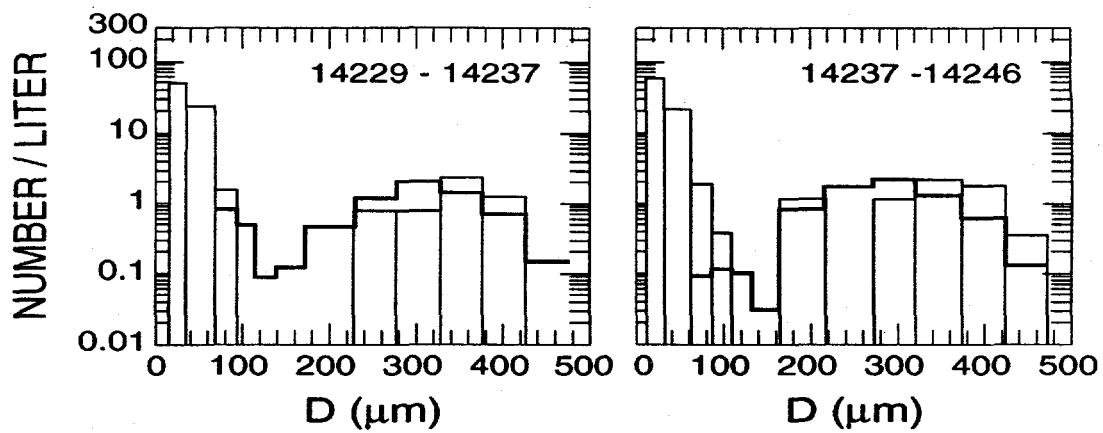
Figure 2—Ice-crystal size distributions observed by conventional Particle Measuring Systems 2-DC probes (heavy) and new replicator instrument developed at the Desert Research Institute from the University of North Dakota Citation on 22 November 1991 during the FIRE Cirrus-II field experiment (courtesy of W. Arnott, Y. Dong, and J. Hallett). Observations confirm the presence of significant numbers of radiatively important small ice crystals previously undetectable using conventional instrumentation.
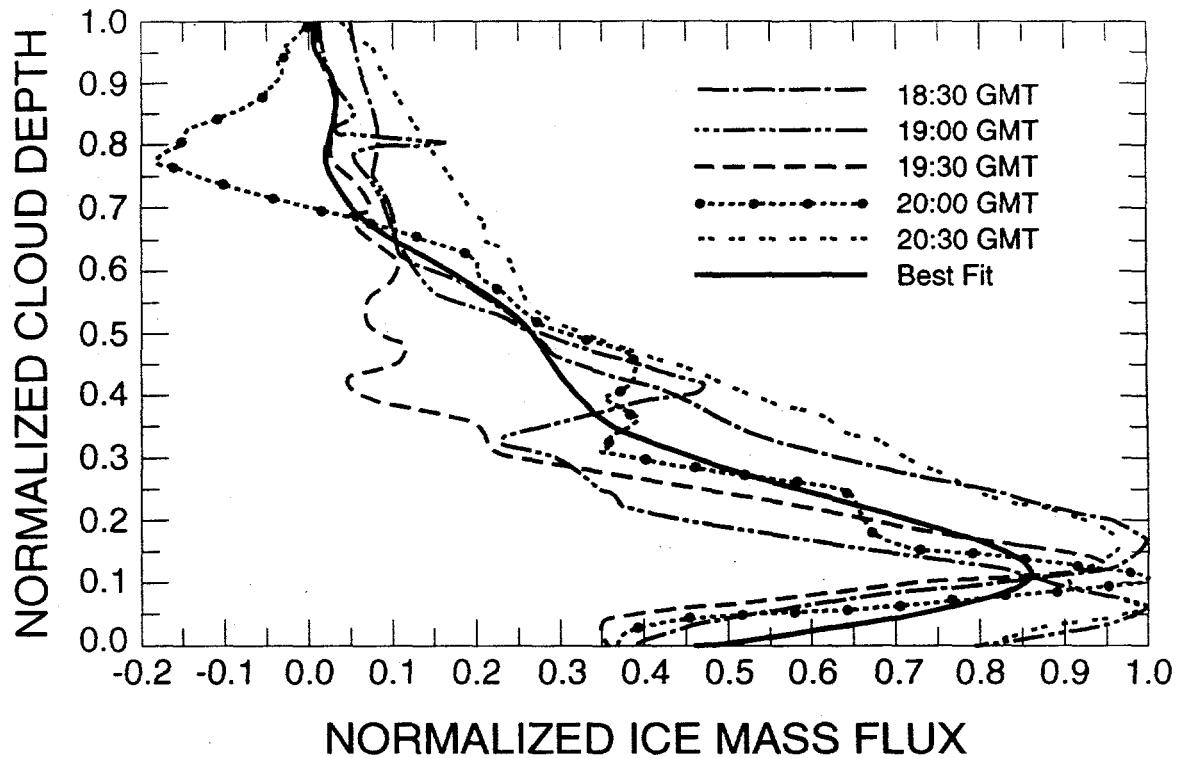
Figure 3—Vertical profiles of the vertical flux of ice mass computed from observations by the NOAA Wave Propagation Laboratory 8.6-mm Doppler cloud radar on 26 November 1991 during the FIRE Cirrus-II field experiment (courtesy of B. Orr and R. Kropfli). Profiles have been averaged over 30-minute time periods and normalized for cloud depth and maximum average flux. They illustrate the typical effects of vertical structure in cloud ice-water content and particle size distribution on the vertical transport of ice in cirrus.

Parameterization of Cloud Microphysics for Numerical Atmospheric Models

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A scheme for parameterization of cloud microphysics is deduced, containing the three mechanisms for release of precipitation: autoconversion, coalescence, and Bergeron-Findeisen effects (Sundqvist, 1993). The scheme accounts for ice existence in clouds and precipitation. Cloud water is the only prognostic variable. Temperature is adopted as the primary indicator for appearance of ice in supercooled water. The employed ice probabilities are based on observations. The emphasis of this study focuses on the Bergeron-Findeisen effects since the parameterization of the liquid-water microphysics has already been discussed and studied more extensively in other papers.

A formulation of the enhancing effect of the Bergeron-Findeisen mechanism on release of precipitation is suggested. Numerical experiments have been carried out with a one-dimensional model with prescribed rate of condensation to study the effect of the three aforementioned mechanisms. The parameter values of the approach have been chosen such that the coalescence and Bergeron-Findeisen factors have equal magnitudes, and the vertically integrated cloud water has a realistic magnitude when all mechanisms are included. Substantially different steady-state vertical distributions of cloud water content follow from the three mechanisms. The Bergeron-Findeisen effect has an impact only in a limited temperature range. Therefore, the location of a cloud layer with respect to temperature is more influential on the Bergeron-Findeisen effect and the consequent cloud water distribution than is the exact choice of ice probability assumption. In comparison to the coalescence effect, the deduced Bergeron-Findeisen mechanism has a greater influence on stratiform clouds than on convective clouds. See Figure 1.

The suggested approach appears to facilitate realistic simulations of cloud water content. It is also concluded that there is an evident need for data from measurements to allow for calibration and tuning of introduced parameters. Such data should consist not only of cloud water content, but also of the vertical distribution of liquid and ice-phase partitioning. An estimate of the vertical distribution of precipitation rate would also provide valuable information in this context.

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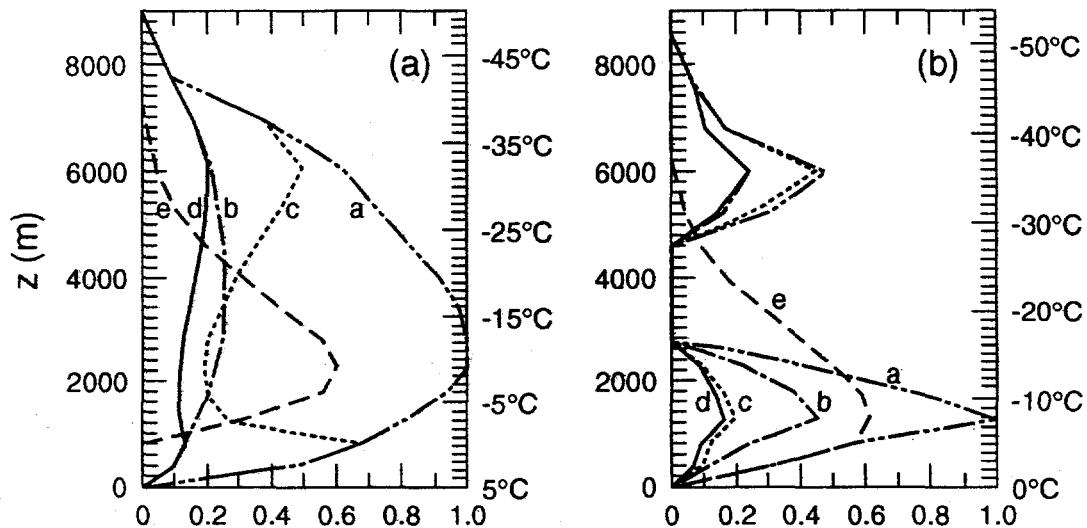
Figure 1a—Steady-state distributions of cloud water content for different mechanisms in the release process of precipitation in a convective-type cloud. Curve a due to autoconversion, a nonlinear function of the cloud water content; curve b due to autoconversion and coalescence effects; curve c due to autoconversion and Bergeron-Findeison mechanism; curve d due to autoconversion, coalescence effects, and Bergeron-Findeisen mechanism. The effective Bergeron-Findeisen curve is given by curve e. (Curves a-d are normalized by the maximum value of a.)

Figure 1b—The same as 1a, but for a two-layer stratiform-type cloud.

Session 5: Panels

Panel 1, GCM Studies
J.F. Geleyn, Chair
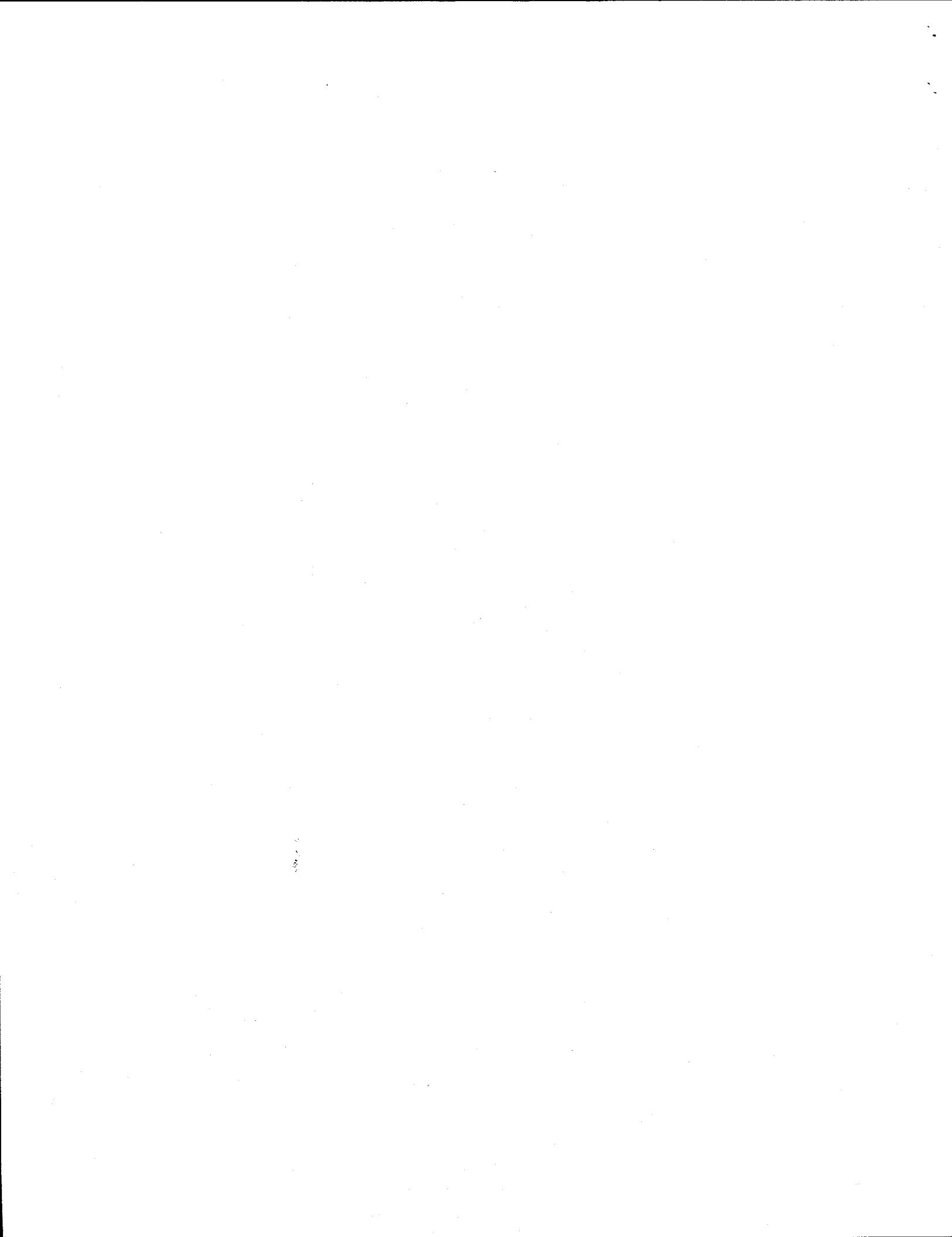
Atmospheric Radiative Properties and the CCC-GCM's Cold, Dry Bias

Howard Barker
Canadian Climate Centre

Zhanqing Li
Canada Centre for Remote Sensing

The equilibrium, present-day climate of the CCC-GCM (generation II and III) is too old and dry. Numerous different initial conditions lead to the same state. Several adjustments to the shallow and deep convection schemes suggest that they are unable to alleviate the biases. Current investigations into the source of the biases revolve around cloud emissivities and water-vapour absorption of shortwave radiation.

Consider first cloud emissivities. Lou et al. (1994) presented evidence from AVHRR satellite imagery suggesting that the 11-μm emissivity ε of marine stratocumulus clouds is approximately A_c where A_c is cloud amount. They argue that the ratio of "edge material" to "core material" increases as A_c decreases and since the edges are optically thin due to entrainment of dry air, ε will be substantially less than 1. Furthermore, they maintain that the relation between ε and A_c is independent of cloud optical depth. Since they show that the relationship is fairly independent of viewing angle, the same relationship must hold approximately for flux emissivities. The cloud sensitivity parameterization used in the CCC-GCM results in almost black clouds ($\varepsilon > 0.97$) for visible optical depths >4.5 and is independent of A_c (i.e., no account for subgrid inhomogeneity of clouds).

Clearly, the relation of Lou et al. would lead to less cooling from marine stratocumulus clouds (and possibly other clouds) and perhaps a slightly warmer and moister atmosphere. Therefore, their relation was tried in the CCC-GCM but virtually nothing happened. This was puzzling since the monthly mean A_c was close to ISCCP estimates (~0.5 to 0.6 in marine stratocumulus regions). The problem is that, while the CCC-GCM attempts to predict layer cloud amounts in grid cells, the clouds tend to "blink" catastrophically between $A_c = 0$ and 1 (see Figure 1): Lou et al.'s relation was rarely activated since it has corresponding limits of $\varepsilon = 0$ and 1 (like the CCC relation) but has its maximum impact for A_c between 0.25 and 0.5. Distributions of A_c for the CCC-GCM are like beta functions, while Lou et al. and Chang and Coakley (1993) show more normal distributions. If the GCM could get an abundance of medium values of A_c, cooling rates for marine stratocumulus layers would be reduced by 50% to 70% (Figure 2). Furthermore, one can only speculate about feedbacks imparted on the system by high-frequency noise injected by the extreme radiative effect of clouds.

The second avenue being investigated has to do with water-vapour absorption of shortwave radiation. Li and Barker (see their report in the section

of this document for Panel 2, Satellite Observations) compare the disposition of solar radiation as calculated by three GCMs to values inferred from ERBE data by Li et al.'s (1993) algorithm. They found that for all sky conditions on a global and annual basis, the GCM surfaces absorb about 10-30 W m^{-2} more than the ERBE estimates. The CCC model, in particular, absorbs about 15 W m^{-2} too much by the surface and 25 W m^{-2} too little by the atmosphere, and reflects about 10 W m^{-2} too much. Similar discrepancies were also found for clear skies (Figure 3). Therefore, it is hypothesized that the sources of the differences lie (in order of descending importance) with: parameterization of water-vapour transmittance, too dry an atmosphere, and neglect of atmosphere aerosols. While results from the CCC-GCM shortwave radiation code agree very well with median values for narrow- and broad-band models in ICRCCM standard cases, corresponding line-by-line models appear to be from a separate population. The code used to produce Li et al.'s algorithm, however, is based on Lowtran 6 and does agree with ICRCCM LBL results.

