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Climate-Radiation Feedbacks: The Current State of the Science

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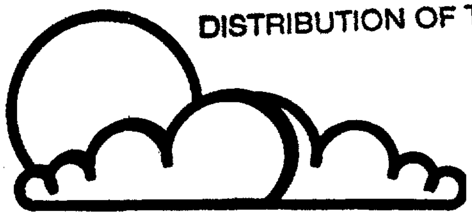

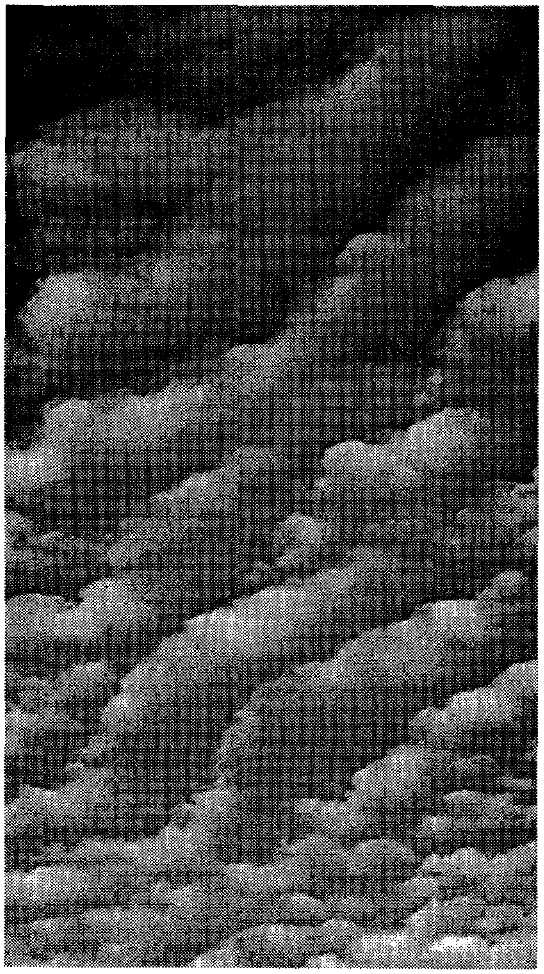

Elements of Change

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Climate-Radiation Feedbacks: The Current State of the Science

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CATHERINE GAUTIER
Co Chairs

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Writer-Editors

session 1

July 10 to July 23 1994

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I *Climate-Radiation Feedbacks: The Current State of the Science*
II *Anticipating Global Change Surprises*
III *Biological Invasion as a Global Change*

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VIDEOTAPES AND REPORTS

Videotapes of the presentations documented in this report, as well as additional copies of this report are available from Aspen Global Change Institute. Publications of AGCI are available on-line from Global Change Research Information Office (GCRIO) at http://www.gcrio.org/agci-home.html.

The views expressed in this report are summaries of participant presentations by the writer/editors, and do not necessarily represent those of the Aspen Global Change Institute, its directors, officers, staff or sponsors.

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Preface

Richard C. J. Somerville
Catherine Gautier

Co Chairs

The uncertainty in model responses is directly due to a lack of fundamental understanding of the physical processes involved.

The Aspen Global Change Institute (AGCI) devoted its first of three 1994 summer science sessions to the topic of climate-radiation feedbacks and the credibility of atmospheric models. This summer institute took place at the AGCI headquarters in Aspen, Colorado from July 10 to July 23, 1994. Twenty-five scientists participated, including three graduate students, a few young postdoctoral researchers, and a preponderance of senior people. Nearly all of the group stayed for the full two weeks.

The topic was picked because of its scientific importance and timeliness. Cloud-radiation interactions have long ranked as one of the most critical areas in global change research. In particular, when climate models are intercompared, cloud-radiation parameterizations are responsible for most of the global-mean differences in sensitivity to greenhouse gas increases. The uncertainty in model responses is directly due to a lack of fundamental understanding of the physical processes involved. A major research effort is underway worldwide in response to this challenge. As one prominent example, the Atmospheric Radiation Measurement (ARM) Program, the flagship global change effort of the U. S. Department of Energy, has been undertaken in response to this pressing scientific need. Furthermore, closely related research areas, such as the role of atmospheric aerosols in climate, are also beginning to receive the attention they deserve. We felt that the time was ripe to devote a two-week AGCI summer session to this general area, with a format designed to encourage a thorough examination of the key scientific issues, something that is impossible at a typical research meeting which lasts a few days and is made up of many short talks.

This AGCI session was an invitational meeting, with the participants chosen to ensure that a broad range of relevant topics was covered. The represented areas of expertise included climate modeling, satellite remote sensing, in situ measurements, theoretical dynamics, radiation, and cloud physics, among others. Several of the group were actively involved in general circulation model (GCM) research, especially developing parameterizations for GCMs. Several of the group were involved in major field programs, such as ARM, CEPEX and COARE. Although we had considered inviting a few representatives of the policymakers who are most interested in climate and global change, we ended up not having any people from the policy world. Thus, essentially all the expertise of the participants was in various aspects of the physical climate system.

We had written in advance to the participants, asking them each to give a talk, for about an hour, on a topic of their choice. Typically, the topic was on some aspect of their own recent research related to the general subject area of cloud-radiation interactions and closely allied fields. We suggested to each invitee that it would be especially interesting to hear about new work, work in progress, and thoughts on important directions for future work. We advised them that their audience would be the group of all the other participants, so that the general level of the talk should be that of a research seminar.

We did not require the speakers to provide any advance write-up of their talk, or even a title. We wanted to encourage spontaneity, and we especially wanted the participants to talk about their current research interests, rather than to report on work which they might have already finished, or even published. We did ask participants to feel free to bring reprints and preprints with them, however, and AGCI photocopied and distributed a considerable amount of this kind of material, together with copies of the transparencies used in each of the talks.

We scheduled two or three of these lectures on each of the ten weekday mornings, so it was possible to accommodate all the participants, even allowing generous time for discussion. Because the discussions were spirited, many of the talks lasted far beyond the one-hour limit. Those who wished to give more than one talk were encouraged to do that too. During the afternoons, several specialized discussion groups formed around topics which the participants themselves selected. In addition, we held

We wanted to encourage spontaneity, and we especially wanted the participants to talk about their current research interests, rather than to report on work which they might have already finished, or even published.

impromptu tutorials on GCMs and on fractals and multi-fractals, in which experts in these areas provided background material for the research talks. We also held wrap-up sessions at the end of each of the two weeks, in which we tried to summarize our progress and identify key issues for further attention. Finally, we held two public lectures, open to the Aspen community.

The speakers worked with writer-editors to produce a summary of each talk, including figures and references as appropriate. Edited versions of these summaries make up this report of the meeting.

When good scientists are brought together for two weeks in a pleasant and unstructured environment with few distractions, then worthwhile scientific interactions occur spontaneously. Every working scientist knows that new ideas and new research collaborations often spring from such meetings, and they were among the most valuable products of this AGCI session. Our goal was simply that at the end of the two weeks, the participants should feel that the experience had been intellectually worthwhile and that the seeds of some promising research had been sown. This goal was certainly met at this AGCI session.

When good scientists are brought together for two weeks in a pleasant and unstructured environment with few distractions, then worthwhile scientific interactions occur spontaneously.

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Summary

Climate-Radiation Feedbacks: The Current State of the Science

Richard C. J. Somerville
Catherine Gautier

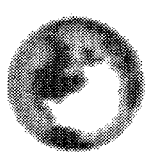
Co Chairs

Cloud Dynamics and Microphysics

The climate modeling community now realizes clearly that cloud feedback processes are not limited to macrophysical cloud properties, such as cloud amount and cloud altitude.

For many years, virtually all general circulation models (GCMs) treatments of clouds were based on simple algorithms relating cloud amount to relative humidity. Such parameterizations usually produced positive global-average cloud-radiation feedbacks in numerical experiments simulating greenhouse-induced climate change. For example, in a typical integration performed with a GCM developed a decade or two ago, a climate warming due to increased atmospheric carbon dioxide concentrations would lead to increased average cloud heights and/or decreased average cloud amounts. It is easy to understand qualitatively why such feedbacks were positive. First, higher clouds are colder and so less effective infrared emitters, and they generally have lower albedos than lower clouds, so the cloud-height feedback was positive (i. e., the change in clouds produced by the warming tended to amplify the warming). Second, average model clouds, like average real clouds, contribute more strongly to the planetary albedo than to the planetary greenhouse effect (the shortwave cloud forcing is larger than the longwave cloud forcing by about 20 Watts per square meter (Wm^{-2}). Hence, a reduction in cloud amount reduces the shortwave effect more than the longwave effect of clouds. Thus, the cloud amount feedback is also positive.

Climate models are now more numerous and more complicated, however, and model responses to increased greenhouse gas concentrations are more varied. GCMs today attempt to take into account a broader range of physical processes involved in cloud-radiation feedbacks. The climate modeling community now realizes clearly that cloud feedback processes are not limited to macrophysical cloud properties, such as cloud amount and cloud altitude. In recent years, many GCMs have begun to include cloud parameterizations which include explicit treatments of cloud physics. Several talks were concerned with the connections between climate and the micro-



physical aspects of clouds.

K.-N. Liou used a radiation model, together with theoretical and observational estimates of the temperature dependence of cirrus ice crystal size distribution and ice water content, to study feedback processes associated with ice microphysics. In a one-dimensional radiative-convective model, he found that the positive longwave feedback dominated the negative shortwave one. P. Norris has analyzed ASTEX data, including liquid water and radiative flux measurements. He estimated optical depths from aircraft liquid water and effective radius measurements and found that a theoretical albedo calculation based on these observations agreed well with direct albedo measurements. Norris is also developing a three-dimensional non-hydrostatic numerical model of a cloud-topped marine stratocumulus boundary layer, based on a code developed to simulate laboratory cellular convection.

K. Stamnes also discussed using a combination of observational estimates of cloud microphysical properties and theoretical calculations of their radiative effects in order to infer the climate sensitivity to variables such as drop size. He points out, among other results, that the infrared properties of clouds are sensitive to cloud scattering, and so clouds ought not to be treated as black bodies.

S. Twomey also provided estimates of the partial derivatives which characterize the sensitivity of climate change to factors such as extinction and absorption. These cloud radiative properties are themselves sensitive to cloud microphysical aspects such as droplet concentrations. The sensitivity is strong enough to raise serious questions as to how the predictability of climate might be affected by relatively small changes in microphysical quantities.

S. Warren summarized recent improvements in the well-known surface-based cloud climatology which he and others have developed over a period of years. Among many other refinements, the observational estimates of the diurnal cycle of cloud cover have benefited from the use of a moonlight criterion to distinguish nights on which adequate illumination was available. The current best value for global average cloud cover is 64%.

Atmosphere-Surface Interactions

Recent years have seen renewed interest in the simple question of which physical processes are responsible for the observed large-scale upper bound of about 304K on sea surface temperature (SST). In a sense, this question itself is an indicator of our lack of understanding of fundamental properties of the climate system, espe-

The sensitivity [of cloud radiative properties] is strong enough to raise serious questions as to how the predictability of climate might be affected by relatively small changes in microphysical quantities.

cially of the role of clouds. Many other such questions, seemingly simple in form but impossible to answer conclusively, could be posed. For example, why is the global cloud cover about 60%, and why is the planetary albedo about 30%? Because we cannot account theoretically for these observed properties of the present climate, we are at a loss to explain convincingly how they might change in some future climate, such as one modified by increased greenhouse gas concentrations.