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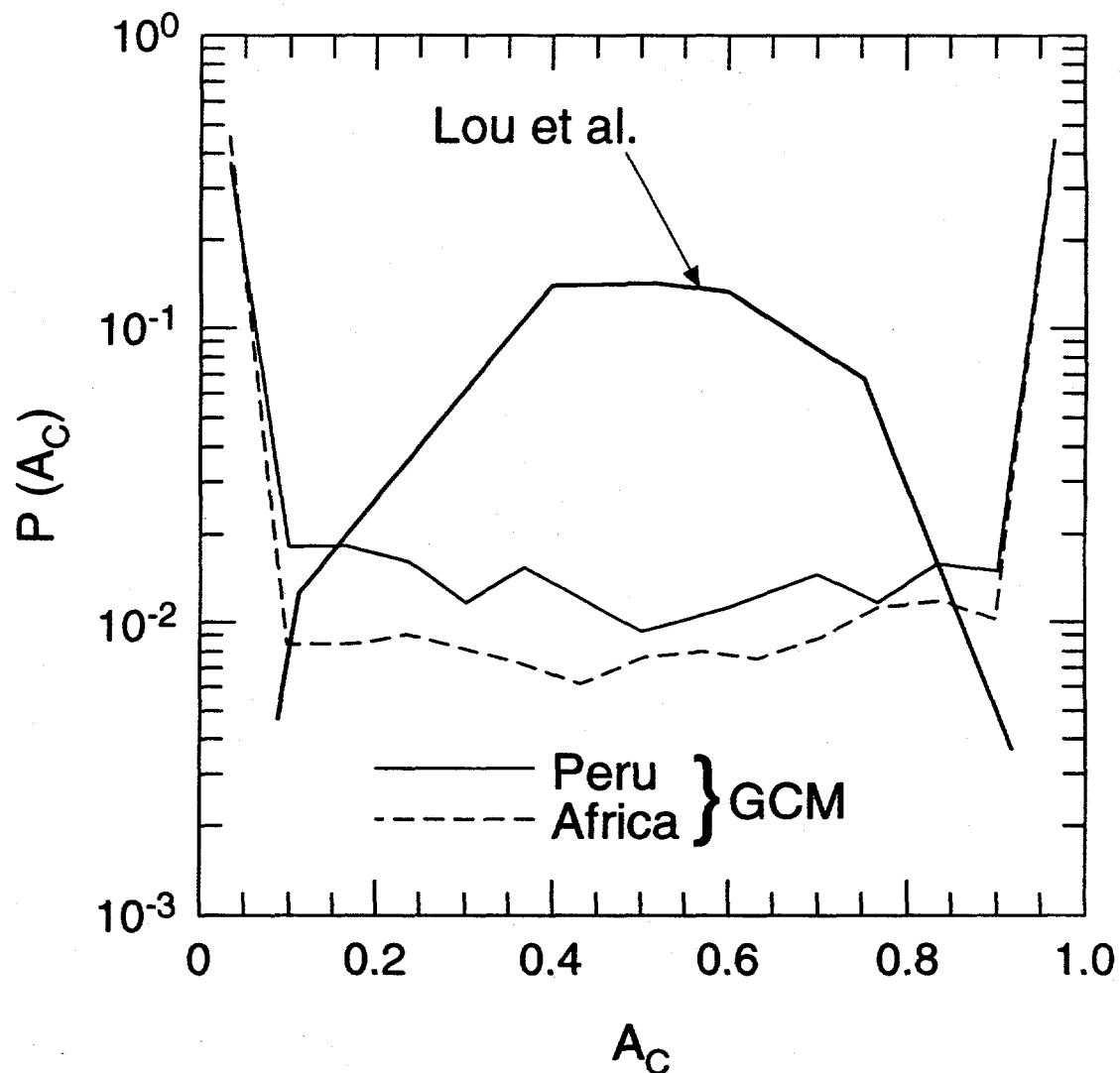
Figure 1—Frequency histograms of total cloud amount for marine stratocumulus regions off the coasts of Peru and Namibia (Africa) for the CCC-GCMIII and from Lou et al. (1994) (same region of Peru as used for the GCM). GCM values are 12-h samplings for July while Lou et al.'s values are 250-km averages from AVHRR data from March to July 1985. Note that the clear and overcast cases for Lou et al.'s curve have been omitted but are fairly minor regardless.

CLOUD HEATING RATE

NET LW @ SURFACE
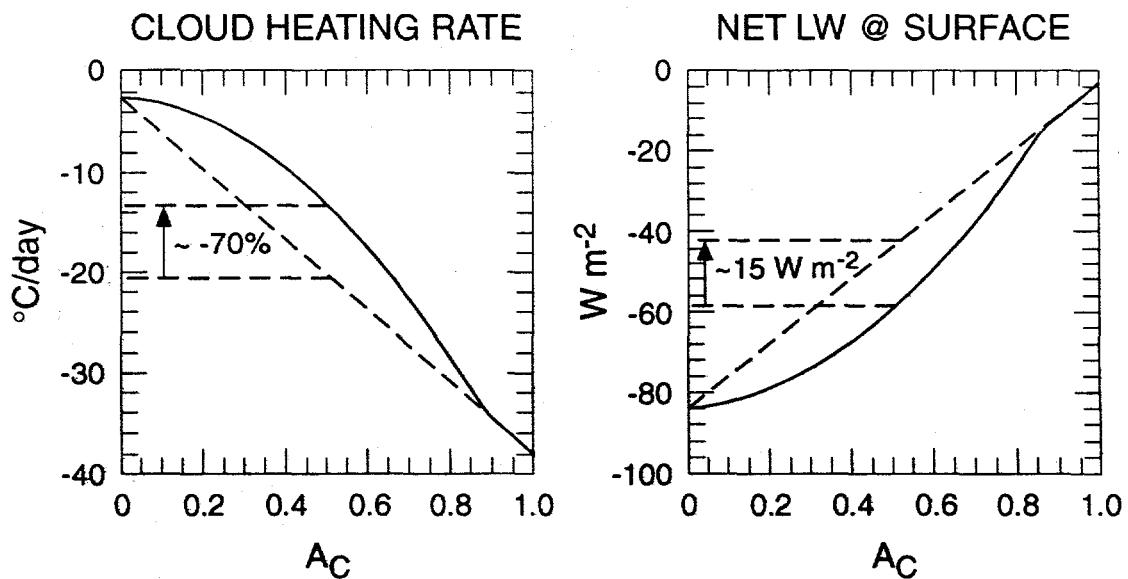
Figure 2—Longwave heating rate as a function of cloud fraction for a layer containing a cloud with its top 400 m above the surface and visible optical depth of 7 in the mid-latitude summer standard atmosphere. Also shown are the corresponding net longwave fluxes at the surface. The dashed line is for the current CCC-GCM parameterization of cloud emissivity, and the solid line is for Lou et al.'s (1994) relation.
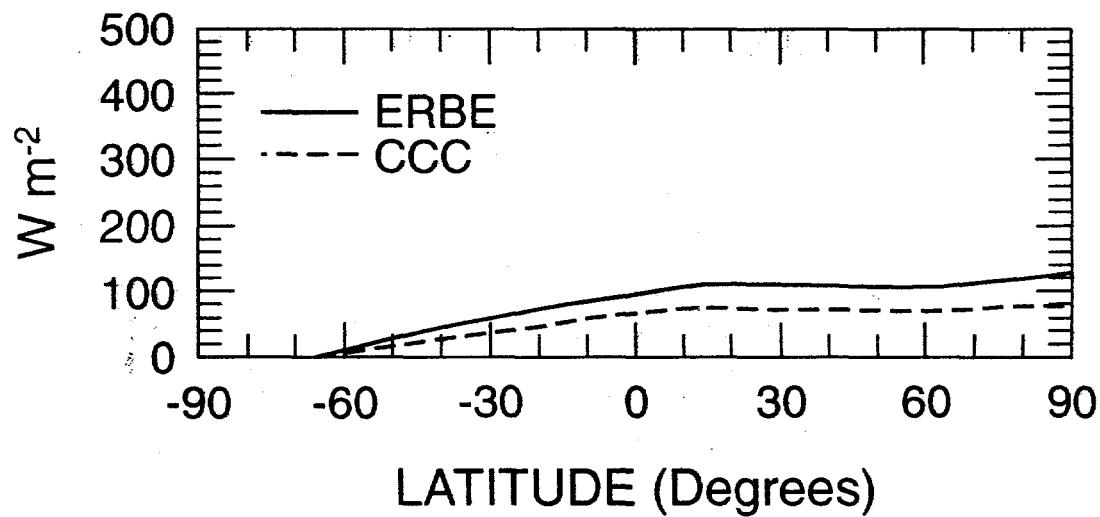
Figure 3—Clear-sky atmospheric absorption as a function of latitude for the CCC-GCMII (AMIP simulation) and inferred by Li et al.'s (1993) algorithm from ERBE data. Results are for July 1985-1988.

Some Results from Numerical Experiments on the Estimation of Cloud-Radiation Interaction Effect on Meteorological Variables' Predicted Patterns

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Numerical experiments on the evaluation of the impact of radiation heat influx on the meteorological fields were carried out using the research version of both hemispheric and regional-scale operational short-range forecasting models. Both models comprise 11 levels over the vertical, covering the domain from the surface to the 100-hPa isobaric level and incorporate the effect of the diabatic influx of heat, moisture, and momentum. The radiation algorithm of the models is based upon the integral transmission functions in the infrared and longwave spectral regions and on the account of the ozone influence in the visible spectral region. The cloud amount is estimated using the predicted relative humidity, with its threshold value being specified. The results of numerical experiments show that the radiation flux divergences calculated with the account of the influence of lower, middle, and upper clouds exert a significant direct and/or indirect influence on the predictions of temperature and geopotential patterns and of some other meteorological variables. Predicted and observed mean algebraic (numerator) and mean absolute (denominator) 24-hour changes of the 500- and 1,000-hPa heights and the 500-hPa temperature for the initial data of 0000 UTC, 3 October 1993, over the Hydrometeorological Center's Moscow responsibility area are given in the table below.

Level (hPa)	Actual	Prediction Model Versions		
		$E=0$	$E=E_1+E_2+E_3+E_4$	$E=E_1$

Geopotential height (m)

Level (hPa)	Actual	$E=0$	$E=E_1+E_2+E_3+E_4$	$E=E_1$
500	36.4/53.1	49.1/60.5	37.9/52.8	45.8/58.3
1,000	15.9/38.6	20.2/44.3	17.5/41.2	18.7/43.1

Temperature (°C)

Level (hPa)	Actual	$E=0$	$E=E_1+E_2+E_3+E_4$	$E=E_1$
500	0.9/2.3	1.4/2.3	0.3/2.2	1.2/2.0

Here, E_1, E_2, E_3, and E_4 are the heat influx contribution due to the radiation, eddy exchange, condensation, and convection, respectively. On the basis of the amount of prediction experiments, the contribution of the radiation and other heat influxes to the fields' evolution and the spatial distribution of meteorological variables was assessed. Verification statistics of the geopotential height, temperature, wind, and humidity prediction by the hemispheric diabatic model were obtained.

Improved Diagnostic Cloud Parameterization in NMC's Global Model

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If an atmospheric model is capable of accurately simulating the three-dimensional distribution of moisture, then a diagnostic cloud parameterization scheme should be able to produce the accurate large-scale cloud cover needed for numerical weather prediction (NWP). Moisture is probably the least accurate variable in an NWP model, so some tuning to observed cloud data is desirable. NMC is routinely validating and experimentally tuning its global spectral model's Slingo-type cloud parameterization using the U.S. Air Force (USAF) Real-Time Nephanalysis (RTNEPH; see Hamill et al., 1992), which is being received via the processing communications link shared by USAF and the U.S. National Environmental Satellite, Data, and Information Service (NESDIS) of the National Oceanic and Atmospheric Administration (NOAA). Concurrently, NESDIS is developing a multisatellite cloud analysis, which will address some of the shortcomings in the USAF analysis. A major component of the NESDIS effort is use of multispectral AVHRR data from NOAA polar orbiting satellites (Stowe, 1991). Total cloud, from the latter, is now available, and distinct layered cloud analyses are projected to be available by autumn 1994.

The RTNEPH data, vertically compacted into the high-, middle-, and low-cloud domains of the global model, is used to develop stratiform cloud/relative humidity (RH) relations for a number of geographical regions. The procedure, developed independently by Rikus and Hart (1988) and Mitchell and Hahn (1990), maps cumulative frequency distribution of observed cloud to the model's RH distribution. We have observed sensitivity of the computed cloud/RH relationships to changes in season (Figure 1a), to differences in cloud type (i.e., high, middle, low—Figure 1c), to changes in the forecast model which alters its three-dimensional RH structure (e.g., new convection parameterization—Figure 1d), to surface type (land and ocean), to region (tropics and middle latitude), and to forecast hour (primarily during the first 24 hours). The cloud/RH relations, however, do not change appreciably for horizontal resolutions of T62 and T126 (Figure 1b). Sufficient data must be accumulated in order to produce stable cloud/RH relationships, either through use of large geographical regions or by accumulating the data for long enough time periods (15 days appears to be sufficient). In most of the regions, the new relations significantly differ from the currently operational quadratic cloud/RH relationship (critical RH = 0.8).

In addition, changes are being made to the way stratiform cloud is treated in the presence of convective cloud (currently, stratiform not used) as well as to the radiative properties of the clouds (currently, preset). The new scheme merges convective and stratiform cloud, and computes cloud properties from estimated cloud optical depth (Harshvardhan et al., 1989). Preliminary tests show that there are a number of improvements to the model-diagnosed cloud. The overall cloud fraction is larger, the zonal mean middle-cloud fraction is more correct in the tropics, and correlation scores, relative to verifying Air Force analyses, have improved. The radiative impact shows a reduction of both

upward longwave radiative flux at the top of the atmosphere (TOA) and downward shortwave radiative flux at the earth's surface in tropical latitudes. Both effects are more realistic relative to deficiencies seen in other model comparisons with observed TOA longwave data (ERBE and AVHRR) and with surface shortwave flux estimates (made from observed TOA shortwave data and ISCCP cloud, Pinker and Laszlo, 1992).

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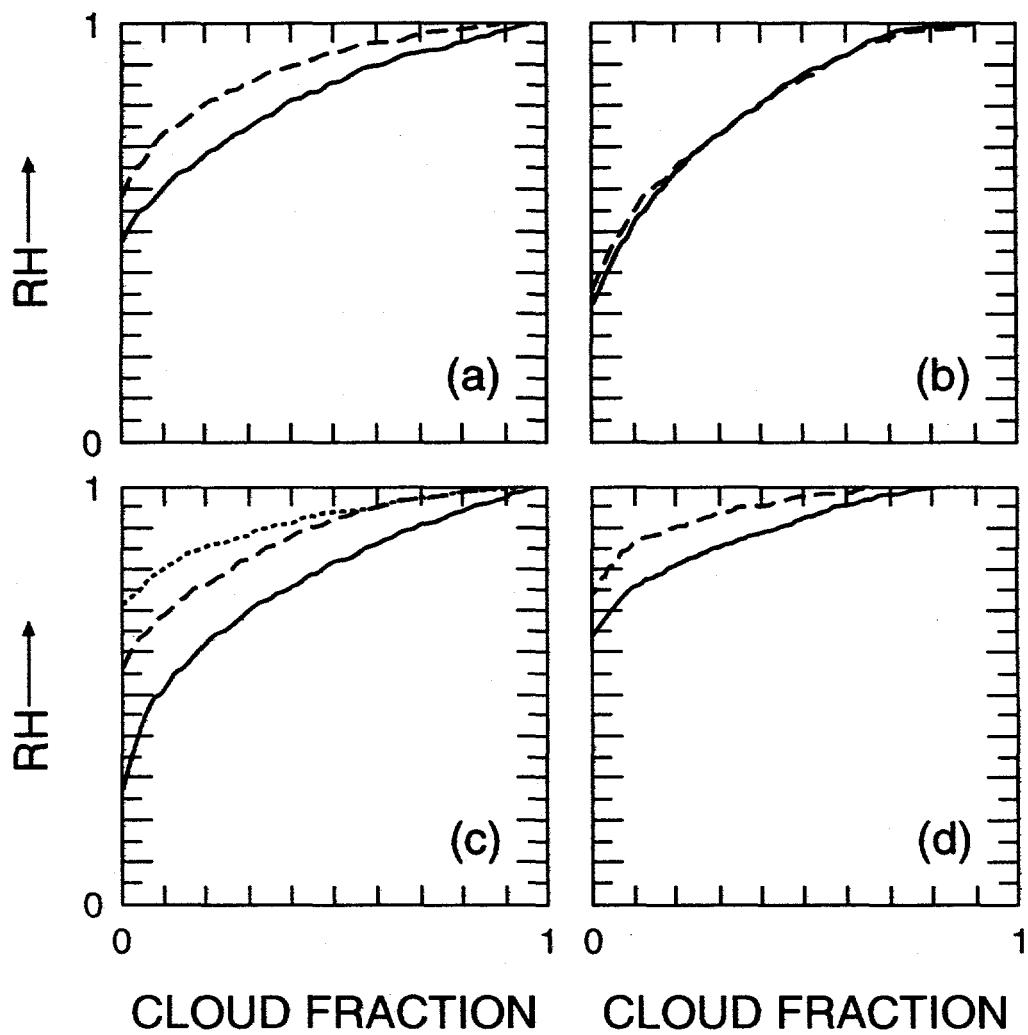
Figure 1—Examples of cloud-RH relationships produced from model RH and USAF RTNEPH data for various regions, for the NMC global spectral model:

a. High cloud, Northern Hemisphere, land, forecast day 0, July (solid) and February (dashed) 1993.

b. Low cloud, global, land, forecast day 5, T126 (solid) and T62 (dashed) resolutions, July 1993.

c. Southern Hemisphere, ocean, forecast day 0, low (solid), mid (dashed), high (dotted) cloud, April 1993.

d. High cloud, Southern Hemisphere, land, forecast day 0, operational Kuo (solid) and NEW (dashed) convective parameterization, April 1993.