R. Grossman used Coupled Ocean-Atmosphere Response Experiment (COARE) and Central Equatorial Pacific Experiment (CEPEX) data, together with simple models, to explore the role of mesoscale convective systems in regulating sea surface temperatures in the equatorial Pacific. He finds that no single simple mechanism can account for the observed limits on SST variability. Instead, a suite of processes appear to be involved, including not only cirrus shading and the super-greenhouse effect, but also evaporation, ocean mixing and sensible heat transfer. S. Sherwood has developed a simple box model with which to explore atmosphere-SST feedbacks. His preliminary results suggest that in regions of deep convection, the dominant physical processes affecting SST variations are shortwave cloud forcing and surface fluxes, but that cloud optical properties or cloud lifetimes must also be involved if either of these processes is to be effective in stabilizing tropical mean SST changes.

E. Smith reported on results from FIFE, an experiment in central Kansas aimed at assessing the ability of GCMs to simulate surface fluxes. He was able to evaluate both a biosphere model and a suite of conventional GCM turbulence closure schemes. The biosphere model showed promise as both a route to improved flux accuracy and a theoretical tool for improving understanding of GCM results. Nevertheless, at their present stage of development, the biosphere models are still much too complex by GCM standards, and there is also a need to solve the problem of a scale mismatch with GCMs. The turbulence closure schemes, by contrast, in general seemed to be too simplistic to be applicable to the diversity of situations which occur in actual atmospheric boundary layers. For example, under unstable conditions, substantial overestimates of sensible heat fluxes occurred with all the tested schemes, in part because the schemes had not been adequately calibrated against data from sources such as FIFE.

One way to define the awkward term parameterization is simply as an algorithm uniquely relating the statistical effect of small-scale processes on large-scale fields, with the critical restriction that the algorithm must be an explicit function of the large-scale fields themselves.

Parameterizations

One way to define the awkward term *parameterization* is simply as an algorithm uniquely relating the statistical effect of small-scale processes on large-scale fields, with the critical restriction that the algorithm must be an explicit function of the large-scale fields themselves. The common GCM expedient of making cloud amount dependent on relative humidity illustrates the nature of the parameterization problem. Relative humidity is calculable as an explicitly predicted model variable on the GCM grid scale. Cloud amount has substantial subgrid variability, however, and there is no obvious way to relate cloud amount to relative humidity based on first principles. In general, a sufficiently moist but subsaturated GCM grid volume will contain some clouds, and a saturated one will presumably be overcast, but there is no evident route to specifying a universal and deterministic relationship between cloud cover and relative humidity.

Not only are we uncertain how much of the observed variability of clouds can be related to relative humidity, we are also unable to say with any confidence whether other large-scale variables, such as vertical velocity, need to be invoked. Indeed, the fundamental question of parameterizability, the determination of the extent to which parameterization is possible in principle, is unanswered. Thus, a great variety of ad-hoc formulas have been devised, justifiable only empirically to the extent that they are justifiable at all.

A conspicuous feature of existing parameterizations is that there is a noticeable similarity between the approaches taken by the different GCM groups. In particular, the cloud parameterizations developed by the various groups tend to have many properties in common. For example, virtually all current parameterizations of cloud amount attempt to relate gridpoint quantities, such as cloud cover, to the GCM variables at that gridpoint alone, neglecting large-scale structure. This practice of treating each gridpoint independently sometimes leads to undesirable results in the form of substantial horizontal gradients on the smallest resolvable GCM spatial scales. In addition, modern developments, such as the advances made in fractal and multifractal representations of variability, have not yet found their way into common practice in GCMs.

Many of the participants in this session are actively involved in one form or another of parameterization research, and there was extensive discussion of the development and validation of a wide diversity of parameterizations. The participants themselves represented a broad variety of backgrounds and perspectives. Thus, the presentations ranged from observational tests of existing algorithms to theoretical treatments of novel proposed approaches.

Indeed, the fundamental question of parameterizability, the determination of the extent to which parameterization is possible in principle, is unanswered.

J. Kiehl reported on GCM experiments in which enhanced absorption had been incorporated by modifying the cloud single scattering albedo.

H. Hanson described an attempt to parameterize shortwave transmittance through clouds, using nondeterministic characterizations of cloud populations, together with an attempt to take the distribution of all three phases of water into account in a unified manner. Harshvardhan discussed the use of satellite remote sensing data. Using Landsat and ISCCP measurements, he finds that cloud liquid water path (LWP) is almost invariant with cloud fraction over a wide range of cloud fractions and pixel sizes, so that the mean LWP can be regarded as the average over a population of clouds, each of which has essentially constant LWP. An important implication of this result is that cloud fraction can in principle be inferred from knowledge of the gridpoint average LWP.

J. Kiehl summarized the present state of one especially active research area, that concerned with so-called anomalous absorption of solar radiation in the atmosphere. He reported on GCM experiments in which enhanced absorption had been incorporated by modifying the cloud single scattering albedo. By tuning the top-of-atmosphere solar radiation budget back to the observed values, using LWP and cloud amount as free parameters, he finds that the partitioning of the absorbed solar radiation between surface and atmosphere is changed by an amount equivalent to half the global average latent heat flux. Kiehl emphasized that the physical mechanisms responsible for this anomalous absorption are still unknown.

E. Roeckner described the current state of the radiation budget simulated by the ECHAM atmospheric GCM. This model is based on the ECMWF global numerical weather prediction model, to which modified physical parameterizations have been added. The ECHAM model has been extensively tuned to match ERBE observations of top-of-atmosphere radiation budget quantities. The global longwave budget is well simulated, but there still are noteworthy areas of unrealistic shortwave forcing, associated with failure to realistically simulate certain types of cloud, such as marine stratus off the west coasts of North and South America.

B. Soden discussed a cirrus parameterization scheme in which cirrus ice water path (IWP) is diagnosed as a function of temperature, pressure, vertical velocity and lapse rate. These parameters are in turn obtained from ECMWF analyses of conventional meteorological data, while ISCCP retrievals provide information on the occurrence of cirrus and on cirrus optical depth. Among other results, he finds that monthly-average cirrus occurrence can be predicted from relative humidity,

provided that corrected relative humidity fields, in which satellite data supplement the ECMWF analyses, are used. On a daily basis, however, cloud cover and relative humidity are not well correlated.

R. Somerville described the use of a single-column diagnostic model and a GCM in validating cloud-radiation parameterizations against ARM observational data. The single-column model accurately mimics one column of a GCM in terms of physical parameterizations, but it is forced and constrained with horizontal flux convergences from observational data. Products of the model, such as net surface solar irradiance, which are sensitive to cloud occurrence and cloud radiative properties, can be compared with observational data to test the parameterizations. He noted that the corresponding GCM experiments with the NCAR CCM2 model, in which a liquid water budget parameterization was tested in an inverse climate change experiment driven by SST perturbations, led to a strong temperature increase in the upper troposphere. This phenomenon could be traced to the large vertical heat transport produced by the CCM2 mass flux convection scheme, illustrating that other model-dependent properties could strongly affect the behavior of a given cloud parameterization in any specific GCM.

C. Walcek reported on an extensive series of observational tests of the relative humidity dependence of cloud cover. He finds that relative humidity is the best single indicator of the occurrence of cloud. However, it appears that cloud coverage decreases exponentially as relative humidity drops below 100%. Additionally, cloud cover is not zero below a fixed relative humidity threshold, as is often assumed in GCM algorithms. Among many other interesting results, Walcek has determined that the lower planetary boundary layer is the atmospheric region in which cloud cover is most sensitive to relative humidity.

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Radiative Transfer Developments and Investigations

One of the most important recent developments in radiative transfer involves three-dimensional radiative transfer computations through complex distributions of liquid water (or ice). New formalisms are slowly emerging to facilitate radiative transfer computations in three dimensions, but a main thrust of research activities is in the use of Monte -Carlo models (a direct simulation of the physical processes involved in radiative transfer in which the path of a photon is described by probability functions) and of approximate radiative transfer methods. W. Wiscombe and W. O'Hirok discussed Monte-Carlo techniques and their application to the calculation of radiation interaction with complex multifractal cloud liquid water distributions whose properties have been derived from observations. F. Evans presented a backward Monte-Carlo approach to estimate photon path length probability distribution. This approach is based on the order of scattering solution of a deterministic system and expresses the radiative response explicitly in terms of the medium optical properties. While a general solution would include all of the paths, the approximation presented by Evans assumes just two successive paths and seems to be accurate when compared to aircraft observations. P. Gabriel discussed two approximation methods to calculate the domain-averaged bulk radiative properties of clouds such as albedo, flux divergence and mean radiance without using cloud fraction as a specifier of cloud inhomogeneity. N. Byrne discussed his stochastic radiative transfer through a mixture of binary material and investigations of classes of solutions with different closure approximations.

Many of the proposed stochastic approaches presented have substantial appeal for the development of new GCM parameterizations of radiation transfer through inhomogeneous clouds. The most important aspects of the spatial variability of clouds for radiative transfer (e.g., photon path probability distributions, multifractal parameters) could be characterized from observations (e.g., cloud probes, millimeter-wave radars, microwave radiometers) and then expressed with a few key parameters that GCMs predict (e.g., cloud fraction). It seems likely that fast radiative transfer methods based on these parameters could be developed to include the effects of cloud inhomogeneity in cloud radiation GCM parameterizations.

Many of the proposed stochastic approaches presented have substantial appeal for the development of new GCM parameterizations of radiation transfer through inhomogeneous clouds.

Results from a number of studies using one- to three-dimensional radiative transfer models applied to a variety of problems were presented. One topic investigated by several participants was the so-called anomalous absorption of solar radiation by clouds or possibly by other constituents. J. Kiehl investigated it from the GCM point of view, addressing questions of absorption sensitivity to microphysical parameters, particularly the single scattering albedo (in terms of co-albedo), hypothesizing that it could differ from those computed by Mie scattering theory if cloud droplets were composed of mixtures of water and absorbing medium (aerosols). Other possible mechanisms suggested for cloud anomalous absorption include vapor-droplet overlap, finite cloud effects and continuum absorption. Kiehl also presented implications for GCM simulations of increased atmospheric absorption. C. Gautier performed a series of studies of total column atmospheric absorption of solar radiation due to the presence of cloud, attempting to assess the sensitivity of this absorption to micro- and macrophysical cloud parameters, as well as to atmospheric and surface parameters. She found that the absorption sensitivity was largest to cloud effective radius (and cloud phase), and also to cloud altitude. This suggests that cirrus and stratus, for instance, have very different effects on the absorption of solar radiation in the atmosphere.

K. Stamnes presented results from observational and radiative transfer modeling studies on atmospheric absorption of solar radiation in high latitudes, particularly over highly reflective snow and ice surfaces. He found that the absorption was harder to characterize with conventional approaches under these conditions. W. O'Hirok studied the role of cloud inhomogeneity on total column atmospheric bulk absorption of solar radiation and found that larger absorption could be expected with similar cloud microphysical properties for inhomogeneous clouds than for homogeneous (one-dimensional) clouds.

Two studies addressed climate sensitivity and feedback issues with highly detailed radiative transfer models. K.-N. Liou used a radiation model that includes the delta-four-stream approximation for radiative transfer in nonhomogeneous atmospheres and ice clouds to investigate the impact of cloud microphysics on climate. His preliminary results indicate that a net positive temperature-emissivity feedback dominates the net negative temperature-albedo feedback. K. Stamnes used a radiative convective model with an accurate treatment of radiative transfer including clouds to study the climate sensitivity to changes in mean drop size and optical thickness. He also used a radiative transfer model for the coupled atmosphere/sea ice/ocean system to study the partitioning of radiative energy between the three strata, and discussed the potential for testing such a model in terms of planned experiments in the Arctic.