On the Accuracy of the Cloud Amount and Radiation Flux Calculations in Hydrodynamical Models of the Atmosphere

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The accuracy of the radiation characteristics in hydrodynamical models of different time and space scales is defined by many factors. The similar property of the radiation processes for all kinds of models is the constant action of radiation during the whole time of the model integration. In connection with this effect, the errors in the radiation calculations play the same role as the systematic errors in models. The common requirement important for all kinds of models is accurate surface radiation balance calculations. The accuracy of the vertical distribution of flux divergences is more important for climate model results.

To investigate the question about the accuracy of the initial data, some experiments were carried out with different combinations of cloud amount and cloud location. The radiation algorithm used was developed by L. Neelova and E. Podolskaya (1986) and based upon using the integral transmission functions.

The results of the experiments are presented in Table 1, where Ch, Cm, and Cl are the high-, middle- and low-cloud amounts, respectively; Co is the general cloud amount; and Rs and R^* are the surface and upper-boundary radiation balance.

Table 1

N group	I			II					III		
N exp	1	2	3	4	5	6	7	8	9	10	11
Ch (300 hPa)	0	0.6	0.3	0.6	0	0.3	0	0.3	0.3	0	0.6
Cm (700 hPa)	0	0.3	0.6	0	0.6	0	0.3	0.3	0	0.3	0.6
Cl (850 hPa)	0	0	0	0.3	0.3	0.6	0.6	0	0.3	0.3	0
Co	0	0.72	0.72	0.72	0.72	0.72	0.72	0.51	0.51	0.51	0.84
Rs (W m^{-2})	352	280	245	269	211	219	196	295	283	255	231
R^* (W m^{-2})	297	339	278	335	212	261	209	308	301	246	323

N group	IV			V			VI		VII
N exp	12	13	14	15	16	17	18	19	20
Ch (300 hPa)	0.6	0	1	0	0	1	1	0	1
Cm (700 hPa)	0	0.6	0	1	0	1	0	1	1
Cl (850 hPa)	0.6	0.6	0	0	1	0	1	1	1
Co	0.84	0.84	1	1	1	1	1	1	1
Rs (W m^{-2})	207	159	305	183	130	140	101	51	38
R^* (W m^{-2})	314	195	336	137	87	375	377	141	381

The calculations were conducted under the vertical humidity and temperature distribution for moderate latitude taken from McClatchy et al. (1972). Surface albedo is 0.2; zenith angle is 60°; So = 1,382 W m^{-2}; cloud albedo ah = 0.21 and am = 0.54, al = 0.66 for visible radiation and am = 0.46, al = 0.5 for infrared radiation.

The results are combined in seven groups. Each group has the same value of Co. In spite of this, the values of Rs and R^* have a significant dispersion. Table 2 presents a comparison of the maximum difference in Rs and R^* values depending on cloud situation for the special combinations of the experiments. It follws from Table 2 that the greatest errors in the calculations of Rs and R^* may be in connection with the errors in the definition of the upper cloud layer (experiments 4,5 and 4,6).

Table 2

N exp	ΔRs (W m^{-2})	ΔR^* (W m^{-2})
2,3	35	60
4,6	50	75
5,7	15	3
4,5	60	125
6,7	25	50

Figure 1 presents the dependence of Rs and R^* on the redistribution of cloud amount and its values Cgr for groups III, IV, and VI.

The results show that correct definition of the cloud vertical distribution is of great importance. But most of the present methods for calculating cloud amount are very approximate and are based on the relations between cloud amount and relative humidity. The principal moment in such parameterizations is the definition of the relative humidity critical value, Hcr. The comparison conducted by Kurbatkin et al. (1988) shows that Hcr differs greatly from model to model (Figure 2) and as a consequence the cloud amount differs greatly too (Figure 3).

So, modeling of clouds is the main problem which must be solved to obtain adequate radiation fields. It is not enough to know the general cloud amount. It is necessary to know the vertical distribution of clouds.

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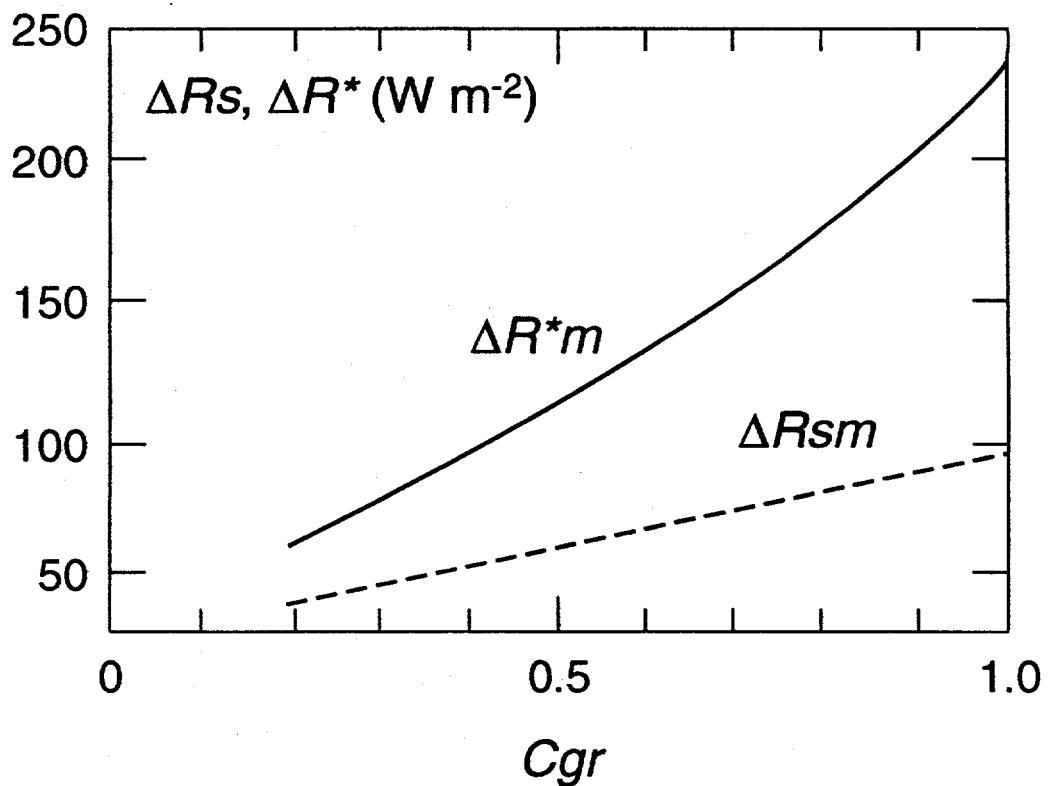
Figure 1—The dependence of *Rsm* and *R**m on the redistribution of cloud amount for groups III, IV, and VI.
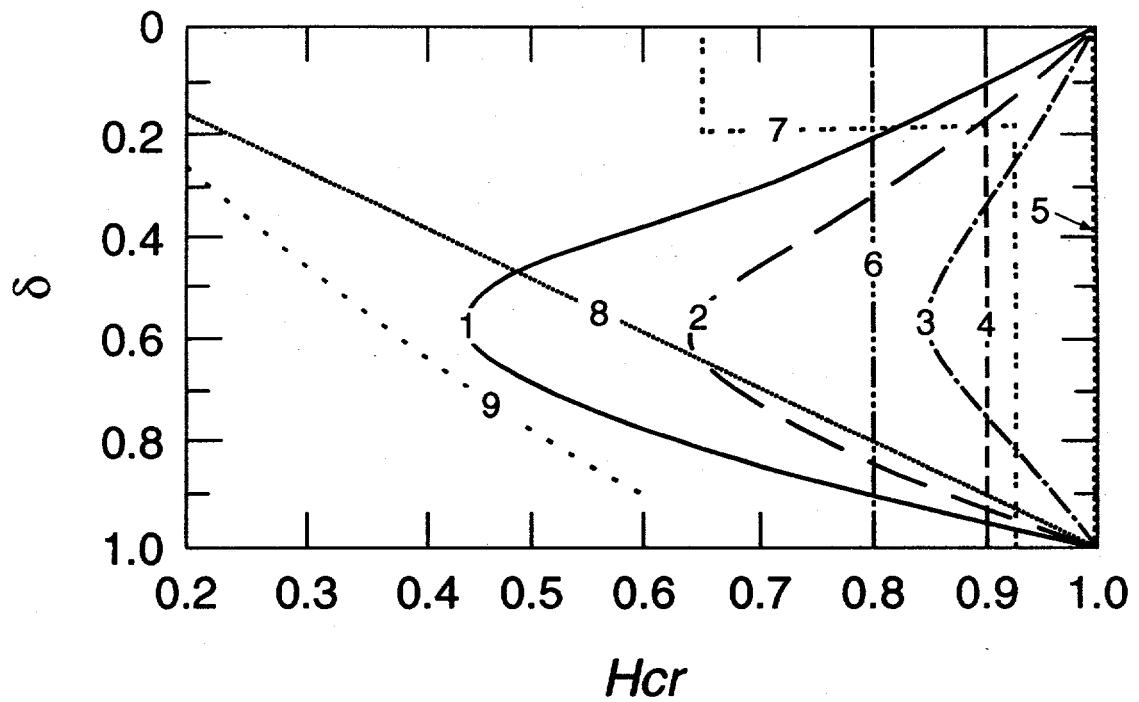
Figure 2—The vertical distribution of *Hcr* in the different models listed in Figure 3.
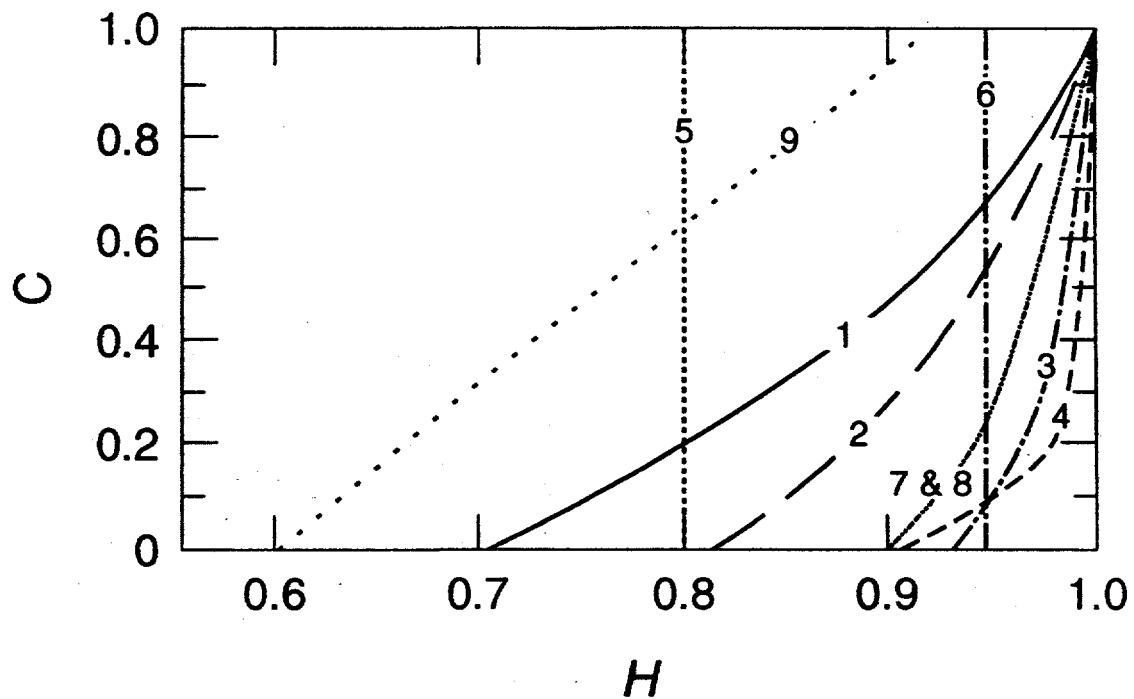
Figure 3—The cloud amount distribution as it depends on relative humidity (δ = 0.9). Curve 1 is ECMWF; curve 2 is DW1, curve 3 is DW1/2, curve 4 is CCC, curve 5 is GFDL, curve 6 is NCAR, curve 7 is UKMO, curve 8 is JMA, and curve 9 is J. Smagorinsky.

Real-Time Validation of the Cloud Scheme in the BMRC NWP Model

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The way in which cloud and its interaction with radiation are parameterized in a model have a strong influence on its climate. This sensitivity is reflected in medium- to long-range forecasts and affects the analysis part of an assimilation cycle via the first guess in data-poor regions. Hence the cloud-radiation parameterization scheme in a model needs to be closely monitored to check that it is producing realistic results and that its performance does not vary dramatically with season or synoptic situation.

There are a number of reasons for implementing a real-time cloud validation scheme for operational weather prediction models. When it is made a part of the operational suite, cloud validation can be achieved without the need for extra model runs, uses the correct synchronous cloud data, and samples all synoptic situations. Also, since model cloud is inherently linked to the hydrological processes of the model, it is an important diagnostic for parameterization errors as they occur. In addition, if a suitable real-time cloud data set is available, it can be used to implement a statistical objective cloud scheme in the model with parameters that are adjusted on a daily basis to force realistic model cloud fields (Rikus, 1993).

The cloud validation scheme implemented at BMRC is basically a "model-to-satellite" scheme (Morcrette, 1991). GMS, GOES, and METEOSAT brightness temperature data are averaged onto the appropriate points of the model physics grid. These are then directly comparable to brightness temperatures calculated from the model's thermodynamic and cloud fields using the infrared window bands of the model's longwave code (Schwarzkopf and Fels, 1991). The advantages of geostationary satellites are that they are available at the standard operational archive times, cover a large area, and require only simple spatial navigation.

To aid in identification of systematic errors in the cloud parameterization, additional "satellite-to-model" diagnostics have been incorporated, including cloud detection based on the infrared part of the ISCCP algorithm, and cloud-height algorithm based on the assumption of blackbody emitting cloud and the model temperature field. In the future the scheme will be extended to incorporate visible data to facilitate improved cloud detection and the validation of the model's shortwave optical properties.

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Clouds and Climate Sensitivity

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The use of fixed-SST (sea surface temperature) anomaly experiments to represent climate change is commonplace. Cess et al. (1990) compared cloud feedbacks from 19 models using fixed SSTs with ± 2-K anomalies and perpetual July forcing, and concluded that whilst all the models showed good agreement in the simulation of the clear-sky sensitivity (λ_C), there was considerable spread in the overall climate sensitivity (λ). This suggests that differences in cloud response to climate change may be the main factor in the range of climate sensitivities produced by contemporary models.

Senior and Mitchell (1993) discuss results from seasonally varying 2 x CO_2 experiments with the UKMO model using four different cloud schemes. Unlike the models in Cess et al. (1990), the values of λ_C show considerable variations, but fall within the range of Cess et al., when the influence of surface albedo changes is removed (Table 1, column 3). The range of overall climate sensitivity in the experiments is 5.2° to 1.9°.

Senior and Mitchell repeated the Cess et al. experiments with three versions of their model. In contrast to the large range of climate sensitivities found in the 2 x CO_2 experiments the value of λ varies very little with the different cloud parameterizations. The version of the model with interactive cloud radiative properties (CWRP) showed little variation in the latitudinal distribution of temperature using an interactive ocean and retains a similar climate sensitivity in the fixed-SST experiments. In the other 2 x CO_2 experiments, the combination of positive albedo feedbacks at high latitudes and negative lapse rate feedbacks in the tropics gives an enhanced high-latitude warming. This enhances the positive cloud feedback in the extratropics, and increases the climate sensitivity above that in the fixed-SST experiments. The use of perpetual July forcing in the fixed-SST experiments minimizes the effect of the considerable reduction in cloud in the Southern Hemisphere, particularly in RH, which again reduces the climate sensitivity in the fixed-SST experiments when compared to the seasonally varying 2 x CO_2 experiments. These and possibly other factors make the use of fixed-SST experiments an unreliable guide to the relative sensitivities of models to changes in CO_2.

Table 1—Comparison of λ and λ_C for Uniform ΔSST and 2 x CO_2 Experiments
(after adjusting for changes in surface albedo)

| Model* | λ | | λ_C | |
	2 x CO_2	Uniform ΔSST	2 x CO_2	Uniform ΔSST
RH	1.29	0.59	0.54	0.50
CW	0.67	0.47	0.48	0.49
CWRP	0.45	0.61	0.46	0.51

*See Senior and Mitchell (1993) for descriptions of model versions.

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Panel 2, Satellite Observations
G. Stephens, Chair

Impact of a New Cloud Optical Parameterization on the Earth's Radiation Balance and Zonal Temperature and Winds

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A new cloud optical parameterization in which the liquid water content, the shortwave and infared optical depth, and cloud emissivity are related to cloud temperature as extracted from the University of Melbourne GCM is presented. The model is used to study the effect of clouds on the Earth's radiation balance and on the zonal temperature and winds.