Finally, S. Lovejoy and D. Schertzer addressed the issue of radiative transfer through mono- and multifractal clouds. When monofractal clouds occupy only a fractal subset of the space, two fundamental limits exist: the optically thick and optically thin cases. For sufficiently thick clouds, they found that plane parallel predictions could be seriously inaccurate. In the case of multifractal clouds there is a fundamental qualitative difference between clouds with many and

In the case of multifractal clouds there is a fundamental qualitative difference between clouds with many and few low-density regions.

few low-density regions. For thick clouds, the near linearity of the photon path moment scaling function allows the renormalization of the optical density to an "equivalent" plane parallel density. These stochastic radiative transfer results can explain the success of first-order Markov approximations which ignore high-order correlations in scatterings.

Multifractal and Stochastic Cloud Analysis and Modeling

Clouds have long been described as plane parallel infinite layers of liquid water or ice despite the fact that such clouds can never be found in nature. However, almost all measurements of cloud liquid water content (LWC) from aircraft show intermittent dry patches embedded within clouds. While different LWC records appear quite distinct in terms of the amount of variability, their power spectra are generally quite similar over a wide range of scales. The analysis of satellite observations of clouds in the visible or infrared spectral bands show similar scaling characteristics.

Clouds have long been described as plane parallel infinite layers of liquid water or ice despite the fact that such clouds can never be found in nature.

These observations taken together suggest that, although clouds have a complex structure, that structure can generally be described by probability distributions fully characterized by a small number of parameters (i. e., three) derived from multifractal theory. The observed differences among clouds can be attributed to the anisotropy of the fields in which they are embedded; the anisotropy resulting from the differential vertical stratification of the atmosphere and the earth's rotation, according to D. Schertzer and S. Lovejoy. They have developed a general framework for anisotropic scaling expressed in terms of isotropic self-similar scaling. Fractal and multifractal concepts have been introduced which explain why only three parameters are sufficient to fully describe the statistics of highly intermittent cloud liquid water fields. These parameters represent: (1) how non-conservative the mean field is; (2) how fractal the mean field is; and (3) how multifractal the field is. These three characteristics describe the statistical nature of the field fully. Obviously, other statistical characterizations of cloud distributions can be and have been used which simplify the description even more. Such measures still contain information about the statistics of the distribution that characterize the average distribution of particular realizations.

N. Byrne, for instance, presented models of stochastic radiative transport in which the atmosphere is represented as a mixture of two materials (cloud and clear air), each having unique and definite radiative properties. Statistical approaches to studying clouds are appropriate because cloud observations are inherently statistical, and it is the mean radiative effect of complex 3-dimensional cloud structure that is usually desired.

The multifractal framework, together with simpler examples, has been used to simulate cloud properties (e. g., liquid water distributions) which have characteristics that are similar to those observed. Several methods exist to generate fractal and multifractal LWC fields with both intermittency and non-stationarity. Among these are the bounded cascade model used by W. Wiscombe and colleagues and the fractionally-integrated cascade used by Schertzer and Lovejoy's group. These LWC fields (or other cloud descriptors) can then be used to determine the dependence of cloud radiative properties on the fractal characteristics of the clouds.

Observations

Most of the participants presented data in one form or another and most were users of data, not instrument developers. The one exception was E. Eloranta, who built a High Spectral Resolution Lidar (HSRL) that resolves the high spatial variability of optical depth in clouds. The inversion of the backscatter signal necessary for estimating optical depth (a process which can be complicated by the fact that both molecular and aerosol backscatter signals are present) is facilitated by the HSRL. Its large dynamic range permits the study of aerosols and clouds with optical depths varying from 0.01 to 3. Depolarization measurements which are used to determine the nature of hydrometeors present (i. e., water vs. ice) show that water clouds must almost always be taken into account during cirrus observations. One of the most promising new developments with this instrument is the possibility of measuring effective radius via diffraction peak width and variable field-of-view measurements.

Cloud liquid water content (LWC) measurements from a number of sources were used in many of the results presented. W. Wiscombe discussed the many ways to measure cloud LWC, ranging from traditional aircraft hot wire probes, such as the Johnson-Williams or King probes, to the FSSP which provides cloud droplet spectra to estimate LWC. Measurements from a new optical probe, the Gerber probe, were emphasized by several investigators. The Gerber probe is a promising instrument which can provide high quality LWC and effective radius measurements at much improved rates. Both Wiscombe and F. Evans analyzed data from that instrument taken during the Atlantic Stratocumulus Transition Experiment (ASTEX).

One of the most promising new developments with the High Spectral Resolution Lidar is the possibility of measuring effective radius via diffraction peak width and variable field-of-view measurements.

Ice crystal size distribution and ice water content are systematically dependent on temperature.

Evans used Gerber cloud probe data from ASTEX to compute path probability distributions in clouds. He found good agreement between ASTEX cloud data and his Monte Carlo stochastic radiative transfer results. P. Norris used profiles of cloud liquid water and particle effective droplet size (and derived cloud optical depth) and radiative flux data from aircraft during ASTEX. K.-N. Liou used aircraft measurements of crystal size distribution and ice water content (IWC) in mid-latitude cirrus clouds to show that the ice crystal size distribution and ice water content (IWC) are systematically dependent on temperature. Other cloud liquid water observations from the surface were discussed, such as those from microwave radiometers which provide a good estimate of cloud liquid water path.

Measurements from the Multi-Filter Shadowband Radiometer (MFRSR), which measures direct and diffuse solar radiation deployed in the ARM program, were exploited by both N. Byrne and K. Stamnes. Byrne used them in conjunction with cloud cover estimates from GOES to test the theory which he developed together with F. Malvagi, G. Pomraning and R. Somerville. The theory describes spatial averages at one time, but observationally only one suitable radiometer is available at the Oklahoma ARM site. Therefore, he analyzed a time series from about a dozen half-days, for which MFRSR and GOES data were both available. He showed that the stochastic description provided a somewhat better fit to the data than a fractional cloud cover model, but far more data will be required to settle the issue. Stamnes explored the potential for deriving optical depth from narrowband measurements and mean drop size from bispectral transmittance measurements in terms of the channels available in the MFRSR. The optical depth can be reliably inferred from the 862 nm channel (which is less influenced by atmospheric aerosols than channels at shorter wavelengths), while the mean drop size could be determined from a combination of measurements in the 862 nm channel and a channel centered at 2.2 microns. While the latter channel is currently not available, it would be a valuable addition to narrowband instruments such as the MFRSR.

Conventional surface observations such as sea surface temperature (SST) were reported by themselves but were most often utilized in conjunction with large-scale satellite observations from ERBE or ISCCP. R. Grossman reported on his use of TOGA-COARE measurements of atmospheric and oceanic variables in the western tropical Pacific and found that SST shows a cycle of 3-4 months. However, clearly, a longer observation period would be necessary to confirm this result. He also found indications that, at least some of the time, high SSTs were associated with low wind speeds, and low SSTs followed periods of high wind speed.

High-resolution satellite observations (Landsat data) were used by Harshvardhan but in a degraded form to simulate the various resolutions used by ISCCP. They were then thresholded to classify pixels into clear and cloudy. Liquid water path (LWP) in cloudy pixels was retrieved from these data and found to be essentially invariant to the cloud fraction, at least in the range 0.2 - 0.8 for any pixel resolution. At high cloud fractions (greater than ~0.8) the LWP can be considerably higher than the relatively constant value for lower fractions.

S. Sherwood used monthly averaged ERBE observations of longwave cloud radiative forcing (CRF) during the 1985-89 period, together with Reynolds' analyses of SST during the same period, to investigate the influence of SST on the tropical atmosphere. The SST components which average to zero over a large area were found to be associated with large shifts of CRF (20-25 $W/m^2/K$) toward higher SSTs. These include the annual component of the seasonal cycle and the time-average distribution within the Pacific warm pool region. Conversely, components involving mean SST changes over large areas (areas that include most deep convective activity) are not associated with significant changes in CRF. These components include El Niño, La Niña, and the biannual component of the seasonal cycle.

E. Smith used the data from a network of surface flux stations operated during the First ISLSCP Field Experiment (FIFE) for 143 days in 1987 and 21 days in 1989. Annual, intraseasonal, synoptic, and diurnal time scales were found to be the four predominant temporal scales of variability for the fluxes. Cloudiness was found to be the dominant control on flux magnitudes. Precipitation and its resultant effects on soil moisture distribution were found to be the dominant control on evaporative fraction or Bowen ratio. The processes of burn treatment, grazing conditions, topography, and cloudiness on radiative, sensible heat, and moisture fluxes had a much smaller effect than cloudiness, which was found to be the dominant control on the modulation of sensible and latent heat fluxes. For sensible heat, the amplitude of the effect of cloudiness was largest during the senescent period, while for latent heat, it was largest during the growing season. The RMS uncertainties in the measured fluxes were estimated to be approximately 30 Wm^{-2}. When a

Cloudiness was found to be the dominant control on flux magnitudes.

persistent gradient of soil moisture was observed across the site, a gradient in evaporative fraction and thus a cross-site difference in sensible heating of the boundary layer were found. A resulting secondary boundary layer circulation was established with significant daytime vertical velocities.

D. Sowle discussed measurements from the Unpiloted Aerospace Vehicle (UAV) program. Four new instruments under development were briefly presented: HONER, a novel net flux radiometer; MPIR, a multi-spectral cloud imaging radiometer; CDL , a cloud detection lidar; and UAV-AERI, an IR interferometer. All UAV flights include a standard meteorological package to measure temperature, pressure, and relative humidity. K. Stamnes used broadband surface albedo and solar irradiance measurements from the NOAA/CMDL station in Barrow, Alaska. The seasonal variation in cloud optical thickness at Barrow, Alaska was derived using these data for the period April 1988 through August 1988.

In contrast to current GCM methodologies, clouds exist over a wide range of relative humidities, rather than disappearing below some arbitrarily defined threshold.

Large scale surface and satellite observations of clouds were used by a number of investigators to study cloud climatology or relate cloud variability to that of other parameters. In particular, C. Walcek employed the U. S. Air Force database (so-called 3DNEPH) of cloud data to investigate its correlation with relative humidity fields produced by assimilating radiosonde observations using a mesoscale meteorology model. He found that, in contrast to current GCM methodologies, clouds exist over a wide range of relative humidities, rather than disappearing below some arbitrarily defined threshold, typically 60-80%, depending on height in the atmosphere. S. Warren used surface weather observations from stations on land and ships in the ocean to obtain the global distribution, at 5°x5° latitude-longitude resolution, of total cloud cover and the average amounts of the different cloud types: cumulus, cumulonimbus, stratus, stratocumulus, nimbostratus, altostratus, altocumulus, cirrus, cirrostratus, cirrocumulus, and fog. Diurnal and seasonal variations were derived, as well as interannual variations and multi-year trends were then estimated. Great emphasis was put on the difficulty of detecting clouds at night due to inadequate illumination of the clouds, and on how to remove this bias by selection of observations made under sufficient moonlight.

1

A Field Test of a Simple Stochastic Radiative Transfer Model

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The problem is stochastic in that one prescribes only the statistics of the mixture and then seeks the average of the solution over an ensemble of particular realizations.

The problem of determining the effect of clouds on the radiative energy balance of the globe is of well-recognized importance. One can in principle solve the problem for any given configuration of clouds using numerical techniques. This knowledge is not useful however, because of the amount of input data and computer resources required. Besides, we need only the average of the resulting solution over the grid scale of a general circulation model (GCM). Therefore, we are interested in estimating the average of the solutions of such fine-grained problems using only coarse grained data, a science or art called stochastic radiation transfer.

Byrne's research, in cooperation with Profs. Somerville (UCSD) and Pomraning (UCLA), has three components. These are the development of models of stochastic radiative transport, comparison of the predictions of such models with those currently used by GCMs, and validation of their applicability to global change problems using results from the ARM program.