The January and July simulated longwave and shortwave cloud radiative forcing (LW and SW CRF) at the top of the atmosphere show that the LW CRF is comparable in magnitude with the ERBE results for the equatorial and tropical regions. However, it is slightly overestimated at high latitudes. The SW CRF for all latitudes agrees well with the ERBE ones. Analysis of the results shows that the computed high cloud liquid-water content reaches lowest values towards the poles and that the high cloud emissivity varies from 0.1 to up to 0.9 in tropical regions. A comparison of the simulated LW CRF and SW CRF with other GCMs' computations shows that in general the simulations were enhanced.

An important feature of the new cloud parameterization is the incorporation of variable liquid-water content and cloud emissivity (for the first time in the Melbourne GCM) related to cloud temperatures. The effects of this parameterization on the Melbourne GCM results show that the upper tropical troposphere is warmed and the cooling of the winter hemisphere is reduced. The tropical and winter jets are also considerably reduced. The results show that the liquid-water content and cloud emissivity parameterization enhanced the radiation budget and zonal temperature and wind simulations.

Solar Energy Disposition: Intercomparison between Satellite Estimation, GCM Simulation, and Surface Observation

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The solar energy reaching Earth is reflected to space, and absorbed by the atmosphere and by the surface. This energy disposition is controlled by complex feedback processes in the Earth's climate system. It is therefore one of the most important parameters for testing a global climate model. Owing to recent advances in satellite observation and inversion techniques, knowledge of the disposition of solar energy has improved considerably. This study investigates the differences of solar energy disposition obtained from surface observation, satellite estimation, and GCM simulation.

1. Overall Comparison

Table 1 lists the global annual mean solar energy disposition on (1) worldwide surface radiation measurements from GEBA and empirical computations (Ohmura and Gilgen, 1993); (2) ERBE satellite data using the Li et al. (1993) algorithm (Li and Leighton, 1993); and (3) ISCCP data using the algorithm of Pinker and Laszlo (1992), which is part of the WCRP surface radiation budget (SRB) product (version 1.1). Also listed in Table 1 are the values simulated by three GCMs: CCCII, CCM2, and ECMWF (EC3). Given the averaging domain and the importance of the quantities, the disagreement is surprisingly large. Major disagreement happens to be the separation between the atmosphere and surface absorption. GCM results are systematically larger than those from other sources, with the maximum discrepancy being more than ten times the radiative effect of doubling CO_2.

Table 1—Global annual mean solar energy disposition (W m^{-2})

Sources	GEBA	ERBE	ISCCP	CCC	CCM2	ECMWF
Solar constant	1365*	1365	1365*	1365	1370	1384
Reflected to space	101.2*	101.2	101.2*	111.3	94.3	96.0
Absorbed in atmos.	98.1	83.0	68.9	58.0	67.6	66.0
Absorbed at surface	142.0	157.0	171.2	172.0	180.6	184.0

*According to ERBE

2. Satellite-Surface Comparison

To validate the satellite products, monthly means of surface solar irradiance were compared to GEBA data that were averaged over 280 x 280 km^2

ISCCP C1 grids. The overall bias errors (satellite-surface) are 0.3 and 10.1 W m^{-2} for ERBE SRB and ISCCP SRB, respectively. Their random errors are estimated to be on the order of 5 W m^{-2}. It appears that the difference between GEBA-based and ERBE-based global mean surface absorption is due mainly to the lack of surface observations over large areas where empirical formulae were employed (Ohmura and Gilgen, 1993). The bias error of the ISCCP SRB is consistent with the differences in global annual mean surface-absorbed flux between ERBE SRB and ISCCP SRB. The ISCCP SRB values appear to be systematically overestimated (Li et al., 1994).

3. Satellite-Satellite Comparison

An intercomparison between ERBE- and ISCCP-based SRB products shows large regional differences, in addition to systematic differences. The differences were investigated in terms of discrepancies in both input data and algorithm. It was found that large regional differences are associated mainly with top-of-atmosphere (TOA) flux differences, whereas systematic differences are due to the use of different algorithms. Most of the regional differences between ERBE and ISCCP TOA fluxes are attributed to problems in angular and spectral corrections for ISCCP data. Systematic discrepancies are accounted for by different methods for computing water-vapour absorption. Lacis and Hansen's (1974) scheme was used in Pinker and Laszlo's algorithm, whereas Lowtran 6 (L6) was employed in the development of the Li et al. (1993) algorithm. In comparison to line-by-line (LBL) results, the Lacis and Hansen scheme significantly underestimates water-vapour absorption (Ramaswamy and Freidenreich, 1992), while L6 moderately overestimates absorption (Table 2). If both algorithms use the same water-vapour absorption scheme and the same input data, their global annual means of surface net solar radiation agree to within 1 W m^{-2} (Li, 1994).

Table 2—Solar atmospheric absorption by water vapour only (W m^{-2}) for the middle-latitude summer atmosphere computed by different methods (surface albedo = 0.2). The results of LBL and Lacis and Hansen are taken from Ramaswamy and Freidenreich (1992) and ICRCCM from Fouquart et al. (1991).

SZA	LBL	LH	L5	L6	L7	L7(B)*	CCC	ICRCCM
30°	178.1	162.3	161.0	185.7	191.3	181.1	165.9	167.0
75°	71.4	63.6	59.5	73.3	74.4	69.7	64.4	64.2

*L7(B) represents Lowtran 7 band model, while L7 includes both band and continuum models.

4. Satellite-GCM Comparison

Figure 1 shows zonal-mean comparison between ERBE and CCC GCM II for solar fluxes at the TOA, within the atmosphere, and at the surface for both clear and all skies. Again, the agreement for the TOA is much better than those for the surface and for the atmosphere. Moreover, the disagreement for clear skies is comparable to that for all skies, suggesting that cloud absorption is not the major cause of the differences. The similar magnitudes of the differences for clear skies between atmosphere and surface-absorbed fluxes also rule out the

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major responsibility of surface albedo. Thus it is concluded that clear-sky atmospheric absorption accounts for the large difference. Table 2 shows that, to a large extent, the difference is also attributed to the computation of water-vapour absorption. For comparison, Table 2 also includes the results of L5, L7 (band and band plus continuum), and the median values of the radiative transfer codes participating in the ICRCCM program (Fouquart et al., 1991). The values of Lacis and Hansen, CCC, ICRCCM, and L5 are all significantly less than the LBL results, whereas L7 is much higher. However, the L7 band model is very close to LBL. Note that many of the methods in Table 2 are in use at present. In addition, the difference between the CCC GCM and ERBE SRB is also caused by other factors such as water-vapour amount and aerosol loadings.

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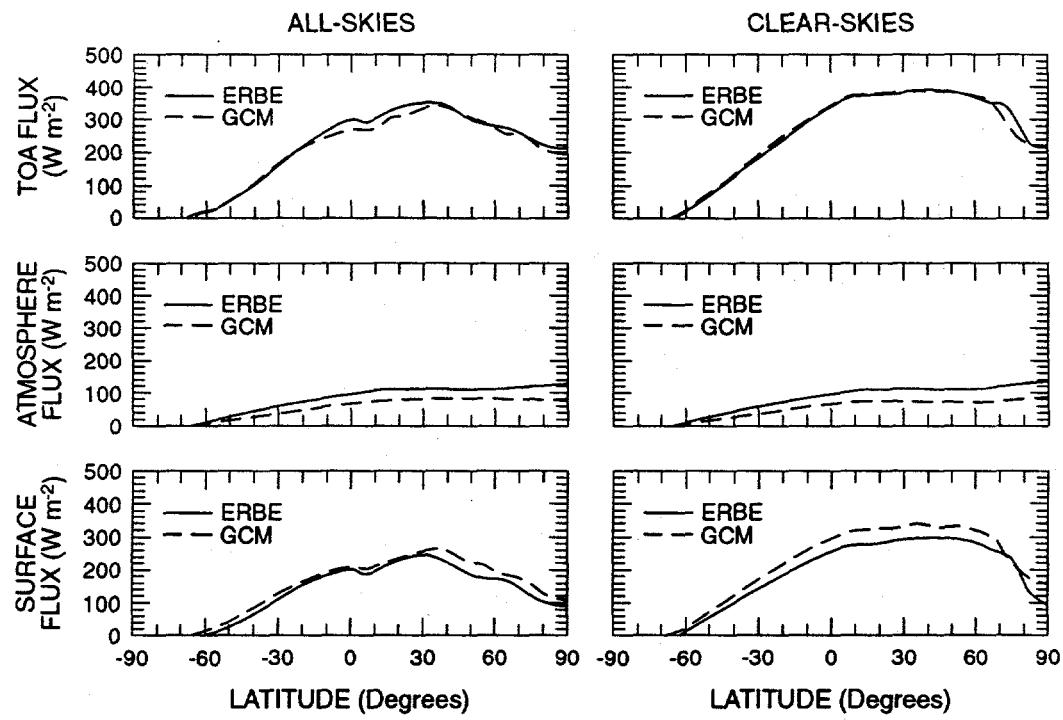
Figure 1—Zonal mean net solar fluxes at TOA, in the atmosphere, and at the surface, obtained from ERBE and a CCC AMIP simulation for July mean (1985-1988).

Satellite Perspective of Ice-Cloud Microphysics and Radiation

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To be properly utilized in climate models, remotely sensed cloud optical properties must be consistent with the physical characteristics of the cloud particles. Cloud-droplet effective radius, a parameter commonly used to represent a characteristic set of optical properties, can be converted to cloud liquid-water path through a simple relationship involving the optical depth of the cloud. Thus, it is a relatively simple matter to convert a given amount of water condensed by the model into a realistic set of optical properties. Conversely, an estimate of cloud effective radius can be derived from satellite measurements and used to determine the amount of water in the observed cloud. Ice clouds, however, are composed of particles that are much more complex than the simple spheres in liquid-water clouds. The conversion from the water frozen in the model to a realistic set of optical properties is not so straightforward. It has been shown that ice spheres are an inadequate representation of the optical properties of cirrus clouds. Simple, ideal, randomly oriented hexagonal ice columns yield a much better quantification of the optical properties of cirrus clouds (Minnis et al., 1993). This paper examines how consistent the physical properties of those idealized ice crystals are with those of real cirrus clouds. It begins the effort to determine how much we can simplify the complex microphysics of cirrus clouds while maintaining consistency between the amount of frozen water and the optical properties.

The ice-water path, IWP, can be related to optical depth for a given cloud by

$$\text{IWP} = \frac{P_i V \tau}{QA}$$

where V is the crystal volume, A is the effective cross-sectional area for randomly oriented crystals, P_i is the density of ice, Q is the extinction efficiency, and the optical depth is τ. For simplicity, V may be expressed in terms of $D\varepsilon$, the effective diameter, which is computed from the volume assuming a sphere. This relationship is shown in Figure 1 for three randomly oriented hexagonal ice column distributions (Takano and Liou, 1989), where C20 is the smallest ice crystal, with effective size increasing from the cirrostratus (CS) distribution to the cirrus uncinus (CU) distribution. The scattered points in Figure 1 correspond to matched IWP and τ data taken over Coffeyville, Kansas, during the November 1991 FIRE field program. The IWP results are based on surface radar measurements (Matrosov et al., 1992), while the optical depths were derived from GOES visible and infrared data using the method of Minnis et al. (1993) with a CS optical model. The observations show a relatively good correlation between the two variables but are slightly askew to the theoretical lines. Some of the slope differences can be attributed to the use of the CS model to derive τ for all cases. The C20 model would shift the points to the left while the CU model

would shift the data to the right. Nevertheless, there appears to be good potential for matching the optical and physical properties with the satellite data.

Figure 2 shows a comparison of $D\varepsilon$ derived using the surface radar (Matrosov et al., 1992) and a three-channel analysis of AVHRR data (Young et al., 1994) over Coffeyville during 28 November 1991. The histogram shows the 1-minute frequency of occurrence of $D\varepsilon$ derived from the radar for a half-hour period compared to the average $D\varepsilon$ for each 1-km pixel for an area including the cloud that passed over Coffeyville 2 h earlier. Despite the large time separation, the satellite and surface results are in excellent agreement. A similar analysis corresponding to each half hour between 1830 and 2130 UTC also shows good agreement in the mean values of $D\varepsilon$ which increased steadily during the time interval.
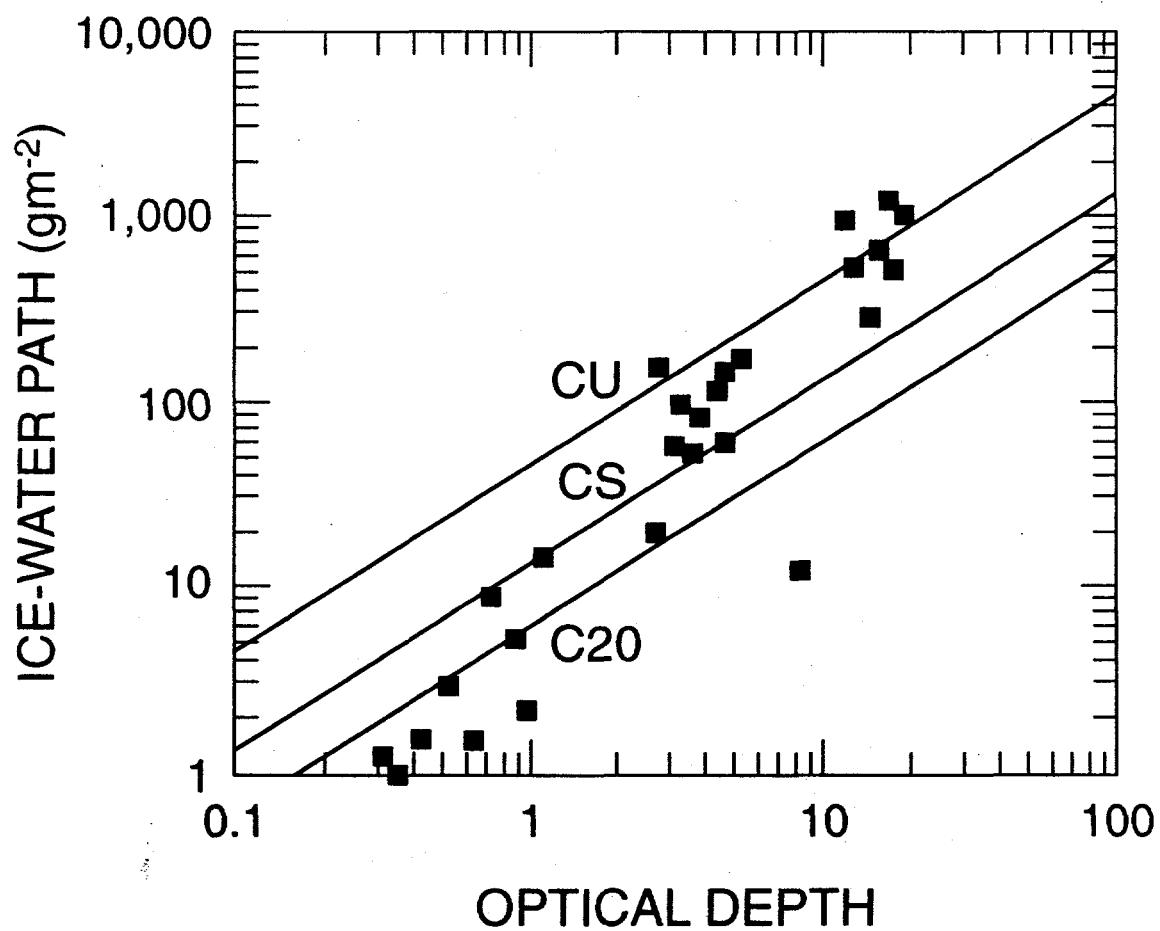

Figure 1—Comparison of FIRE II, radar-derived IWP and GOES-derived optical depth with theoretical calculations (lines) for three ice-crystal sizes.
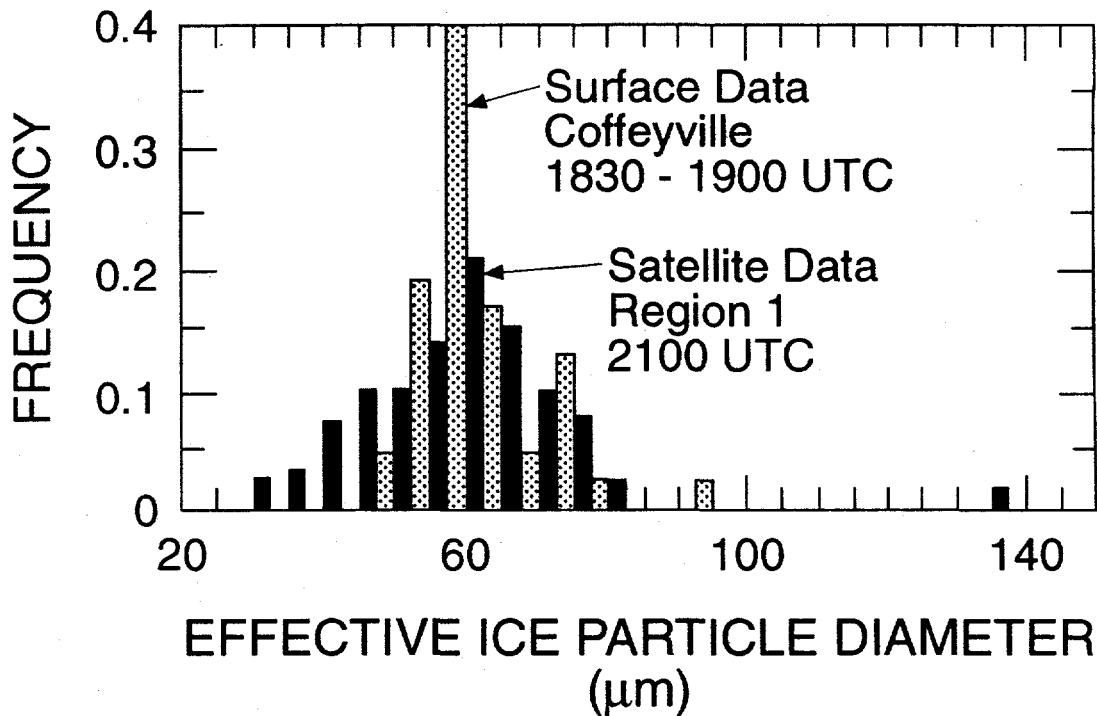
Figure 2—Comparison of surface-radar-derived and AVHRR-derived cirrus cloud-particle sizes during FIRE II, 28 November 1991. Region 1 corresponds to Coffeyville at 1845 UTC.