This work uses a model radiative transfer system which possesses some of the complexities of the cloud-radiation system yet is still simple enough to be analyzed. It is a binary mixture of two materials, each of which has unique and definite radiative properties. The problem is stochastic in that one prescribes only the statistics of the mixture and then seeks the average of the solution over an ensemble of particular realizations. Byrne and his collaborators have found an exact but unclosed solution to this model and have investigated a whole class of approximate solutions, differing only in their closure assumptions. The accuracy of any proposed closure can be estimated by comparing to known solutions, such as a Markovian assemblage of pure absorbers, or to tendencies in known extreme limits, or by comparison to the average of large ensembles of solutions generated numerically, or potentially by comparison to laboratory experiment. The question at issue here is a mathematical one: the accuracy of the solution of a certain exactly specified model system, so appeal to observation

of naturally occurring atmospheric phenomena is probably not useful.

But it is useful to compare the prediction of the model equations to reality, because the system may contain enough of the essentials of the cloud-radiation problem to have predictive power in spite of the simplicity of the underlying model. The ARM site should provide a good data set for this purpose. In practice not all of the planned instruments are in place and reporting, and not all of the needed measurements are even in the plan, so the results to date are only preliminary.

ARM provides some MFRSR radiometer data (one of 25 is now reporting) on the ground, reporting direct and diffuse flux every minute. Additionally, there are site-wide cloud cover estimates from GOES every hour. The theory describes spatial averages at one time, but only one radiometer is available. Therefore, a time series from about a dozen half-days, for which MFRSR and GOES data were both available (Figure 1.1), have been analyzed. The results are that the stochastic description (figure 1.2) is a somewhat better fit to the data than is a fractional cloud cover model (figure 1.3), but far more data will be required to settle the issue.

More data will be coming soon, though, and in the next few years it should be possible to measure the performance of existing GCM models as well as stochastic ones put forward by us and others in the community.

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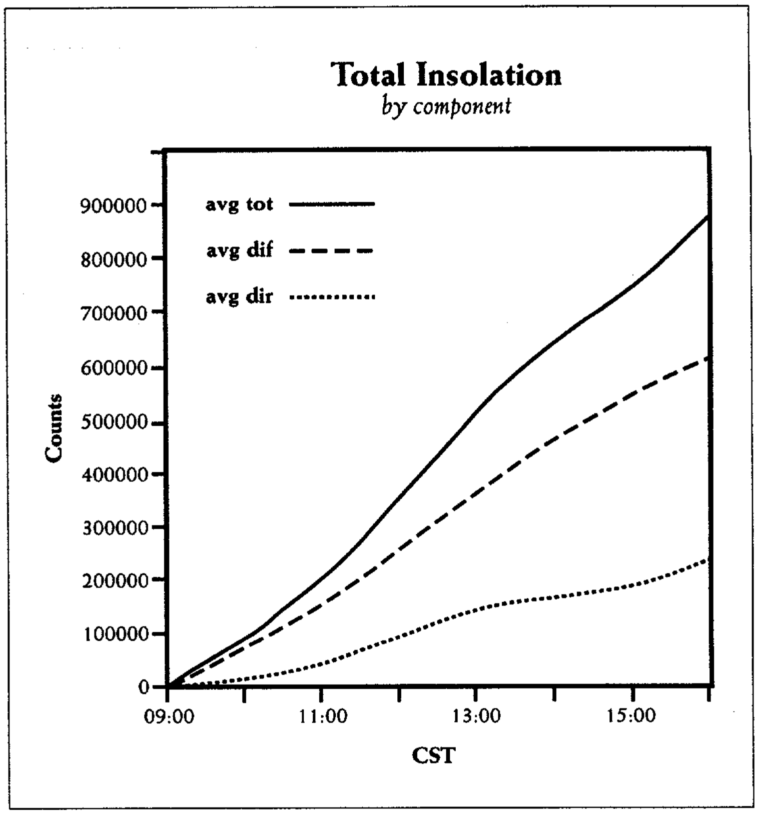
The system may contain enough of the essentials of the cloud-radiation problem to have predictive power in spite of the simplicity of the underlying model.

Figure 1.1:
Time series of measured radiances (total, direct, and diffuse)



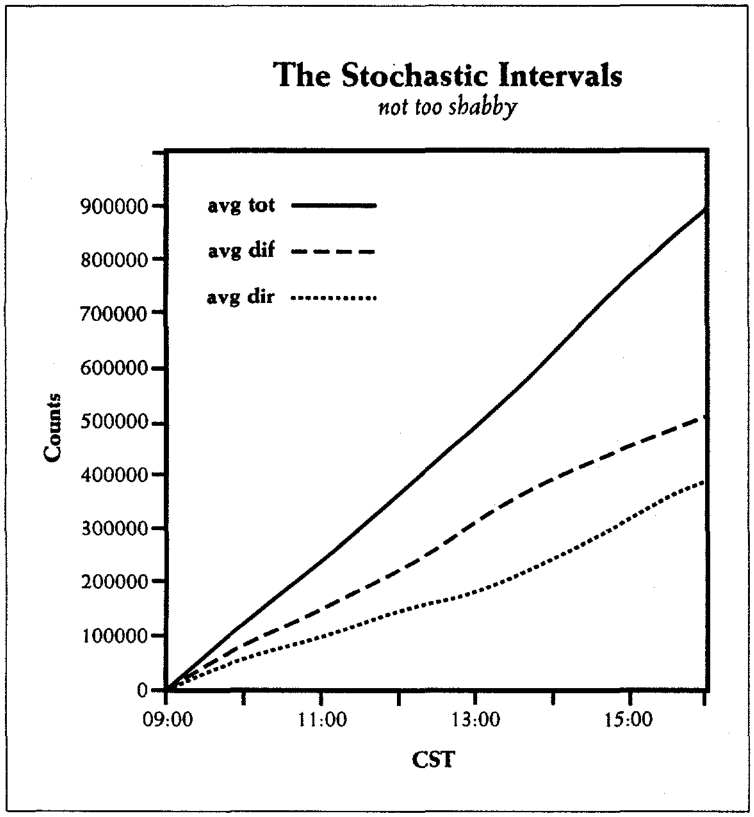


Figure 1.2:
Time series of calculated radiances using the stochastic method

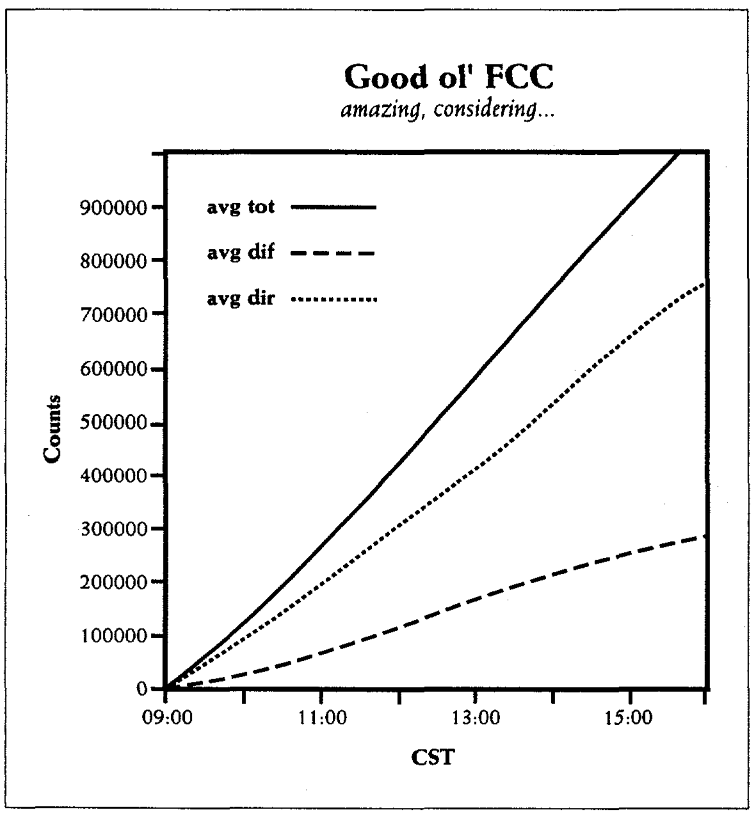


Figure 1.3:
Time series of calculated radiances using the fractional cloud

2

The High Spectral Resolution (Scanning) Lidar (HSRL)

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Depolarization measurements are able to distinguish between ice and water. Results indicate that ice is only found below 0°C, and water only above -35°C (to 5°C accuracy).

Lidars enable the spatial resolution of optical depth variation in clouds. The optical depth must be inverted from the backscatter signal, a process which is complicated by the fact that both molecular and aerosol backscatter signals are present. The HSRL has the advantage of allowing these two signals to be separated. It has a huge dynamic range, allowing optical depth retrieval for t = 0.01 to 3. Depolarization is used to determine the nature of hydrometeors present. Experiments show that water clouds must almost always be taken into account during cirrus observations. An exciting new development is the possibility of measuring effective radius via diffraction peak width and variable field-of-view measurements.

Operating Principles: The aerosol backscatter is a sharp peak superposed at the central wavelengths of the doppler broadened molecular signal. This peak can be removed by an iodine vapor absorption cell, which leaves only the wings of the broad molecular signal intact. The full molecular signal can be restored if the atmospheric pressure and temperature profiles are known.
The HSRL is operated at room temperature; it has a very fast transmission rate (4000 Hz), allowing a 15-30m vertical resolution while remaining nominally eye safe. Successive pulses are horizontally and vertically polarized allowing fast depolarization measurements. A state-of-the-art photon counting system gives the HSRL a huge dynamic range. Aerosol backscatter signal strength is used to measure cloud optical depth. Depolarization measurements are used to determine the nature of the hydrometeors. The molecular signal provides a good check of whether the molecular-aerosol signal separation is being performed correctly. Figure 2.1 shows an example of an inversion. Figure 2.2 shows a scan image of a cirrus cloud.
Depolarization measurements are able to distinguish between ice and water. Results indicate that ice is only found below 0°C, and water only above -35°C (to 5°C accuracy). Depolarization measurements also sometimes show the existence of high (4-6km) irregular aerosol particles (soil or

pollen perhaps) which may have been lofted up by deep convection.

The strong point of the HSRL is the retrieval of optical depth. The practical optical depth range is 0.01 to 3 (for a several minute integration). This implies a huge dynamic range of e^{-6} (round-trip photon travel). The range can be extended by using more power but a broader beam (to keep the lidar eye safe) and a telescope to collect the beam. Photon counting performance is the dominant limitation.

In a study when the lidar was turned on only to study cirrus clouds, it was found that 40% of the time some liquid water clouds were also present. This highlights the need to take water clouds into account when making cirrus observations.

The possibility of measuring effective radius via diffraction peak width and variable field-of-view measurements is an exciting new development. It is found that there is a significant relationship between effective radius and diffraction peak width. The width of the diffraction peak is obtained from measurements at different field-of-view widths.