These initial results indicate that it may be possible to use simplified representations of complex ice crystals to model both the ice content and radiation in cirrus clouds. Much more research needs to be performed, however, to confirm these early observations and to develop a robust method for including such satellite retrievals in operational algorithms. Such efforts will require additional theoretical modeling as well as extensive field programs that include in-situ measurements in various climatic regimes. There will also be a need for considerable interaction between cloud modelers and remote-sensing researchers.

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Studies of Precipitating Layer Clouds in Australia

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CSIRO Division of Atmospheric Research, Australia

Over the last 25 years in Australia, there has been a great deal of fragmented research into the dynamical and microphysical structure of mid-latitude precipitating clouds. For example, in the 1970s, Mossop and his co-workers at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Cloud Physics made a detailed study of ice crystals in cumulus, stratocumulus, and altostratus clouds (see, e.g., Mossop et al., 1972; Mossop, 1985).

There have been three major cloud seeding experiments where detailed microphysical measurements have been made. These cloud seeding programs were conducted by CSIRO in Tasmania (1964- 1971), in the Wimmera region of western Victoria (1979-1980), and by Melbourne Water in the catchment area for the Thomson River (1988-1992). In the case of the Wimmera (1979-1980) and Thomson River (AWSE I, 1988, and AWSE II, 1990), CSIRO made an extensive investigation of the clouds using the CSIRO Fokker F-27 research aircraft.

The thermodynamic and dynamic structure of summertime cold fronts was investigated during the Australian Cold Fronts Research Program, 1980, 1981, and 1984 (see, e.g., Ryan et al., 1985, and Reeder and Smith, 1992). Studies of the structure of wintertime cold fronts have also been made by May et al. (1991) and as part of AWSE (Long, 1993; Long and Huggins, 1992).

Platt and his co-workers at the CSIRO Division of Atmospheric Research have studied the radiative characteristics of precipitating layer clouds using mostly ground-based lidar and satellite techniques.

The aim of this paper is to synthesize the structure and microphysical properties of precipitating layer clouds in the Australian region using reports from these different studies. In some cases where data was not available, I have consulted with meteorologists from the Bureau of Meteorology and with scientists who participated in the various cloud seeding operations.

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Current Activities in Cloud-Radiation Research in Australia

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I would like to report briefly on several current Australian activities involved with clouds and cloud-radiation interactions.

The three identified activities are SOCEX, ECLIPS, and the U.S. Department of Energy (DOE) ARM program—or more specifically the ARM PROBE in TOGA COARE. These three activities are discussed briefly below.

1. SOCEX

The aim of SOCEX is to investigate the dependence of the solar albedo of marine stratocumulus clouds in the southern ocean on droplet size and concentration. The latter are influenced by the local concentration of cloud condensation nuclei (CCN), which over the clean southern ocean in "base-line" conditions, depend on the emission of dimethylsulfide (DMS) from the ocean. The amount of DMS has a pronounced seasonal variation from minimum in mid-winter to maximum in mid-summer, with a corresponding cycle in the CCN, as observed at the Cape Grim Baseline Air Pollution Station in northwest Tasmania, for a number of years.

SOCEX aims to measure every component in the cycle, from DMS and CCN at the Baseline Station to CCN, droplet spectra, and albedo from an F-27 aircraft. There are also ground-based facilities at the Baseline Station measuring liquid- water and water-vapour columns and cloud-base height, extinction, and emittance.

There will be two phases, July 1993 and January 1985, operating off the northwest coast of Tasmania. Scientists involved from the Commonwealth Scientific and Industrial Research Organisation (CSIRO) Division of Atmospheric Research (DAR) are Jorgen Jensen, Reinout Boers, John Gras, Brian Ryan, Martin Platt, and Stuart Young. There are also scientists collaborating from the U.S. Desert Research Institute, U.S. National Center for Atmospheric Research, Colorado State University, and New Zealand.

2. ECLIPS

The aims of ECLIPS are:
- To demonstrate the feasibility of obtaining a long-term climatology of cloud-base height and cloud optical properties with ground-based lidar, and to formulate a plan of long-term measurement.

- To improve methods of retrieval of cloud data from satellites by comparison of satellite and lidar data.

- To improve the prediction of the surface energy balance from satellite data.

- To obtain a data set of cloud optical properties which would be complementary to the ISCCP data set.

ECLIPS involves about a dozen laboratories globally measuring the following quantities:

Required:
- Lidar characteristics and ancillary site data
- Cloud type and amount
- Cloud-base height
- Cloud depth
- Lidar calibration constant
- Downward infrared flux irradiance
- Surface pressure, temperature, relative humidity.

Desirable:
- Cloud effective extinction coefficient
- Depolarisation ratio
- Cloud emittance
- Rawinsonde data
- Cloud velocity vector.

Optional:
- Downward shortwave flux.

Two observational phases of ECLIPS have been successfully held, in the periods October-December 1989 and April-July 1991. Data sets are being archived at the U.S. National Aeronautics and Space Administration (NASA) Langley Research Center, and data in the archive are available now from:

ECLIPS Data Manager, Aerosol Research Branch M/S 475
NASA Langley Research Center, Hampton, Virginia 23665-5225 USA

Several workshops have been held since 1988, the most recent (5th) being at the Optical Society of America Meeting, Salt Lake City, Utah, U.S.A., March 1993.

There will be a Phase III experiment in 1994, possibly in combination with the LITE Space Shuttle flights.

A general article on ECLIPS, with some example results, has been accepted by the *Bulletin of the American Meteorological Society*. Further details are available from C.M.R. Platt. We welcome additional participation in Phase III, not excluding satellite meteorologists, as the data are taken around the time of AVHRR overflights, thus providing excellent cloud validation data, particularly for ISCCP validations.

The measured surface fluxes, when taken together with the cloud height, extinction, and infrared absorption, provide excellent data sets for the Baseline

Surface Radiation Network. It is anticipated also that ECLIPS data will be useful for the planning and analysis of the U.S. DOE ARM project and for the GCSS, and ECLIPS would like to forge closer links with all the above activities.

Long-term monitoring of clouds by ECLIPS should now be seriously considered.

3. ARM PROBE

CSIRO DAR took part in the PROBE experiment which was a pilot experiment for ARM, to gain some initial data sets, and to gain experience in the operation of observational sites under tropical maritime conditions.

DAR made lidar/radiometer observations of tropical cirrus and mid-level clouds. U.S. scientists made observations of integrated liquid water and water-vapour paths, radiosonde data, infrared interferometric spectra, surface fluxes, and cloud base and structure. The DAR observations covered three weeks, with a much longer series of observations of other quantities.

Preliminary analysis shows the ubiquitous nature of cirrus clouds over Kavieng. Some of these clouds were not related directly to thunderstorms, although there was outflow of cirrostratus from larger disturbances. Some cirrus persisted for several days, thickening during the daylight hours. At times it was over 6 km deep.

4. Other Activities

(1)   CSIRO DAR is involved with the NASA LITE to fly on shuttle in mid-1994, particularly in the detection of clouds.

(2)   Scientists at DAR are studying the application of the ATSR on ERS-1 to the global measurement of cirrus height and optical depth, using the radiometer's unique scanning qualities to obtain two viewing slant paths through the same volume of cirrus.

Panel 3, Process Studies
H. Sundqvist, Cochair
D. Starr, Cochair
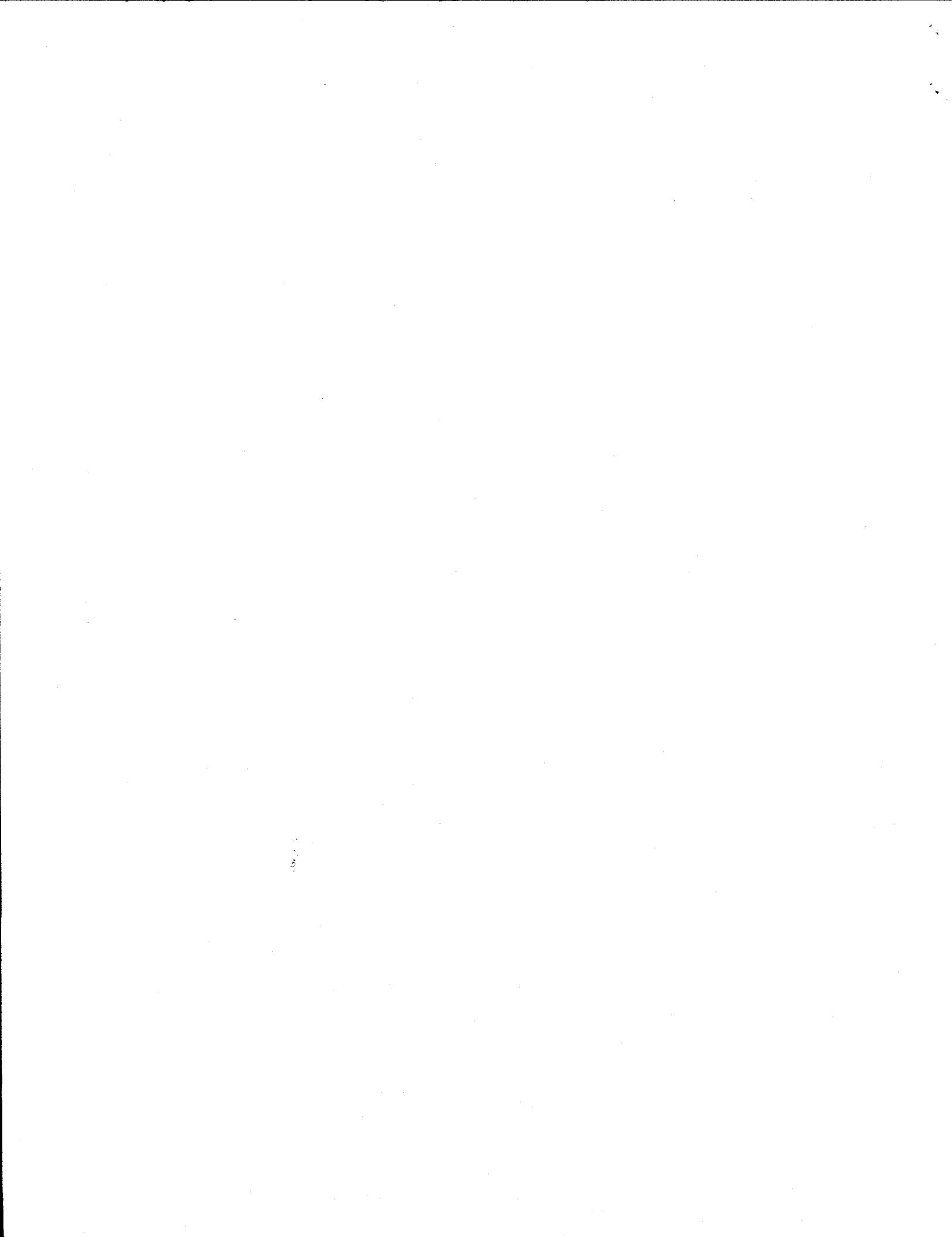
Progress Review, Process Studies

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Process studies performed since the 1978 Oxford Cloud-Radiation Workshop have provided many new remote and in-situ measurement systems to obtain a better understanding of cloud-climate-radiation interactions. Many of these systems were deployed from the ground and/or aircraft. High-resolution lidar systems have enabled us to observe structure of clouds on scales as small as a few meters. Deployment of Raman lidar has enabled us to observe high-resolution temperature and water-vapor structures which are precursors to actual cloud formation. Millimeter cloud radars have been employed to observe cloud base, height, and microphysical structures; a Dopplerized version of the millimeter cloud radar has been developed and applied to observe cloud-scale velocity patterns. Infrared interferometry with spectral resolution ≤ 1 cm^{-1} in the spectral band 5 to 20 μm has been applied to infer emittance properties of cloud systems and to infer lower-troposphere temperatures.

A number of remote-sensing applications spawned by cloud radiation process studies have been applied both from the Earth's surface and from satellites. Passive microwave radiometry has been refined and applied to the continuous observation of total liquid water. Water-vapor overburden has similarly been inferred from ground-based applications of microwave radiometry. Process studies also spawned a variety of remote-sensing applications from passive solar and infrared observations to infer droplet/particle size distribution properties of clouds; these have been applied both from the surface and from satellites.

Observations of the dynamic structure of cloud layers were first performed by wind profilers during process-study campaigns in the past decade. These systems provided high-temporal-resolution wind structure in both the lower and upper troposphere; the successful development and application of RASS also enabled the continuous monitoring of lower-tropospheric temperature profiles.

Since the 1978 Oxford workshop, process experiments have produced a number of high-precision, broad-band, and spectral radiometers, cloud-particle replicators, video cloud-particle imagers, and a cryogenic frost-point device to measure upper-tropospheric moisture. A unique balloon-borne replicator was also developed specifically to support investigations of cirrus cloud-particle size and shape.

Another extremely significant accomplishment of process studies has been to support the evolution and verification of cloud-field-property remote sensing performed during ISCCP. Significant improvements in ISCCP algorithms and evaluation of confidence limits of ISCCP data have been provided by process-study campaigns and investigations.

In summary, process studies of the past decade have produced a large number of innovative instruments and techniques which have greatly improved our present knowledge of cloud-climate-radiation interactions and will continue to provide additional insights in decades ahead.

Process-Study Remote/In-Situ Sensing Innovations

Instrument/Technique	Platform	Variable
ISCCP	Satellite	Cloud properties algorithm verification
High-resolution lidar	Surface, aircraft	Structure, optical, properties, cloud boundaries
Raman lidar	Surface	Water vapor, temperature
Passive microwave	Surface, satellite	Water vapor, liquid water
Interferometry	Surface, aircraft	Infrared spectra, cloud properties
Millimeter radar	Surface	Cloud structure, microphysics, dynamics
Passive limited-band solar	Surface, aircraft, satellite	Cloud properties, microphysics
Passive limited-band infrared	Surface, aircraft, satellite	Cloud properties, microphysics
Wind profiler/RASS	Surface	Vertical and horizontal winds, temperature
Cloud-particle replicator	Aircraft, Balloon	Cloud microphysics
Cryogenic frost point	Aircraft	Water vapor
Cloud-particle Video imager	Aircraft	Cloud microphysics

Cloud-Radiation Process Investigations/Campaigns Conducted
Since Oxford Cloud-Radiation Workshop of 1978

Program	Host	Objective
FIRE I	USA	Cirrus
FIRE I	USA	Marine stratus
Zvenigorod	Russia	All clouds
ICE	European community	Cirrus
FIRE II	USA	Cirrus
ASTEX	USA	Marine stratus

A Comprehensive Two-Stream Radiation Code

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It is convenient to be able to use a single radiation code for a variety of radiative calculations, ranging from studies of atmospheric processes and simulations of observations to climate modelling in a GCM. We have therefore developed a new radiation code suitable for use in a number of different applications.

The code is based on two-stream approximations in both the visible and the infrared parts of the spectrum. Complete freedom in the division of the spectrum into bands is permitted, and spectral data for a chosen set of bands are generated from a preprocessing package. Within any particular band gaseous transmissions are represented by exponential sum-fitting techniques (ESFT). Continuum absorption is treated as a grey process. The optical properties of ice and water clouds are determined separately, and the overlapping of different layers of cloud may be treated in a variety of ways. Provision has been made for the calculation of the radiative effects of aerosols.

The code has been used to simulate observations from aircraft, and further such studies are planned. For use in the GCM of the U.K. Meteorological Office work is currently in hand to produce a spectrum containing as few ESFT terms as possible whilst still retaining acceptable accuracy. Figure 1 shows an example of the accuracy which may be obtained from a fairly small number of terms.
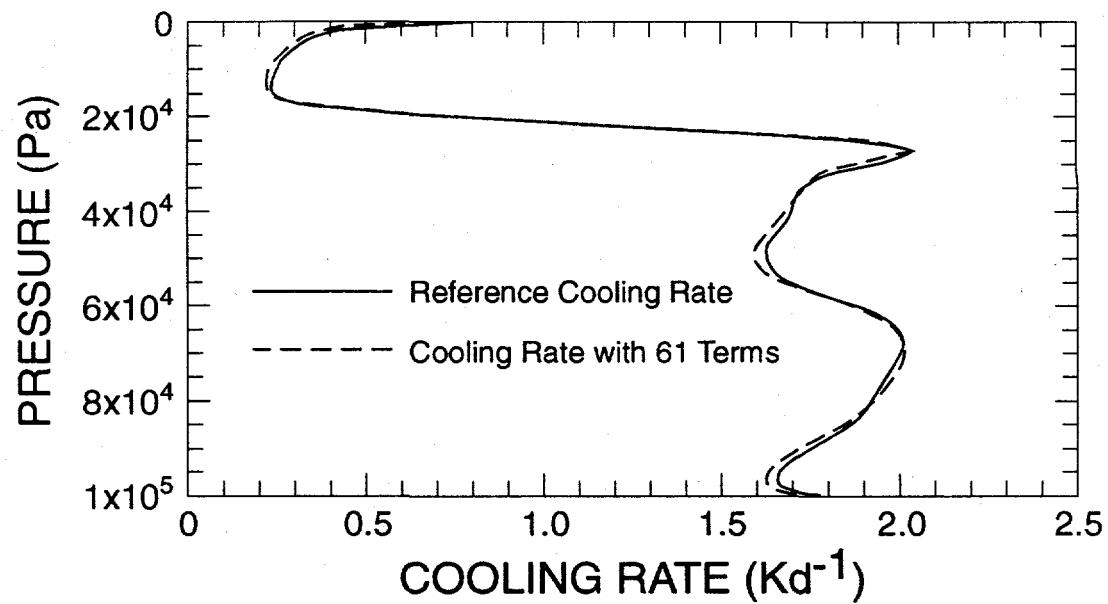
Figure 1—The cooling rate in a mid-latitude summer atmosphere as calculated by the radiation code at a high spectral resolution and as calculated using 61 ESFT terms distributed among 9 bands. Only absorption by lines of water vapour is included in the calculation.

Interaction of Clouds and Radiation

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Our work is being carried out in two directions: The first is fulfillment of special experiments mostly at the Zvenigorod Scientific Station (ZSS) of IAPh. These systematic experiments from 1986 to 1990 were devoted to the investigation of cirrus clouds, according to WCRP. The main participants were: IAPh, the Central Aerological Observatory, and Moscow State University.

The main ideas:

(1)   To obtain information on cloud amounts and their microphysical and optical parameters, mostly by measurements of the integral and spectral radiation coming to the surface. Development and utilization of the corresponding radiative transport theory, solving retrieval problems. Such an approach has advantages:

   (a)   Possibility of continuous measurements at one point of sky per hour (in contrast with satellite).

   (b)   Not disturbing the cloud media (in contrast with aircraft).

(2)   To connect optical cloud properties with thermodynamics to get parameterizations for numerical climate models. For example, we got dependencies of extinction coefficients and optical thicknesses of cirrus clouds on temperature. All results concerning cirrus clouds are published in Atmospheric Science Papers 456 and 516 of the Department of Atmospheric Science at Colorado State University. (We are grateful to Prof. Stephen K. Cox for giving us such an opportunity). Izvestia Academy of Science, Russia, *Atmospheric and Oceanic Physics* (1991, Vol. 27, No. 9), also published these results (English edition, April 1992).

The first experiment on different cloud forms was conducted in September of 1992 at ZSS. The main ideology is the same, but the experimental base is much wider: detailed spectral measurements, actinometry, and determination of liquid-water path. Data from the satellite NOAA-11, instrument AVHRR, were used. The whole results are now published in the same journal of the Izvestia Academy of Science, Russia (1994, Vol. 30, No. 2).

Here I will give a few examples:

Table 1—Comparison of Visual and Satellite Cloud Forms and Amounts

Numerator: Total amount
Denominator: Lower-level cloud amount
Time: 17 hours of local time when the satellite is above ZSS

Date	Visual	Satellite
31/08/92	3/2 Cu.Ac.Ci.	2 Ac
15/09/92	7/4 Cu.Ac. Ci.	5 Cu
22/09/92	4/4 Cu.Cu.Fr.	5 Cu

Table 2—Comparison of Ground Visual and Instrument-Derived Cloud Amounts

Day	Time	Visual	Instrumental
9/09/92	15.3	0.8	0.88
	16.0	0.9	0.95
18/09/92	11.0	0.9	0.88
15/09/92	11.0	0.4	0.49
	11.5	0.4	0.24
	13.0	0.5	0.63
	15.0	0.6	0.70

The ground instrumental cloud-amount evaluation is based on measurements of the sky brightness in zenith I_λ at wavelengths 0.37 μm and 0.74 μm. In case of clear sky $I_{0.74} < I_{0.37}$; at cloud $I_{0.74} \approx I_{0.37}$.

The other direction of our work is the analysis of the totality of data obtained for many decades at the network of actinometry stations of the former Union of Soviet Socialist Republics (USSR).

The center of these data is the Main Geophysical Observatory—a participant of our mutual work. Some examples of the results obtained:

(1)   Linear dependence of radiative fluxes on cloud amount is supposed as a rule in numerical climate models. It is not real as different data show. (See Figures 1 and 2.) Here, $C_Q = Q_{cloud} / Q_{clear}$. Using this relation, we diminish the dependence of the total solar radiation - Q on the zenith angle of the sun and aerosol extinction.

(2)   From 30 years of data of the actinometry stations, there is a negative trend of total solar radiation coming to surface almost on the whole territory of the former USSR (excluding polar stations). As the corresponding direct solar beam also diminished and the scattered radiation only partially increased, we may suppose that the main reason of the total solar trend is mostly the pollution of the atmosphere by gases and aerosol and only in some cases the increasing of the clouds.

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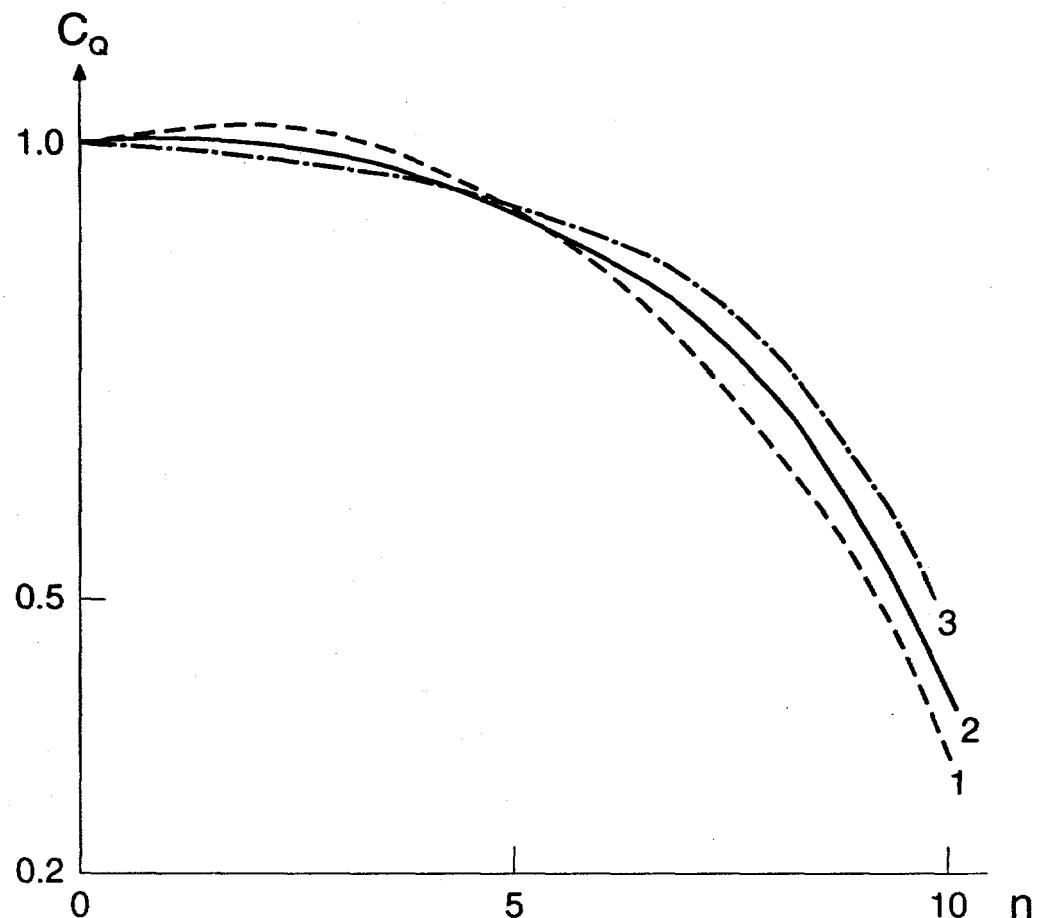
Figure 1—C_Q as a function of cloud amount n. Mean data for many years of measurements on the surface of oceans (Girdjuk et al., 1992). Curves 1, 2, and 3 are for different solar height angles, h, at noon. In curve 1, $h = 20°$; in curve 2, $h = 50°$; and in curve 3, $h = 80°$.
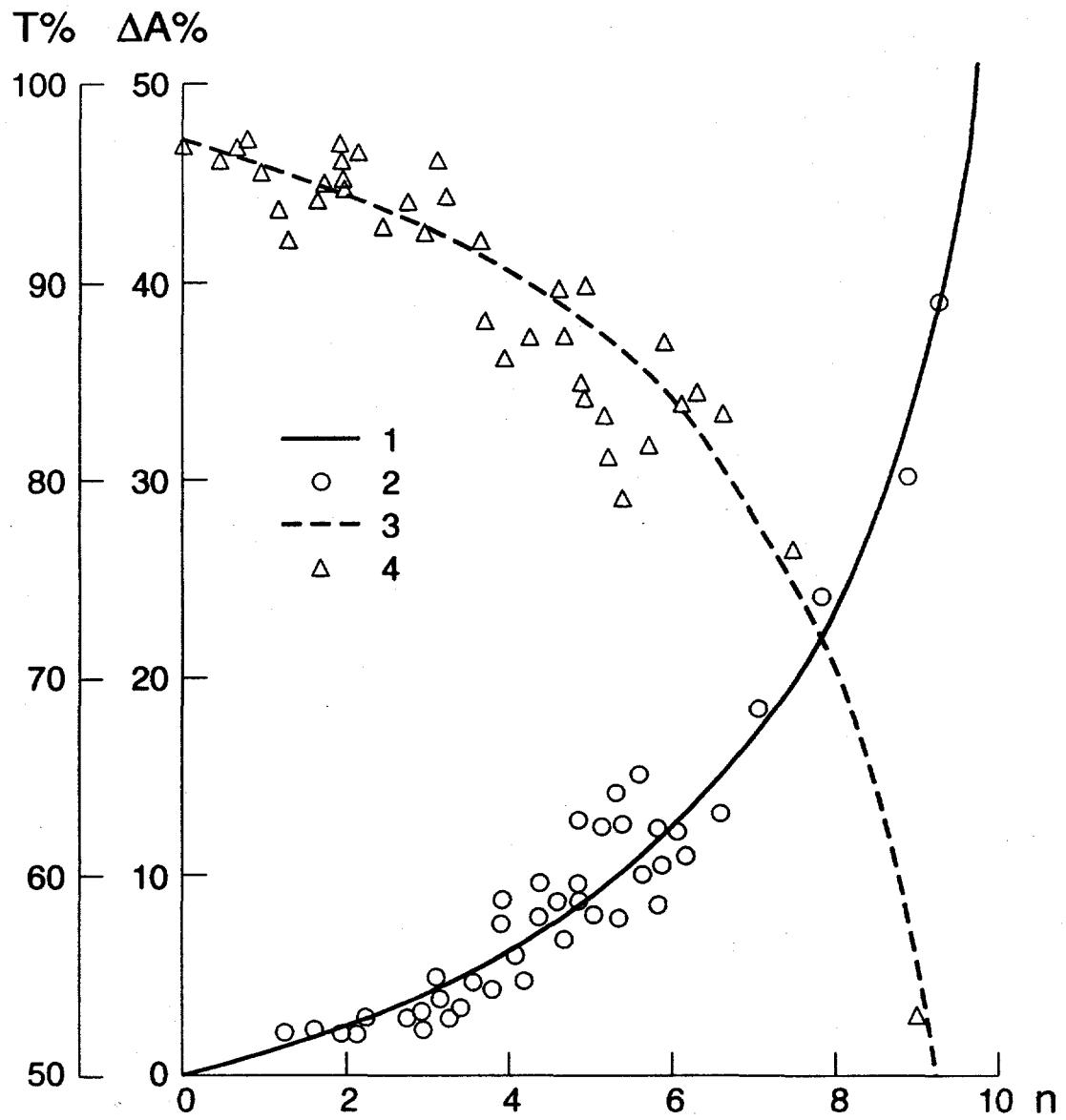
Figure 2—Cumulus cloud fields taken by two aircraft above and under the field (Feigelson and Krasnokutskaya, 1978). A is albedo and T is transparency. In clear skies $A(0)$ is the same as $T(0)$. The solid curve (1 in legend) shows $\Delta A(n)$ calculated by equation (1) below. The circles (2) show $\Delta A(n)$ as measured. The dashed curve (3) shows $T(n)$ calculated by equation (2) below. The triangles (4) show $T(n)$ as measured.

$$\Delta A(n) \% = A(n) \% - A(0) \% = n/(1.03 - 0.082n) \tag{1}$$

$$T(n) \% = T(0) \% - n/(1 - 0.080n) \tag{2}$$

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Parameterization of the Shortwave Properties of Broken Cloud Fields

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It is necessary, in climate models, to parameterize the radiative effects of fields of broken clouds which exhibit considerable variability on a horizontal scale of a few kilometers, in terms of the grid mean cloud water content, and possibly some measures of fractional cloud cover and cloud-droplet size. It is possible to estimate shortwave properties of a broken cloud field, if the in-cloud properties are known and assumed to be the same in all clouds, by averaging the properties of a uniform cloud layer and of the clear air according to the fractional cloud cover. Such an approach has many limitations arising from cloud shadowing effects, nonuniformity of the clouds, and irregularities in the top of the cloud layer.

A Monte Carlo radiative transfer model has been used to investigate the problem. It is shown that, when a broken cloud layer is approximated by a uniform layer broken into a series of identical hexagonal clouds separated by clear gaps, the reflectance of the cloud layer is significantly different from that which would be obtained from the area-weighted average reflectance of uniform cloudy and clear regions. The reflectance is reduced for small solar zenith angles, due to the channelling of radiation through the gaps between the clouds, while it is increased at large solar zenith angles due to shadowing effects. The channelling is related to the absolute width of the gaps between clouds, while shadowing is related to the ratio of the gap to the cloud depth. Although these results indicate the magnitude of the problem, they cannot be used to derive parameterizations because they neglect differences between the clouds and the irregularities in the cloud shapes.

A similar model is being used to study reflection by more realistic modelled clouds. A three-dimensional field of cloud liquid water has been obtained at one time step from a large-eddy simulation of the cloud-capped boundary layer. Since the model uses a bulk microphysical parameterization, the liquid-water content has been used to derive an estimate of the three-dimensional field of droplet effective radius assuming constant droplet concentration and ratio of effective to mean volume radius. The resulting fields were used as input to the Monte Carlo model, assuming periodic boundary conditions at the edges of the domain, and the reflectance of the cloud layer was calculated. The reflectance is compared with that expected for a uniform cloud layer having the domain average cloud water profile. Preliminary results show that the uniform layer approximation results in a reflectance which is significantly lower than that of the broken cloud although the ratio of the reflectances is sensitive to solar zenith angle (Figure 1).