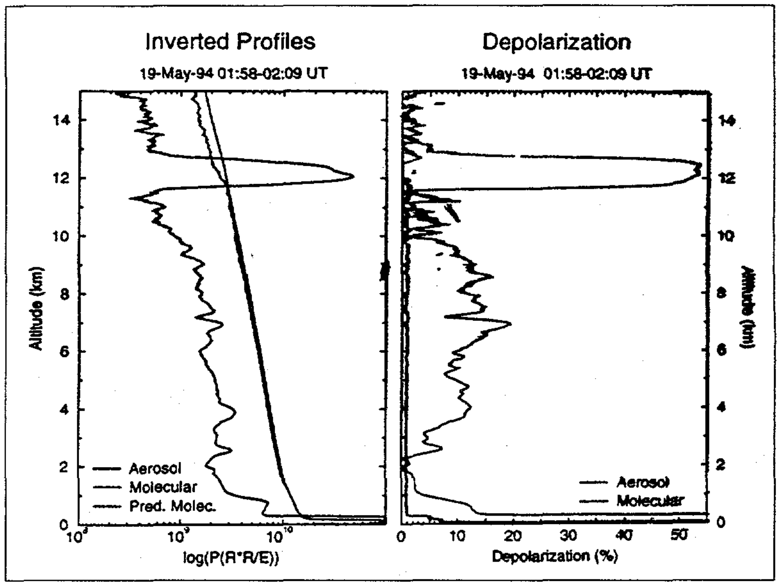

Figure 2.1: An example of an inversion

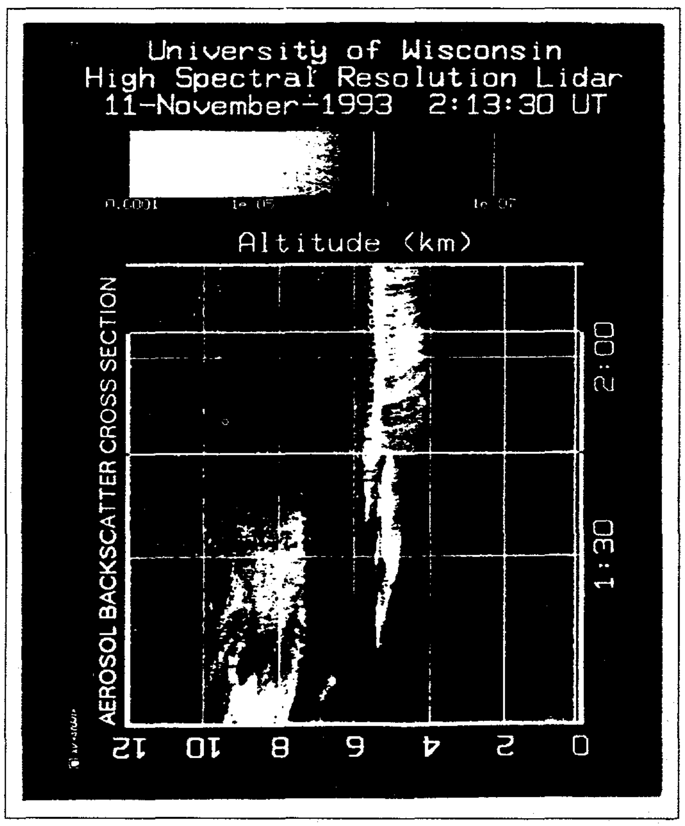

Figure 2.2: A scan image of a cirrus cloud

3

Stochastic Radiative Transfer and Real Cloudiness

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The simplest general way to derive a stochastic solution to the radiative transfer equation is to use the order of scattering solution of the deterministic system.

Plane-parallel radiative transfer modeling of clouds in GCMs is thought to be an inadequate representation of the effects of real cloudiness. A promising new approach for studying the effects of cloud horizontal inhomogeneity is stochastic radiative transfer, which computes the radiative effects of ensembles of cloud structures described by probability distributions. This approach is appropriate because cloud information is inherently statistical, and it is the mean radiative effect of complex 3D cloud structure that is desired.

The simplest general way to derive a stochastic solution to the radiative transfer equation is to use the order of scattering solution of the deterministic system, because this expresses the radiative response explicitly in terms of the medium optical properties. The equation can be then multiplied by the joint probability density function (pdf) and integrated to obtain the ensemble mean radiative response. The deterministic solution has integrals over transmission and two angles for each order of scattering. These high-dimensional integrals are computed with Monte Carlo integration in a procedure called backward Monte Carlo radiative transfer. The stochastic solution for the ensemble mean has in addition integrals over the distances between successive scatterings, which are the stochastic random variables. The general joint pdf would include all of these path distances and also depend on the transmission and angular variables as well. The approximation used here is that the general joint pdf can be expressed in terms of conditional pdfs involving just two successive paths. The form of these path pdfs used here is $f(k|T)$ and $f(k_2|T,k_1)$, where k is the mean path extinction and T is the path transmission. Preliminary testing (Evans 1993) with 3D log-normal multifractal fields compared with many deterministic runs indicated that pdfs describing two paths are adequate, whereas those describing single paths are not.

Path pdfs were computed from Gerber cloud probe data from the Atlantic Stratocumumulus Transition Experiment (ASTEX) for all cloudy segments longer than 2 km. Approximate two path pdfs were derived from 1D extinction traces (made from the particle surface area channel). Assuming isotropic homogeneous cloud structure, the ensemble mean albedo for four stochastic approximations was computed. The independent pixel approximation (IPA) tended to agree with the Monte Carlo stochastic method (though the approximate nature of this stochastic method is evident from lack of flux conservation). The plane-parallel method had 8-13% higher albedo, while the source closure method of Gabriel and Evans (1995) had 6-8% higher albedo.

The good agreement for ASTEX cloud data between the Monte Carlo stochastic radiative transfer method and the IPA is explained by the characteristics of the path pdfs, which are close to those corresponding to the IPA: $f(k|T)=f(k)$, $f(k_2|T,k_1)=d(k_2-k_1)$. In contrast, path pdfs corresponding to the often modeled array of rectangular clouds are completely different, with the pdf of the second path mean path extinction (k_2) almost independent of the first path (k_1) (Figure 3.1).

An appealing approach, based on the fundamental physics of radiative transfer, can thereby be formulated for future studies of radiation and inhomogeneous clouds. The spatial variability of clouds can be characterized with path pdf's obtained from cloud probes, mm-wave radars, and microwave radiometers. Those aspects of real cloud variability that are most important for radiative transfer should be expressed with a few key parameters (cloud fraction, etc.) In principle, fast radiative transfer methods based on these parameters could be developed to include the effect of cloud inhomogeneity in cloud radiation GCM parameterizations. Finally, there would be the need to develop methods of remote sensing cloud inhomogeneity parameters on a global basis.

The spatial variability of clouds can be characterized with path pdf's obtained from cloud probes, mm-wave radars, and microwave radiometers.

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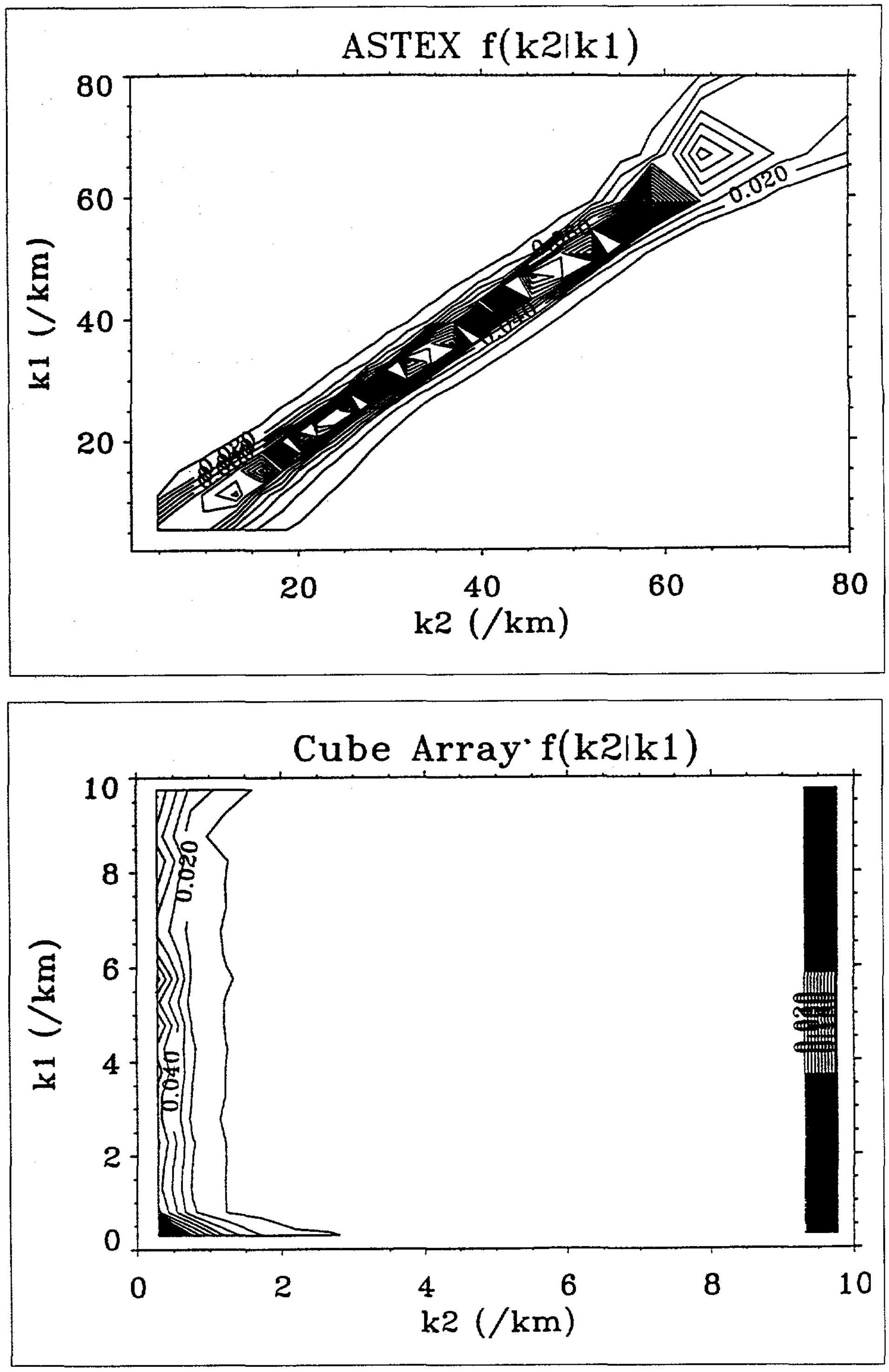

Figure 3.1: The path probability density function of the second path mean extinction, given the first path mean extinction, for overcast cloud runs in ASTEX with Gerber probe data and for a 1x2x2 km rectangular cloud array with fraction 0.25

4

Fast Methods of Computing Bulk Radiative Properties of Inhomogeneous Clouds Illuminated by Solar Radiation

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The use of cloud fraction as a means of incorporating horizontal cloud inhomogeneity in radiative transfer calculations is widespread in the atmospheric science community. This research attempts to bypass the use of cloud fraction in radiative transfer modeling for two-dimensional media. Gabriel describes two approximation techniques useful in calculating the domain averaged bulk radiative properties such as albedo, flux divergence and mean radiance that dispense with the need to use cloud fraction as a specifier of cloud inhomogeneity.

This research attempts to bypass the use of cloud fraction in radiative transfer modeling for two-dimensional media.

The first approximation method is based on a first order closure technique (C1) (see Figure 4.1) which is formulated by exploiting the translational invariance of the equation of transfer, thus leading to a one-dimensional equation of transfer with a modified source term. This approach allows computational speeds that exceed that of the independent pixel approximation (IPA) and also yields a large improvement in accuracy over the IPA as determined by numerical solutions of the two-dimensional equation of transfer. The method is accurate for clouds that do not exhibit a strong forward peak in the phase function. For clouds exhibiting a large asymmetry factor, the closure method provides usable accuracy for optical depths of order 10. In the linear regime, where optical depths are of order unity or less, the closure has been found to be accurate regardless of the asymmetry factor, because of the linearity of the radiative transfer.

The second method of approximation is similar to the IPA, in that it considers horizontal variations in the optical depth, but performs a full three-dimensional computation of the direct beam that is used as the pseudo-source in an independent pixel diffuse radiative transfer calculation. This method is generally more accurate than the closure method but cannot be used to give local net fluxes at cloud boundaries, because, for

example, the computed albedos can exceed unity. The reason for this behavior is that energy can stream only up or down, not laterally. The results suggest that the variability of the medium can largely be accounted for through the pseudo-source term. This conclusion offers hope of parameterizing the equation of transfer in terms of the statistical properties of the medium.

The results suggest that the variability of the medium can largely be accounted for through the pseudo-source term. This conclusion offers hope of parameterizing the equation of transfer in terms of the statistical properties of the medium.

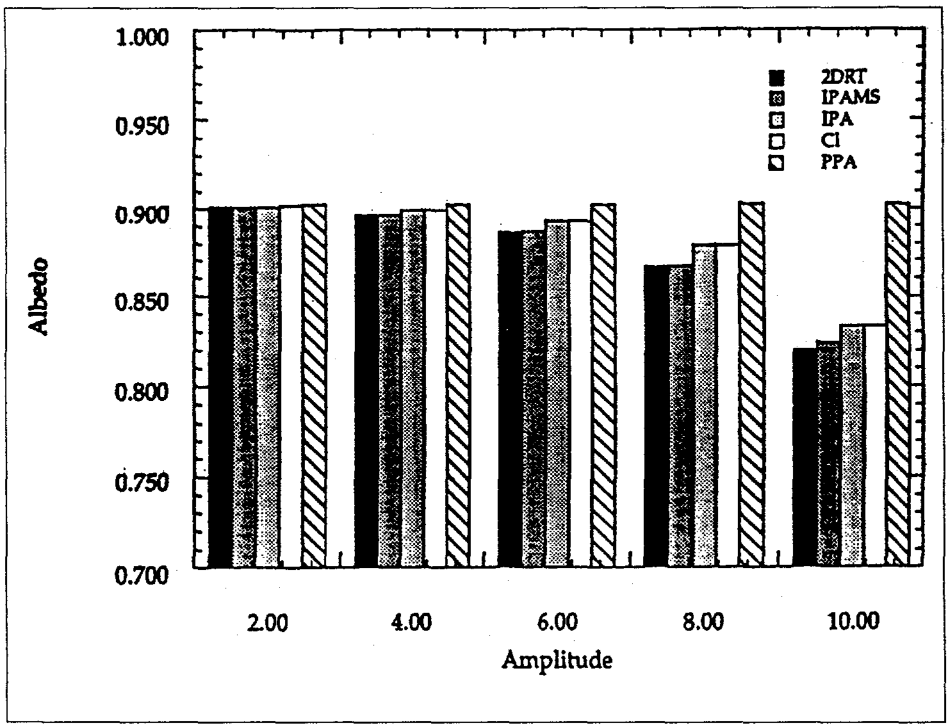

Figure 4.1: Comparison of different radiative transfer methods: 2DRT (exact 2D radiative transfer)
IPAMS (independent pixel approximation with modified source term)
IPA (independent pixel approximation)
C1 (first order closure)
PPA (plane parallel approximation)

5

Solar Radiation Absorption in the Atmosphere Due to Water and Ice Clouds: Sensitivity Experiments with Plane-Parallel Clouds

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Current modeling practice is seriously inconsistent with new observational inferences concerning absorption of solar radiation in the atmosphere.

One cloud radiation issue that has been troublesome for several decades is the absorption of solar radiation by clouds. Many hypotheses have been proposed to explain the discrepancies between observations and modeling results. A good review of these often-competing hypotheses has been provided by Stephens and Tsay (1990). They characterize the available hypotheses as falling into three categories: (1) those linked to cloud microphysical and consequent optical properties; (2) those linked to the geometry and heterogeneity of clouds; and (3) those linked to atmospheric absorption.

Recently, a number of investigators have proposed that current modeling practice is seriously inconsistent with new observational inferences concerning absorption of solar radiation in the atmosphere (regarded as a system including both clouds and clear sky) resulting from the presence of clouds. Using an approach based on a combination of surface and satellite observations of the net broadband shortwave radiation, Cess et al., (1994) have suggested that significant disagreement exists between these observations and radiative transfer computations performed by climate models.

This issue has been investigated, in part, in terms of a ratio (R) of cloud forcing at the surface (measured by upward- and downward-looking pyranometers) to cloud forcing at the top of the atmosphere (Harrison et al., 1992). Combined satellite and pyranometer observations suggest that absorption in the cloud/atmosphere system due to the presence of clouds is drastically underestimated by at least two representative climate models (NCAR CCM2 and ECMWF). Because of the potential importance of such a result, Gautier and her colleagues have investigated this absorption issue with a radiative transfer model for plane parallel conditions.

First, they have addressed the relationship between the absorption taking place in the atmosphere due to cloud (DABSATM = ABSATMcloud - ABSATMclear) and the ratio of surface to TOA cloud forcing (CFSURF/CFTOA). From the definitions used it can be demonstrated that this relationship is:

$$R = 1 + \frac{\text{DABSATM}}{\text{CFTOA}}$$

This indicates that if R is larger than 1, the absorption in the atmosphere when clouds are present is larger than that in clear conditions.

Second, they have performed sensitivity studies to a number of parameters: cloud altitude, cloud drop effective radius, cloud particle type (water or ice), atmospheric water vapor content, surface conditions, and sun zenith angle. A summary of their sensitivity results is presented in Figure 1 which presents DABSATM as a function of R. They find a range of values for R from 1 to 1.8, a range that encompasses the value discussed by Cess et al. (i.e., 1 for models and 1.5 from observations). Furthermore, they find that the relationship between DABSATM and R is not unique but depends on atmosphere and surface conditions. For a given set of atmosphere and surface conditions, the highest values of R corresponds to small optical thickness values. These, on the other hand, are associated with small values of absorption. The largest variations in absorption are related to changes in cloud altitude, but the slope of DABSATM/R varies with atmosphere-surface conditions and cloud optical thickness. To summarize, this figure suggests that there is no unique relationship between R and solar radiation absorption in the atmosphere resulting from the presence of clouds. Gautier and her colleagues contend that an emphasis on R may, therefore, not be the optimal way of addressing the cloud solar absorption issue.

They have also looked for evidence of large absorption induced by the presence of clouds in another way, namely through their work on the surface radiation budget with pyranometer and satellite observations (Gautier et al., 1980, Gautier and Landsfeld, 1994). This is an indirect approach, in which they conclude that a discrepancy in R values from 1 to 1.5 would translate into a rather large absorption difference. For a 100% cloud cover they find that, on the contrary, their model (which is extremely close to a Delta-Eddington model in most important respects, including cloud absorption) provides them with lower values of surface insolation than measured by pyranometers. They attribute this discrepancy to

Gautier and her colleagues contend that an emphasis on R may, therefore, not be the optimal way of addressing the cloud solar absorption issue.

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Surface and satellite measurements neither support nor refute the hypothesis that there is anomalous solar radiation absorption by clouds.

satellite calibration uncertainties and poorly represented cloud bidirectional reflectance effects. They conclude, therefore, that their surface and satellite measurements neither support nor refute the hypothesis that there is anomalous solar radiation absorption by clouds.

Finally, the work performed in collaboration with W. O'Hirok, and reported later in this report, suggests that 3-D cloud effects might, in part, be responsible for the large absorption detected in the data analyzed by Cess et al.

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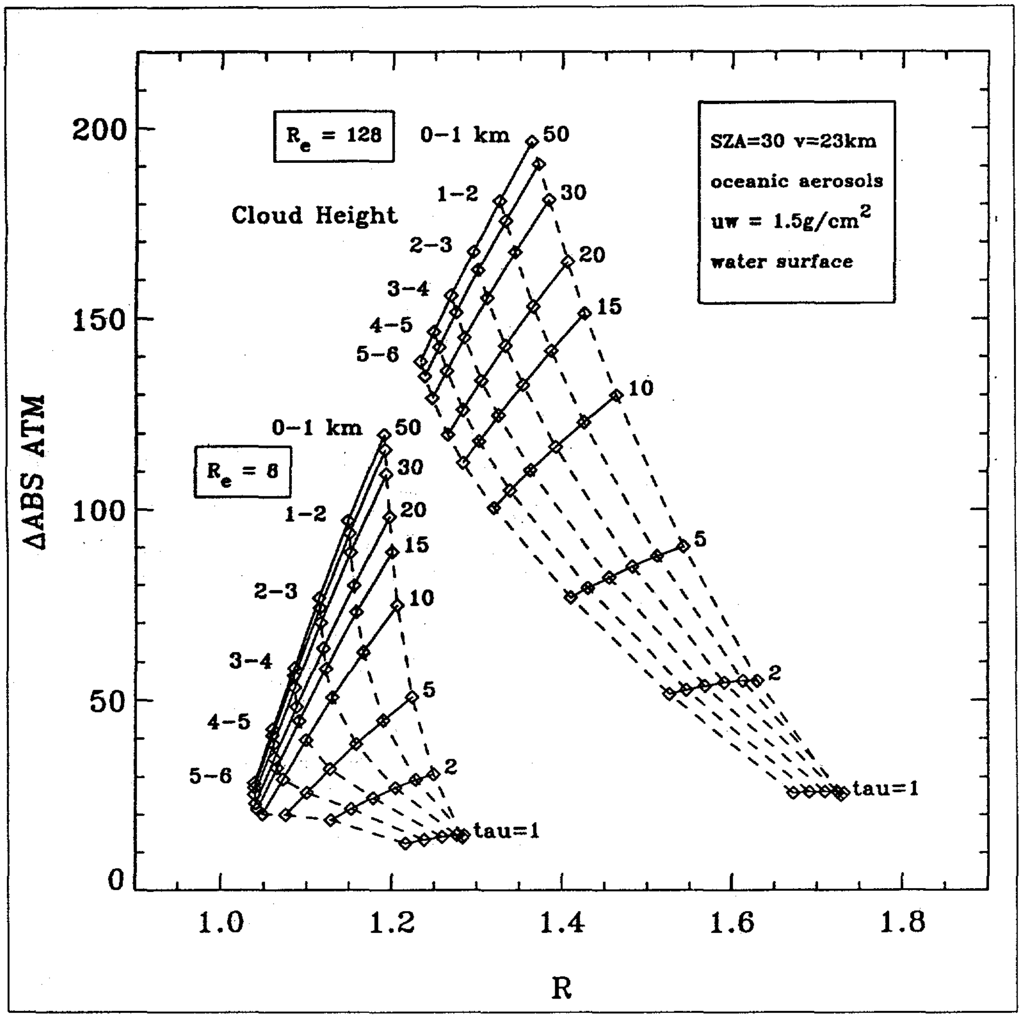

Figure 5.1

Cloud Induced Absorption (ΔABS ATM) vs R

6

Interplay Between Evaporation, Radiation, and Ocean Mixing in the Regulation of Equatorial Pacific Sea Surface Temperature

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A search for mechanism(s) which can account for SST regulation is underway.

Sea surface temperature (SST) regulation in the tropical oceans is an important aspect of global climate change. It has been observed that SST in the equatorial zone has not exceeded 304K over, at least, the past 10,000 years, and probably longer. Furthermore, recent satellite observations from the Earth Radiation Budget Experiment (ERBE) suggest that the greenhouse effect associated with mesoscale organized convection increases with increasing SST at a rate faster than this energy can be re-radiated to space. This suggests that a runaway greenhouse effect is possible in those parts of the tropical oceans where mesoscale convective systems (MCS) are prevalent. However, this is not observed.

Thus, a search for mechanism(s) which can account for SST regulation is underway. The "thermostat hypothesis" of Ramanathan and Collins conjectures that surface shading (relative cooling) by cirrus anvils associated with MCS effectively balances the enhanced greenhouse effect (relative warming) caused by the increase in tropospheric moisture also associated with these cloud systems. The Thermostat Hypothesis related both of these effects to a single parameter, SST. Because of data obtained from two major field expeditions to the equatorial Pacific, COARE and CEPEX, it may be possible to test this hypothesis.