It is planned to repeat the calculations for other time steps from the cloud simulation, and hence to obtain average reflectances over a typical time scale for the evolution of the individual boundary-layer clouds. It is also planned to

make use of results from large-eddy simulations with explicit microphysics in order to relax the simplifying assumptions made in the present calculations.
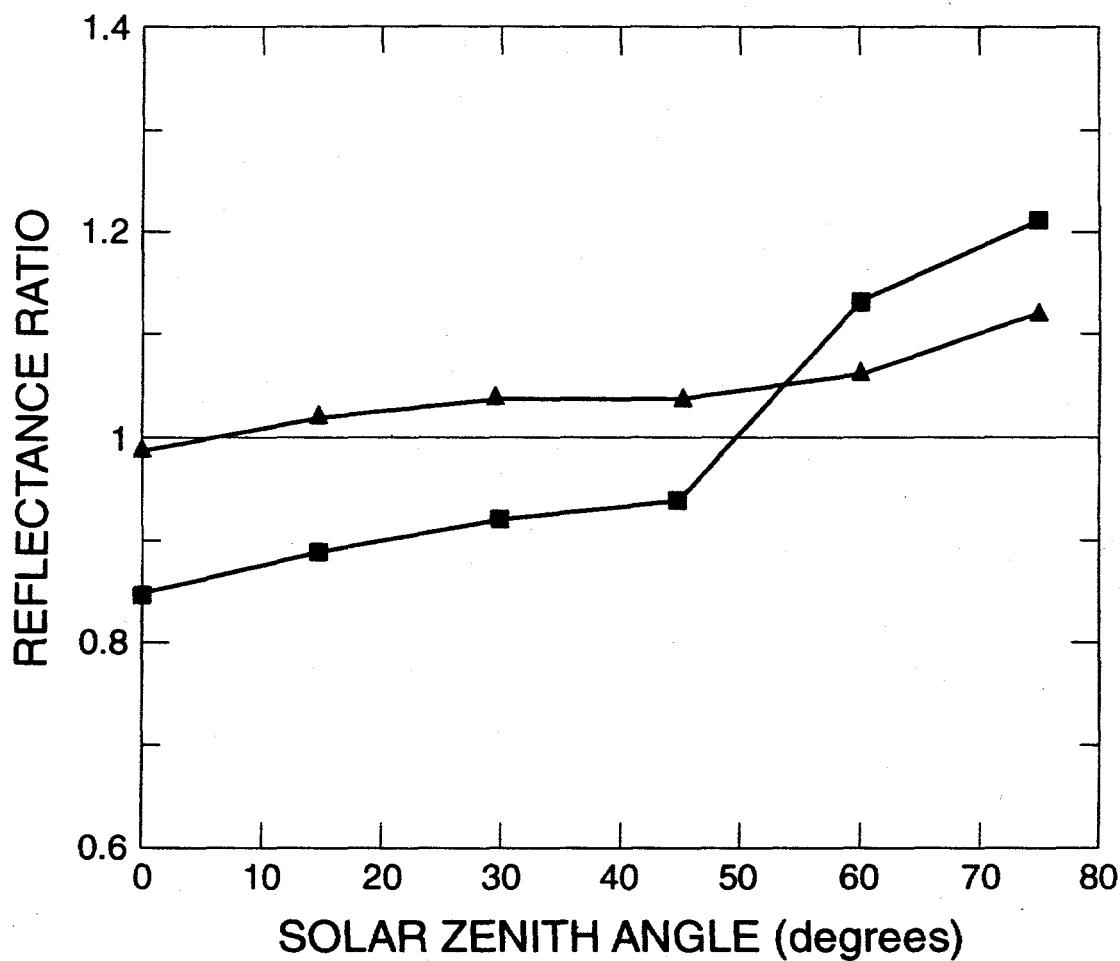
Figure 1—The ratio of the reflectance of a cumulus cloud layer, at 0.45 μm to that calculated assuming an area-weighted average of the reflectances of a uniform cloudy layer and of clean air. The curve denoted by triangles is obtained assuming uniform, interlocking, hexagonal cellular clouds of radius 2.4 km, separated by gaps of thickness 400 m, and with a coverage of 65%. That denoted by squares is for a cloud field obtained from a large-eddy simulation, with a maximum coverage of 45%.

Parameterization of the Radiative Properties of Cirrus Clouds: Problems and Some Solutions

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Problems with the parameterization of the broad-band radiative properties of ice- crystal clouds are presented. These include accounting for (1) the ice-crystal size distribution in terms of mean effective ice-crystal size and ice-water content, (2) the scattering and absorption properties of the irregular ice-crystal shapes such as hollow columns and bullet rosettes, and (3) the vertical and horizontal inhomogeneity of cirrus cloud bands. With respect to items (1) and (2), considerable progress has been made and research in these areas is currently ongoing.

It is shown that a proper incorporation of the single-scattering properties of nonspherical ice-crystals is critical to the interpretation of the solar albedo of cirrus clouds. Moreover, we also point out that establishing a reliable relationship between ice-crystal size distribution and temperature is fundamental in the investigation of feedbacks among cirrus microphysics, radiative transfer, and climate temperature perturbations. Better representation of ice-crystal size distribution as a function of temperature as well as other parameters is required to understand cloud-radiation-climate feedbacks. The effects of small ice crystals (less than about 20 μm, which are often missed by optical probes) on radiative properties of cirrus clouds must be carefully examined, as are the potential effects of vertically and horizontally inhomogeneous cirrus clouds on solar albedo and infrared emissivity. Understanding ice microphysics-radiation interactions in climate and mesoscale cloud simulations, and narrowing down the uncertainties in these interactions require fundamental information concerning the ice-crystal size distribution data as a function of atmospheric parameters and involving their scattering and radiative properties.

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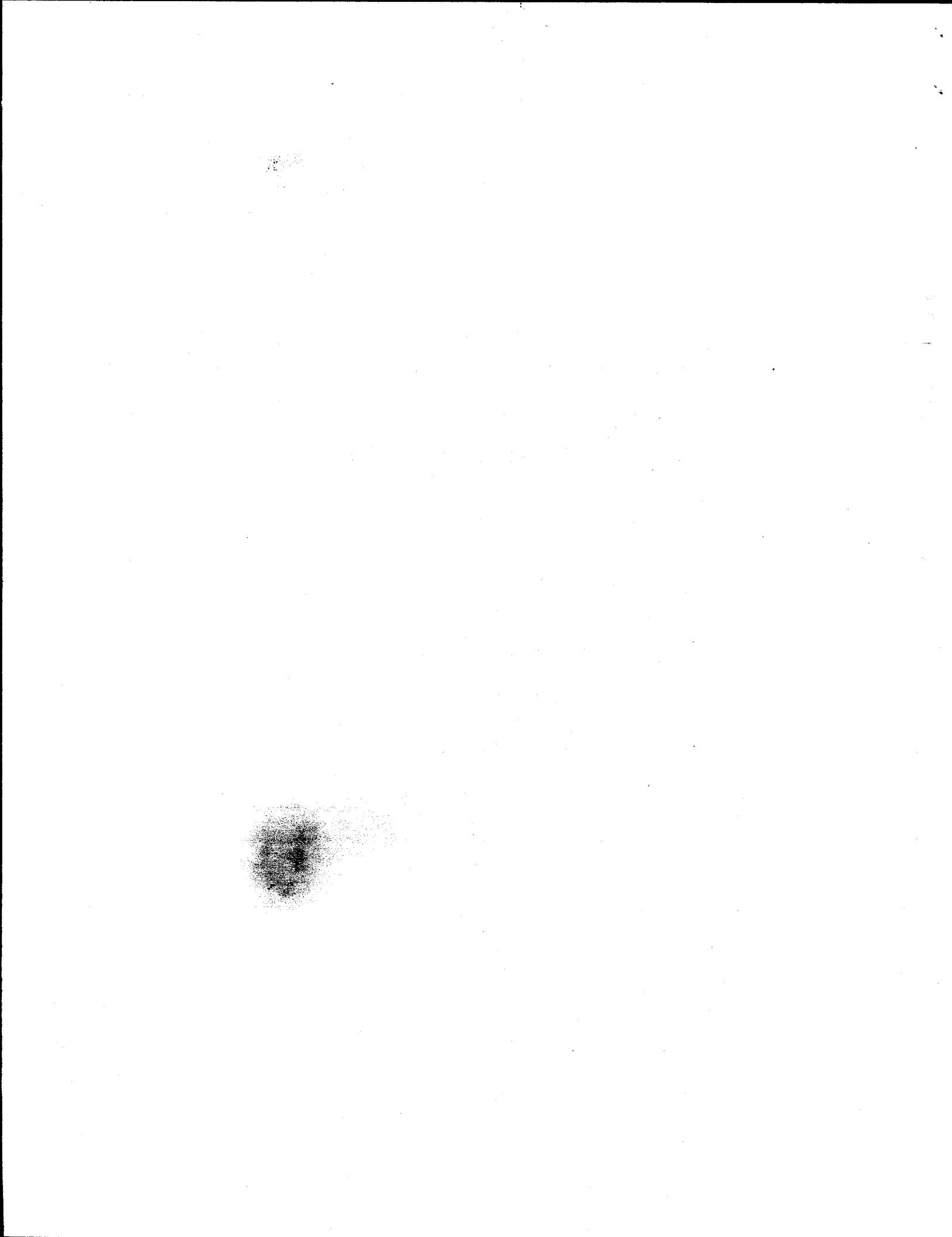
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4. ACRONYMS
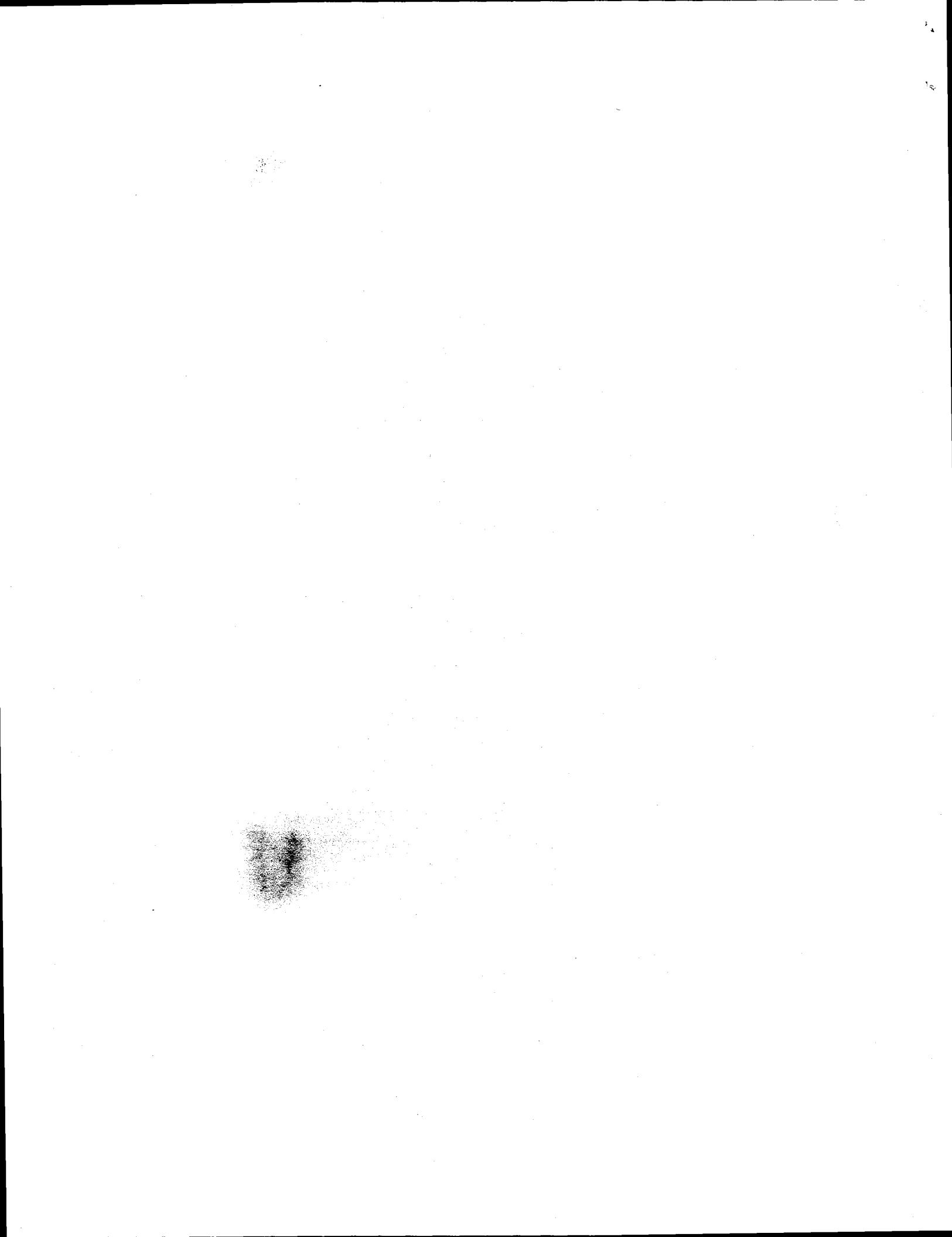
AIRS	Atmospheric Infrared Sounder
AMIP	Atmospheric Model Intercomparison Program
AMS	American Meteorological Society
AMSR	Advanced Microwave Scanning Radiometer
ARM	Atmospheric Radiation Measurement (of U.S. DOE)
ASTEX	Atlantic Stratocumulus Transition Experiment
ATSR	Along-Track Scanning Radiometer
AVHRR	Advanced Very-High-Resolution Radiometer (of U.S. NOAA)
AWSE	Australian Winter Storms Experiment
BMRC	Bureau of Meteorology Research Centre (Australia)
CCC	Canadian Climate Centre
CCM	Community Climate Model (of NCAR)
CCN	cloud condensation nuclei
CERES	Clouds and the Earth's Radiant Energy System
COARE	Coupled Ocean-Atmosphere Response Experiment (of TOGA)
CRF	cloud radiative forcing
CS	cirrostratus
CSIRO	Commonwealth Scientific and Industrial Research Organisation (Australia)
CSU	Colorado State University (U.S.A.)
CU	cirrus uncinus
DAR	Division of Atmospheric Research (CSIRO, Australia)
DMS	dimethylsulfide
DOE	Department of Energy (U.S.)
DWD	Deutscher Wetterdienst
ECLIPS	Experimental Cloud Lidar Pilot Study
ECMWF	European Centre for Medium-Range Weather Forecasts (U.K.)
EOS	Earth Observing System
EOS-AM	EOS AM Platform (10:30 a.m. sun-synchronous orbit)
EOS-PM	EOS PM Platform (1:30 p.m. sun-sychronous orbit)
EOSP	Earth Observing Scanning Polarimeter
ERBE	Earth Radiation Budget Experiment
ERS	ESA Remote-Sensing Satellite
ESA	European Space Agency
ESFT	exponential sum-fitting technique
FANGIO	Feedback Analysis and Intercomparison for GCMs and Observation
FIRE	First ISCCP Regional Experiment
GARP	Global Atmospheric Research Program
GCM	general circulation model
GCRP	Global Change Research Program
GCSS	GEWEX Cloud-System Study
GEBA	Global Energy Balance Archive
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory (U.S.)

GLAS	Geoscience Laser Altimeter System
GLI	Global Imager
GMS	Geostationary Meteorological Satellite (of Japan)
GOES	Geostationary Operational Environmental Satellite (U.S.)
HIRS	High-Resolution Infrared Radiation Sounder
IAMAS	International Association of Meteorology and Atmospheric Sciences
ICE	Intercomparison Experiment
ICRCCM	Intercomparison of Radiation Codes in Climate Models
IFO	Intensive Field Observation (of FIRE)
IMG	Interferometric Monitor
IPCC	Intergovernmental Panel on Climate Change
ISCCP	International Satellite Cloud Climatology Program
IWP	ice-water path
JACCS	Japanese Cloud-Climate Study
LBL	line-by-line
LITE	Lidar-in-Space Technology Experiment (of NASA)
Lowtran	low-resolution transmission code
LW	longwave
LWC	liquid-water content
LWP	liquid-water path
METEOSAT	Meteorology Satellite (of ESA)
METOP	European Meteorological Operational Polar Platform
MIMR	Multifrequency Imaging Microwave Radiometer
MISR	Multi-Angle Imaging Spectro-Radiometer
MODIS	Moderate-Resolution Imaging Spectrometer
MRI	Meteorological Research Institute (of Japan Meteorological Agency)
NASA	National Aeronautics and Space Administration (U.S.)
NCAR	National Center for Atmospheric Research (U.S.)
NESDIS	National Environmental Satellite, Data, and Information Service (of U.S. NOAA)
NOAA	National Oceanic and Atmospheric Administration (U.S.)
NWP	numerical weather prediction
OCTS	Ocean Color and Temperature Scanner
PBL	planetary boundary layer
POLDER	Polarization and Directionality of Reflectances
PROBE	Pilot Radiation Observation Experiment (of ARM)
RASS	radio-acoustic sounding system
RH	relative humidity
RTNEPH	Real-Time Nephanalysis (U.S. Air Force)
SCARAB	Scanner for Radiative Budget

SOCEX	Southern Ocean Cloud Experiment
SRB	surface radiation budget
SSM/I	Special Sensor for Microwave/Imager
SST	sea surface temperature
SW	shortwave
SZA	solar zenith angle
TIROS	Television Infrared Operational Satellite (of U.S. NOAA)
TMI	TRMM Microwave Imager
TOA	top of the atmosphere
TOGA	Tropical Ocean and Global Atmosphere Program
TOVS	TIROS Operational Vertical Sounder
TRMM	Tropical Rainfall Measuring Mission
UCAR	University Corporation for Atmospheric Research (U.S.)
UKMO	United Kingdom Meteorological Office
USAF	U.S. Air Force
UTC	Universal Time coordinate
VIRS	Visible and Infrared Scanner
WCRP	World Climate Research Program
WENPEX	Western North Pacific Cloud-Radiation Experiment

LIST OF REPORTS

WCRP-1   VALIDATION OF SATELLITE PRECIPITATION MEASUREMENTS FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of an International Workshop, Washington, D.C., 17-21 November 1986) (WMO/TD-No. 203)

WCRP-2   WOCE CORE PROJECT 1 PLANNING MEETING ON THE GLOBAL DESCRIPTION (Washington, D.C., 10-14 November 1986) (WMO/TD-No. 205)

WCRP-3   INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP) WORKING GROUP ON DATA MANAGEMENT (Report of the Sixth Session, Fort Collins, U.S.A., 16-18 June 1987) (WMO/TD-No. 210)

WCRP-4   JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the First Session, Unesco, Paris, France, 25-26 June 1987) (WMO/TD-No. 204)

WCRP-5   CONCEPT OF THE GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the JSC Study Group on GEWEX, Montreal, Canada, 8-12 June 1987 and Pasadena, U.S.A., 5-9 January 1988) (WMO/TD-No. 215) (out of print)