Recent work on the global heat budget by Trenberth and Solomon shows the Eastern Pacific to be a maximum of ocean heat transport while the Western Pacific is a maximum in atmospheric heat transport. OLR and HRC atlases show the E. Pacific to be a region of low frequency of occurrence of MCS while the W. Pacific is a well-known maximum. This causes the E. Pacific to be characterized by high insolation while, by comparison, the W. Pacific has relatively low insolation. Further, the E. Pacific has relatively steady strong easterlies compared to the W. Pacific, which is an area of relatively low winds associated with a planetary scale maximum in low-level convergence there; in fact, westerly winds, known as westerly wind bursts (WWB) are intermittently observed in this area. The strong easterlies are associated with basin-scale upwelling in the E. Pacific while the W. Pacific has little upwelling. In the E. Pacific, the SST regulation is a balance between high insolation, relatively high evaporation, and, importantly, the upwelling. In the W. Pacific, Grossman conjectures that the balance is probably between net radiation, evaporation, and ocean mixing (as opposed to upwelling).

Observational and theoretical evidence exists to suggest the importance of other feedback mechanisms as opposed to the cirrus shading and "super greenhouse effect" supported by the thermostat hypothesis. These complementary mechanisms are: evaporation, near-surface and near-thermocline ocean mixing, and sensible heat transfer. Using a variety of data sources from COARE and CEPEX — ship, buoy, and aircraft — Grossman proposes that any model which includes these effects must take into account these recurring sequences of discrete events. One could view these sequences as coherent structures on the climate scale. This research emphasizes four events: fair weather (FW), meso-scale convection (MCS), westerly winds (WWB), and disturbed weather (DW) as important to SST regulation in the W. Pacific warm pool. All of these events are associated with large-scale dynamical patterns in the atmosphere.

MCS is important both to the thermostat hypothesis and to this work. The Gray criteria for the formation and maintenance of MCS were first proposed by Gray in 1968. These are: near-surface convergence, near-tropopause divergence, SST in excess of 301°K, and low shear between the surface and upper troposphere. For example, FW is associated with no near-surface convergence or near-tropopause divergence (often the opposite). The SST criteria are a necessary, but not sufficient criteria for MCS; for example, there are parts of the E. Pacific where SST is greater than 28°C but little MCS; the same is true of the Arabian Sea during pre-monsoon conditions. Large scale dynamics seems to play a part.

Observational and theoretical evidence exists to suggest the importance of other feedback mechanisms as opposed to the cirrus shading and "super greenhouse effect" supported by the thermostat hypothesis.

A simple model of an ocean column, including the surface, shows the effects of the different events. Grossman has used such a model to analyze several events observed in COARE and CEPEX. Each of the components of the columnar heat budget (net insolation, net IR cooling, evaporation, and ocean mixing) had different values for each event. In summary, FW was a heating event (1-7

Interplay Between Evaporation, Radiation, and Ocean Mixing in the Regulation of Equatorial Pacific Sea Surface Temperature

days), WWB was a cooling event (4-10 days), MCS was a cooling event (2-4 days), and DW (1-7 days) was borderline, either little or no heating/cooling.

The sequence of these events and how they could account for the observed SST variability was discussed. The frequency of occurrence of these events is important to the problem. For instance, the strongest cooling was associated with a MCS-WWB couplet, which is consistently observed. However, the MCS-WWB couplet (strong cooling) is very intermittent, as is a long period of FW (strong warming). In between, short periods of FW and DW are often observed followed by MCS. It therefore appears that a strong warming event can follow a strong cooling event, with shorter periods of modest heating and cooling in between. It is relatively easy to build sequences which can explain current observations of W. Pacific SST variability. This "extended" period of modest heating and cooling would be associated with MCS which would be necessary to account for the maximum in atmospheric transport noted by Trenberth and Solomon. Grossman's current research is directed to continuing this investigation using observations from COARE and CEPEX.

At least some of the time, warm SSTs are associated with low wind speeds, and low SSTs follow periods of high wind speed.

In Tropical Ocean Global Atmosphere (TOGA) COARE, measurements of atmospheric and oceanic variables in the Western Tropical Pacific were made for a period of four months. Figure 6.1 shows SST and wind speed variations during this period. It appears that SST shows a cycle of 3-4 months but clearly, a longer observation period would be necessary to confirm this. There are indications that at least some of the time, warm SSTs are associated with low wind speeds, and low SSTs follow periods of high wind speed. Figure 6.2 is a phase diagram showing sequence of heating and cooling of ocean surface and upper ocean (0-200 m) as a function of wind speed.

Sea Surface Temperature & Surface Wind From Daily Ship Reports

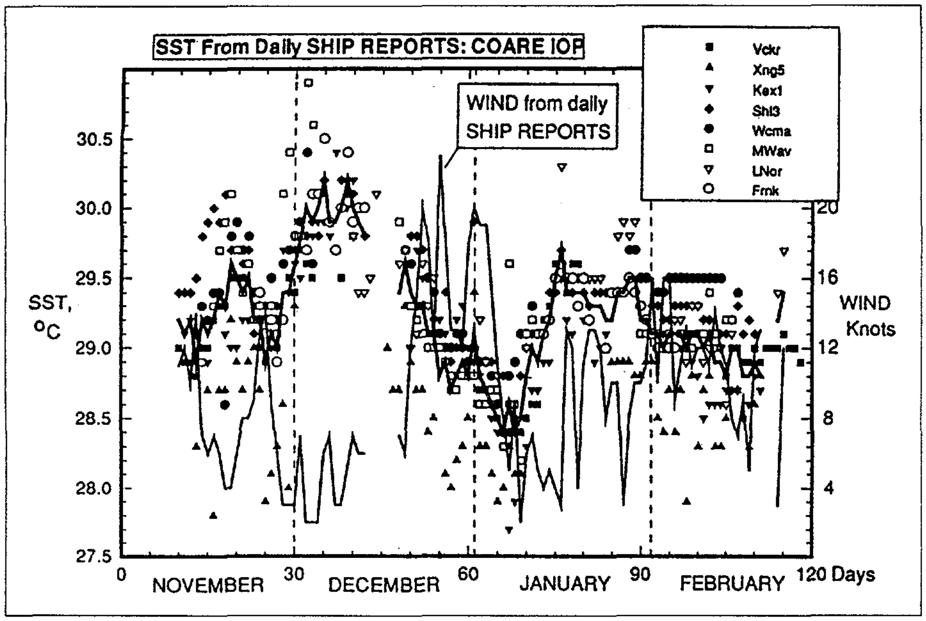

Figure 6.1: SST and wind observations in TOGA COARE

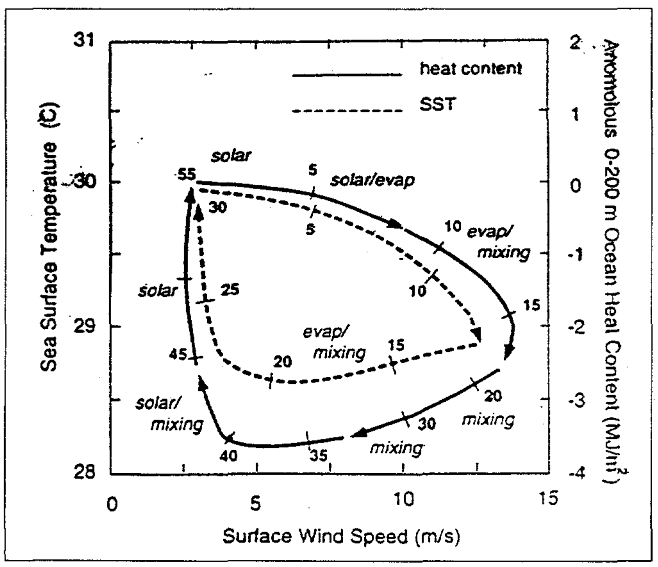

Figure 6.2: Phase diagram showing sequence of heating and cooling of ocean surface and upper ocean (0-200 m) as a function of wind speed. Physical mechanisms similar to those we feel important to the SST limitation problem are presented. Numbers on the curves are days from beginning of the sequence at number 55. Thanks to Peter Webster for sharing this figure which is based upon the Christmas-New Years cooling event in COARE.

7

Fuzzy Cloud Concepts for Assessing Radiation Feedbacks

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The importance of clouds in the climate system is well-known but poorly understood. Modeling and observational studies have suggested that there may be positive feedbacks associated with certain cloud processes, but it is not known how strong these feedbacks are in the context of the overall system. Examples include ice microphysics feedback, as shown by Liou's model, and the relationship between SST and cloud cover in the tropics (Hanson, 1991), which is the focus of this research.

An alternative approach would be to avoid the issue by inferring radiative properties for nondeterministic "fuzzy" cloud populations.

The traditional description of clouds in climate models has been deterministic; the resolved-scale variables in the model are used to diagnose or predict specific cloud distributions. An alternative approach would be to avoid the issue by inferring radiative properties for nondeterministic "fuzzy" cloud populations (nondeterministic, in the sense that there are typically not enough grid box variables to uniquely determine the nature of the cloud). In this approach, the radiative properties of the cloud field are obtained by averaging over probability distributions of clouds with different cloud fractions.

Also, the traditional focus on clouds had proven to be distracting from the more general problem of the radiative properties of water substance (in all three phases) on scales relevant to climate models. Adopting a "fuzzy concept" approach to the problem of clouds in climate models could avoid this distraction and, potentially, lead to increased understanding of how the climate works. In some ways, these approaches to the cloud/climate problem are complementary to observational methods that rely on multifractal-based pattern recognition; in this case, the fuzzy logic is applied from the cloud process perspective.

The combination of these approaches is attempted here for clouds in the subtropical marine boundary layer, with encouraging, albeit highly preliminary, results. Boundary layer models generally require either a specification of, or a closure for, cloud cover. However, in the former mode they provide physically realistic solutions which satisfy external requirements for a limited range of cloud covers. It could therefore be assumed that solutions within this range have an equal probability of occurrence and that the relevant results (e.g. radiative properties) could be obtained by averaging over the range. This is illustrated using a very simple, empirically-based parameterization of cloud transmittance from the Derr *et al.* paper, in a variety of cloud populations. (Figures 7.1 and 7.2)

Treating water in the atmosphere in a unified fashion is a somewhat more daunting concept, but the mixing line approach of Betts offers one possible point of attack. A model due to Betts and Ridgeway (basically a single Hadley cell; figure 7.3) is used here to illustrate how this could be done. Comparisons between this model and the simple, empirical model mentioned above, while imperfect, suggest consistency and the need for follow-up studies. Also, the positive feedback between SST and cloud cover (for subtropical marine boundary layer clouds) is shown to be consistent with these model approaches.

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The traditional focus on clouds had proven to be distracting from the more general problem of the radiative properties of water substance.