WCRP-6   INTERNATIONAL WORKING GROUP ON DATA MANAGEMENT FOR THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Second Session, Madison, U.S.A., 9-11 September 1988) (WMO/TD-No. 221) (out of print)

WCRP-7   CAS GROUP OF RAPPORTEURS ON CLIMATE (Leningrad, U.S.S.R., 28 October-1 November 1985) (WMO/TD-No. 226)

WCRP-8   JSC WORKING GROUP ON LAND SURFACE PROCESSES AND CLIMATE (Report of the Third Session, Manhattan, U.S.A., 29 June-3 July 1987) (WMO/TD-No. 232)

WCRP-9   AEROSOLS, CLOUDS AND OTHER CLIMATICALLY IMPORTANT PARAMETERS: LIDAR APPLICATIONS AND NETWORKS (Report of a Meeting of Experts, Geneva, Switzerland, 10-12 December 1985) (WMO/TD-No. 233)

WCRP-10   RADIATION AND CLIMATE (Report of the First Session, JSC Working Group on Radiative Fluxes, Greenbelt, U.S.A., 14-17 December 1987) (WMO/TD-No. 235)

WCRP-11   WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - DETAILED REQUIREMENTS (Volume I) (WMO/TD-No. 242)

WCRP-12   WORLD OCEAN CIRCULATION EXPERIMENT - IMPLEMENTATION PLAN - SCIENTIFIC BACKGROUND (Volume II) (WMO/TD-No. 243)

WCRP-13   RADIATION AND CLIMATE (Report of the Seventh Session of the International Satellite Cloud Climatology Project (ISCCP) Working Group on Data Management, Banff, Canada, 6-8 July 1988) (WMO/TD-No. 252)

WCRP-14   AN EXPERIMENTAL CLOUD LIDAR PILOT STUDY (ECLIPS) (Report of the WCRP/CSIRO Workshop on Cloud Base Measurement, CSIRO, Mordialloc, Victoria, Australia, 29 February-3 March 1988) (WMO/TD-No. 251)

WCRP-15   MODELLING THE SENSITIVITY AND VARIATIONS OF THE OCEAN-ATMOSPHERE SYSTEM (Report of a Workshop at the European Centre for Medium Range Weather Forecasts, 11-13 May 1988) (WMO/TD-No. 254)

WCRP-16   GLOBAL DATA ASSIMILATION PROGRAMME FOR AIR-SEA FLUXES (Report of the JSC/CCCO Working Group on Air-Sea Fluxes, October 1988) (WMO/TD-No. 257)

WCRP-17   JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Seventh Session, Cairns, Queensland, Australia, 11-15 July 1988) (WMO/TD-No. 259)

WCRP-18   SEA ICE AND CLIMATE (Report of the Third Session of the Working Group on Sea Ice and Climate, Oslo, 31 May-3 June 1988) (WMO/TD-No. 272)

WCRP-19   THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the third Session of the International Working Group on Data Management, Darmstadt, FRG, 13-15 July 1988) (WMO/TD-No. 274)

WCRP-20   RADIATION AND CLIMATE (Report of the Second Session of the WCRP Working Group on Radiative Fluxes, Geneva, Switzerland, 19-21 October 1988) (WMO/TD-No. 291)

WCRP-21   INTERNATIONAL WOCE SCIENTIFIC CONFERENCE (Report of the International WOCE Scientific Conference, Unesco, Paris, 28 November-2 December 1988) (WMO/TD-No. 295)

WCRP-22   THE GLOBAL WATER RUNOFF DATA PROJECT (Workshop on the Global Runoff Data Set and Grid estimation, Koblenz, FRG, 10-15 November 1988) (WMO/TD-No. 302) (out of print)

WCRP-23   WOCE SURFACE FLUX DETERMINATIONS - A STRATEGY FOR IN SITU MEASUREMENTS (Report of the Working Group on In Situ Measurements for Fluxes, La Jolla, California, U.S.A., 27 February-3 March 1989) (WMO/TD-No. 304)

WCRP-24   JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Second Session, Royal Society, London, U.K., 15-16 December 1988) (WMO/TD-No. 307)

WCRP-25   GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (GEWEX) (Report of the First Session of the JSC Scientific Steering Group for GEWEX, Pasadena, U.S.A., 7-10 February 1989) (WMO/TD-No. 321) (out of print)

WCRP-26   WOCE GLOBAL SURFACE VELOCITY PROGRAMME (SVP) (Workshop Report of WOCE/SVP Planning Committee and TOGA Pan-Pacific Surface Current Study, Miami, Florida, U.S.A., 25-26 April 1988) (WMO/TD-No. 323)

WCRP-27   DIAGNOSTICS OF THE GLOBAL ATMOSPHERIC CIRCULATION (Based on ECMWF analyses 1979-1989, Department of Meteorology, University of Reading, Compiled as part of the U.K. Universities Global Atmospheric Modelling Project) (WMO/TD-No. 326)

WCRP-28   INVERSION OF OCEAN GENERAL CIRCULATION MODELS (Report of the CCCO/WOCE Workshop, London, 10-12 July 1989) (WMO/TD-No. 331)

WCRP-29   CAS WORKING GROUP ON CLIMATE RESEARCH (Report of Session, Geneva, 22-26 May 1989) (WMO/TD-No. 333)

WCRP-30   WOCE - FLOW STATISTICS FROM LONG-TERM CURRENT METER MOORINGS: THE GLOBAL DATA SET IN JANUARY 1989 (Report prepared by Robert R. Dickinson, Eddy Statistics Scientific Panel) (WMO/TD-No. 337)

WCRP-31   JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Eighth Session, Hamburg, FRG, 18-22 September 1989) (WMO/TD-No. 338)

WCRP-32   JSC/CCCO TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Third Session, Hamburg, FRG, 18-20 September 1989) (WMO/TD-No. 339)

WCRP-33	TOGA MONSOON CLIMATE RESEARCH (Report of the First Session of the Monsoon Numerical Experimentation Group, Hamburg, FRG, 21-22 September 1989) (WMO/TD-No. 349)
WCRP-34	THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Fourth Session of the International Working Group on Data Management, Bristol, U.K., 26-28 July 1989) (WMO/TD-No. 356)
WCRP-35	RADIATION AND CLIMATE (Report of the Third Session of the WCRP Working Group on Radiative Fluxes, Fort Lauderdale, U.S.A., 12-15 December 1989) (WMO/TD-No. 364)
WCRP-36	LAND-SURFACE PHYSICAL AND BIOLOGICAL PROCESSES (Report of an ad-hoc Joint Meeting of the IGBP Co-ordinating Panel No. 3 and WCRP Experts, Paris, France, 24-26 October 1989) (WMO/TD-No. 368)
WCRP-37	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the Workshop to Evaluate the Need for a Rain Radar in Polar Orbit for GEWEX, Greenbelt, U.S.A., 25-26 October 1989) (WMO/TD-No. 369)
WCRP-38	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the First Session of the WCRP-GEWEX/IGBP-CP3 Joint Working Group on Land-Surface Experiments, Wallingford, U.K., 25-26 January 1990) (WMO/TD-No. 370)
WCRP-39	RADIATION AND CLIMATE (Intercomparison of Radiation Codes in Climate Models, Report of Workshop, Paris, France, 15-17 August 1988) (WMO/TD-No. 371)
WCRP-40	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Scientific Plan), August 1990 (WMO/TD-No. 376) (out of print)
WCRP-41	SEA-ICE AND CLIMATE (Report of the Fourth Session of the Working Group, Rome, Italy, 20-23 November 1989) (WMO/TD-No. 377)
WCRP-42	PLANETARY BOUNDARY LAYER (Model Evaluation Workshop, Reading, U.K., 14-15 August 1989) (WMO/TD-No. 378)
WCRP-43	INTERNATIONAL TOGA SCIENTIFIC CONFERENCE PROCEEDINGS (Honolulu, U.S.A., 16-20 July 1990) (WMO/TD-No. 379)
WCRP-44	GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the 2nd Session of the JSC Scientific Steering Group, Paris, France, 15-19 January 1990) (WMO/TD-No. 383)
WCRP-45	SEA ICE NUMERICAL EXPERIMENTATION GROUP (SINEG) (Report of the First Session, Washington, D.C., 23-25 May 1989) (WMO/TD-No. 384)
WCRP-46	EARTH OBSERVING SYSTEM FOR CLIMATE RESEARCH (Report of a WCRP Planning Meeting, Reading, U.K., 2-3 July 1990) (WMO/TD-No. 388)
WCRP-47	JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Ninth Session, Kona, Hawaii, U.S.A., 23-25 July 1990) (WMO/TD-No. 387)
WCRP-48	SPACE OBSERVATIONS OF TROPOSPHERIC AEROSOLS AND COMPLEMENTARY MEASUREMENTS (Report of experts meeting at Science and Technology Corporation, Hampton, Virginia, U.S.A., 15-18 November 1989) (WMO/TD-No. 389) (out of print)
WCRP-49	TOGA MONSOON CLIMATE RESEARCH (Report of the Second Session of the Monsoon Numerical Experimentation Group, Kona, Hawaii, U.S.A., 26-27 July 1990) (WMO/TD-No. 392)

WCRP-50   TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Fourth Session, Palisades, New York, U.S.A., 13-14 June 1990) (WMO/TD-No. 393)

WCRP-51   RADIATION AND CLIMATE (Report of the First Session, International Working Group on Data Management for WCRP Radiation Projects, New York City, U.S.A., 21-23 May 1990) (WMO/TD-No. 398)

WCRP-52   THE RADIATIVE EFFECTS OF CLOUDS AND THEIR IMPACT ON CLIMATE (Review prepared by Dr. A. Arking at request of IAMAP Radiation Commission) (WMO/TD-No. 399)

WCRP-53   CAS/JSC WORKING GROUP ON NUMERICAL EXPERIMENTATION (Report of the Sixth Session, Melbourne, Australia, 24-28 September 1990) (WMO/TD-No. 405)

WCRP-54   RADIATION AND CLIMATE (Workshop on Implementation of the Baseline Surface Radiation Network, Washington, D.C., 3-5 December 1990) (WMO/TD-No. 406) (out of print)

WCRP-55   GLOBAL CLIMATE MODELLING (Report of First Session of WCRP Steering Group on Global Climate Modelling, Geneva, Switzerland, 5-8 November 1990) (WMO/TD-No. 411)

WCRP-56   THE GLOBAL CLIMATE OBSERVING SYSTEM (Report of a meeting convened by the Chairman of the Joint Scientific Committee for the WCRP, Winchester, U.K., 14-15 January 1991) (WMO/TD-No. 412) (out of print)

WCRP-57   GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the 3rd Session of the JSC Scientific Steering Group, Hamilton, Bermuda, 21-25 January 1991) (WMO/TD-No. 424)

WCRP-58   INTERCOMPARISON OF CLIMATES SIMULATED BY 14 ATMOSPHERIC GENERAL CIRCULATION MODELS (CAS/JSC Working Group on Numerical Experimentation, prepared by Dr. G.J. Boer et al) (WMO/TD-No. 425)

WCRP-59   INTERACTION BETWEEN AEROSOLS AND CLOUDS (Report of Experts Meeting, Hampton, Virginia, U.S.A., 5-7 February 1991) (WMO/TD-No. 423)

WCRP-60   THE GLOBAL PRECIPITATION CLIMATOLOGY PROJECT (Report of the Fifth Session of the International Working Group on Data Management, Laurel, Maryland, U.S.A., 20-21 May 1991) (WMO/TD-No. 436)

WCRP-61   GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the Second Session of the WCRP-GEWEX/IGBP Core Project on BAHC Joint Working Group on Land-Surface Experiments, Greenbelt, Mayland, U.S.A., 3-4 June 1991) (WMO/TD-No. 437)

WCRP-62   SEA-ICE AND CLIMATE (Report of a Workshop on Polar Radiation Fluxes and Sea-Ice Modelling, Bremerhaven, Germany, 5-8 November 1990) (WMO/TD-No. 442)

WCRP-63   JSC/CCCO TOGA SCIENTIFIC STEERING GROUP (Report of the Tenth Session, Gmunden, Austria, 26-29 August 1991) (WMO/TD-No. 441)

WCRP-64   RADIATION AND CLIMATE (Second Workshop on Implementation of the Baseline Surface Radiation Network, Davos, Switzerland, 6-9 August 1991) (WMO/TD-No. 453)

WCRP-65   SEA-ICE AND CLIMATE (Report of the Fifth Session of the Working Group, Bremerhaven, Germany, 13-15 June 1991 (WMO/TD-No. 459)

WCRP-66   GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the First GEWEX Temperature/Humidity Retrieval Workshop, Greenbelt, U.S.A., 23-26 October 1990) (WMO/TD-No. 460) (out of print)

WCRP-67   GEWEX CONTINENTAL SCALE INTERNATIONAL PROJECT (Scientific Plan, December 1991) (WMO/TD-No. 461) (out of print)

WCRP-68   SIMULATION OF INTERANNUAL AND INTRASEASONAL MONSOON VARIABILITY (Report of Workshop, Boulder, CO, U.S.A., 21-24 October 1991) (WMO/TD-No. 470)

WCRP-69   RADIATION AND CLIMATE (Report of Fourth Session of the WCRP Working Group on Radiative Fluxes, Palm Springs, U.S.A., 24-27 September 1991) (WMO/TD-No. 471)

WCRP-70   CAS/JSC WORKING GROUP ON NUMERICAL EXPERIMENTATION (Report of the Seventh Session, Boulder, CO, U.S.A., 24-29 October 1991) (WMO/TD-No. 477)

WCRP-71   GLOBAL CLIMATE MODELLING (Report of Second Session of WCRP Steering Group on Global Climate Modelling, Bristol, U.K., 18-20 November 1991) (WMO/TD-No. 482)

WCRP-72   SCIENTIFIC CONCEPT OF THE ARCTIC CLIMATE SYSTEM STUDY (ACSYS) (Report of the JSC Study Group on ACSYS, Bremerhaven, Germany, 10-12 June 1991 and London, U.K., 18-19 November 1991) (WMO/TD-No. 486)

WCRP-73   TOGA NUMERICAL EXPERIMENTATION GROUP (Report of the Fifth Session, San Francisco, California, U.S.A., 9-11 December 1991) (WMO/TD-No. 487)

WCRP-74   GLOBAL ENERGY AND WATER CYCLE EXPERIMENT (Report of the Fourth Session of the JSC Scientific Steering Group for GEWEX, Tokyo, Japan, 27-31 January 1992) (WMO/TD-No. 490)

WCRP-75   HYDROLOGY AND SURFACE RADIATION IN ATMOSPHERIC MODELS (Report of a GEWEX Workshop, European Centre for Medium-range Weather Forecasts, Reading, U.K., 28 October-1 November 1991) (WMO/TD-No. 492)

WCRP-76   REVIEWS OF MODERN CLIMATE DIAGNOSTIC TECHNIQUES - Satellite data in climate diagnostics, (A. Gruber and P.A. Arkin, November 1992) (WMO/TD-No. 519)

WCRP-77   INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (Radiance Calibration Report, December 1992) (WMO/TD-No. 520)

WCRP-78   GLOBAL OBSERVATIONS, ANALYSES AND SIMULATION OF PRECIPITATION (Report of Workshop, National Meteorological Center, Camp Springs, Maryland, U.S.A., 27-30 October 1992) (WMO/TD-No. 544)

WCRP-79   INTERCOMPARISON OF TROPICAL OCEAN GCMS (TOGA Numerical Experimentation Group, prepared by T. Stockdale et al., April 1993) (WMO/TD-No. 545)

WCRP-80   SIMULATION AND PREDICTION OF MONSOONS - RECENT RESULTS (TOGA/WGNE Monsoon Numerical Experimentation Group, New Delhi, India, 12-14 January 1993) (WMO/TD-No. 546)

WCRP-81   ANALYSIS METHODS OF PRECIPITATION ON A GLOBAL SCALE (Report of a GEWEX Workshop, Koblenz, Germany, 14-17 September 1992) (WMO/TD-No. 558)

WCRP-82   INTERCOMPARISON OF SELECTED FEATURES OF THE CONTROL CLIMATES SIMULATED BY COUPLED OCEAN-ATMOSPHERE GENERAL CIRCULATION MODELS (Steering Group on Global Climate Modelling, September 1993) (WMO/TD-No. 574)

WCRP-83   STRATOSPHERIC PROCESSES AND THEIR ROLE IN CLIMATE (SPARC): INITIAL REVIEW OF OBJECTIVES AND SCIENTIFIC ISSUES (SPARC Scientific Steering Group, December 1993) (WMO/TD-No. 582)

WCRP-84   PROCEEDINGS OF THE INTERNATIONAL CONFERENCE ON MONSOON VARIABILITY AND PREDICTION (Trieste, Italy, 9-13 May 1994) (WMO/TD-No. 619)

WCRP-85   INITIAL IMPLEMENTATION PLAN FOR THE ARCTIC CLIMATE SYSTEM STUDY (ACSYS) (September 1994) (WMO/TD-No. 627)

WCRP-86   CLOUD-RADIATION INTERACTIONS AND THEIR PARAMETERIZATION IN CLIMATE MODELS (Report of international workshop, Camp Springs, Maryland, U.S.A., 18-20 October 1993) (WMO/TD-No. 648)