Fuzzy Cloud Concepts for Assessing Radiation Feedbacks

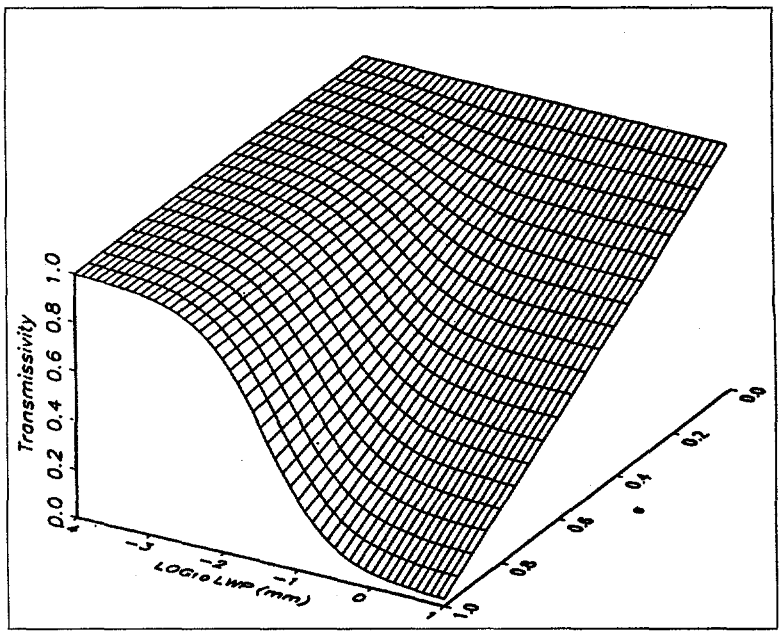

Figure 7.1: Transmissivity as a function of liquid water path and cloud fraction, as parameterized by Derr et al.
Source: Cooperative Institute for Research in Environmental Sciences University of Colorado at Boulder

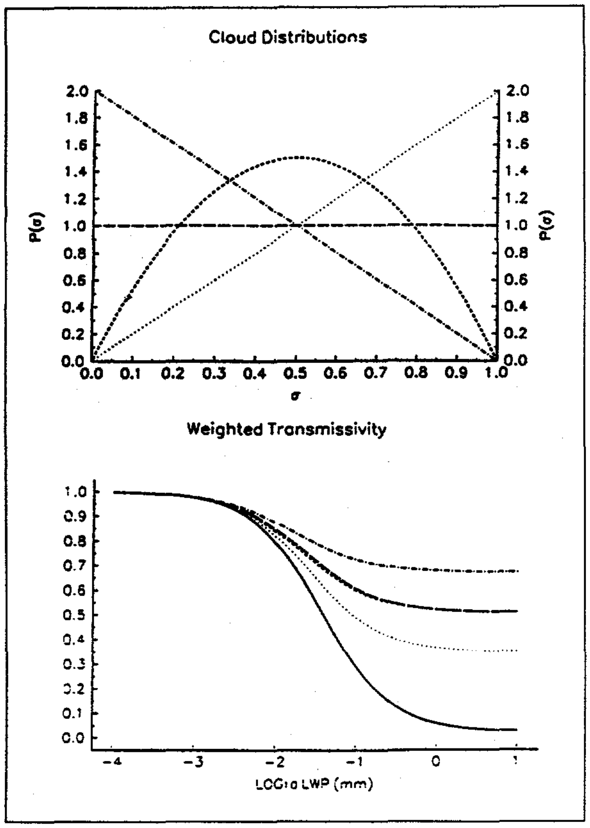

Figure 7.2: Cloud distributions and corresponding transmissivity dependence on liquid water path, as used by Derr et al.
Source: Cooperative Institute for Research in Environmental Sciences University of Colorado at Boulder

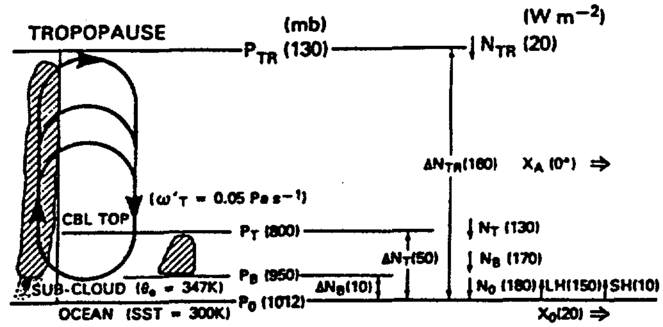

TABLE 2. Model parameters: Base set.

Solar zenith angle	51.74°
Surface albedo	0.07
Incoming SW flux	1360.3 W m^{-2}
CBL parameters	
cloud	β_c = 0 (subcloud); 0.6 (cloud layer)
environment	β_u = 0.2 (subcloud); 1.2 (cloud layer)
Subcloud layer closure parameter	k = 0.25
Tropopause subsaturation	$\mathcal{P}_{TR}$ = −30 mb
Mixing ratio just above CBL	q_T = 4.8 g kg^{-1}
Ocean surface temperature	SST = 300 K
Surface wind parameter	ω_O = 0.1 Pa s^{-1} (≈6.7 m s^{-1})
Tropospheric	θ_{α} = 347 K
Subsidence parameter	$\omega_{T'}$ = 0.05 Pa s^{-1}
Cloud fraction	= 25%

Figure 7.3: A schematic depiction of the Betts and Ridgeway model.
Source: Cooperative Institute for Research in Environmental Sciences, University of Colorado at Boulder

8

The Interpretation of Remotely Sensed Cloud Properties From a Model Parameterization Perspective

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For low-level single-layer clouds it is found that the mean retrieved liquid water path in cloudy pixels is essentially invariant to the cloud fraction, at least in the range 0.2 - 0.8.

The goals of ISCCP and FIRE are, broadly speaking, to provide methods for the retrieval of cloud properties from satellites, and to improve cloud radiation models and the parameterization of clouds in GCMs. This study suggests a direction for GCM cloud parameterizations based on analysis of Landsat and ISCCP satellite data.

High-resolution Landsat data is degraded to the various resolutions used by ISCCP, and then a threshold used for clear/cloudy determination of pixels at those resolutions. For low-level single-layer clouds it is found that the mean retrieved liquid water path (LWP) in cloudy pixels is essentially invariant to the cloud fraction, at least in the range 0.2 - 0.8 (Figure 8.1). Decreasing the pixel resolution does not alter this conclusion - it only reduces the specific constant value of mean LWP within this range (Figure 8.2). At high cloud fractions (greater than ~0.8, say) the LWP can be considerably higher than the relatively constant value for lower fractions.

It appears that, at any instant, the mean LWP of the cloudy areas is the average of a population of clouds each of which has relatively constant LWP. The number of clouds in the population determines the cloud fraction, but as long as the number is not so large that clouds begin to fill the domain, the mean LWP for the cloudy area is the same. The closed and open cells associated with marine stratocumulus and trade cumuli respectively, are seen to exhibit such a feature. Trade cumuli are much narrower and deeper than are stratocumuli, and hence have a larger mean LWP per cloud. But for either type of cloud, increasing the number of clouds, and hence the cloud fraction, will not change the mean LWP of the clouds unless the clouds begin to saturate the domain.

The constancy of mean LWP with cloud fraction implies that the total volume of liquid in a box is a linear function of cloud fraction

(Figure 8.3). This result is very important since it allows the cloud fraction to be estimated if the mean LWP of cloud in a GCM gridcell is known. The prognosed or diagnosed total liquid water in the gridcell can then be distributed according to this cloud fraction. The mean LWP for the clouds needs to be specified either empirically or using some process model.

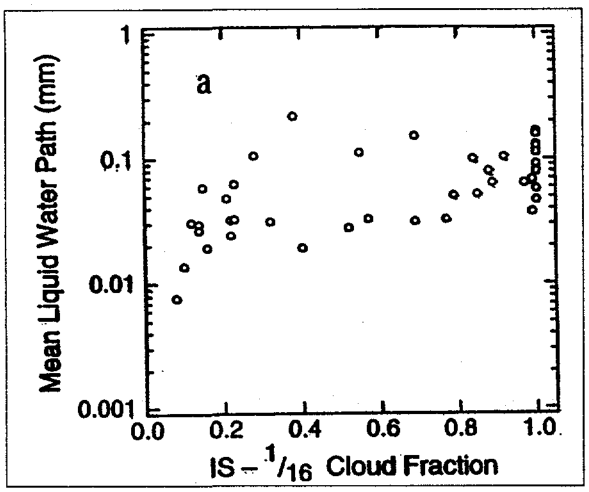

Figure 8.1: Dependence of liquid water path on cloud fraction, based on an analysis of Landsat data

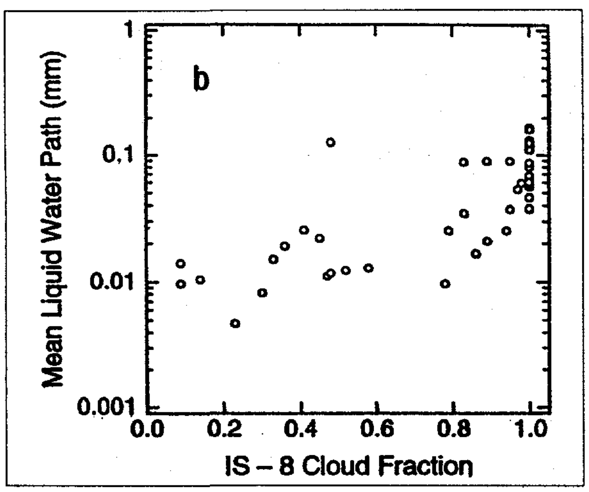

Figure 8.2: As in Figure 8.1, but with degraded pixel resolution

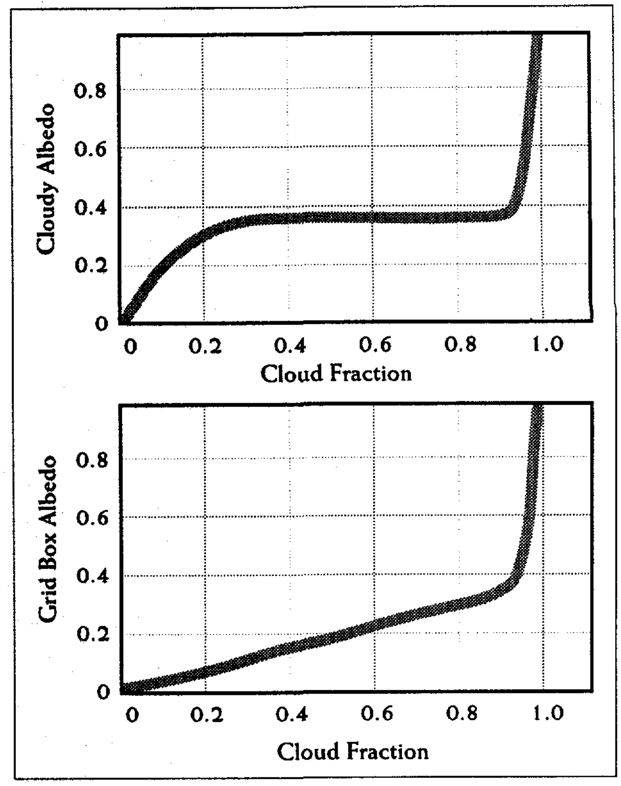

Figure 8.3: Schematic illustration of the dependence of both cloud albedo and grid box albedo on cloud fraction

This result is very important since it allows the cloud fraction to be estimated if the mean liquid water path of cloud in a GCM gridcell is known.

9

Sensitivity of the CCM Climate to Enhanced Cloud Absorption

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Recent indications suggest that clouds may be absorbing more solar radiation than was previously thought. This research investigates some of the evidence for this hypothesis; potential physical mechanisms are briefly discussed as well. The climatic implications of the enhanced absorption are investigated using the NCAR Community Climate Model (CCM). It is found that the model's heat budget in the tropical warm pool agrees more closely with observations when enhanced absorption is included.

The model's heat budget in the tropical warm pool agrees more closely with observations when enhanced absorption is included.

Observational evidence: Cess *et al.* correlated top of the atmosphere (TOA) albedo as a function of normalized surface insolation. Points lie approximately on a line with a slope of ~-0.6 for observations in four locations (Barrow, Boulder, Samoa, and Wisconsin), compared to a slope of ~-0.8 for two GCMs (CCM2 and ECMWF). This implies that the model atmospheres are absorbing too little solar radiation. This result is independently confirmed by comparing the mean short wave cloud radiative forcing (SWCF) at the surface to that at the TOA. The ratio of these two values is 1.5, which is the reciprocal of -0.6, corrected for the surface albedo.

Indirect evidence is provided by Ramanathan *et al* .who evaluate the annual mean surface heat budget for the tropical warm pool, using many years of data, and infer a SWCF at the surface of -105Wm^{-2} and at TOA of -66Wm^{-2}, which yields a ratio of 1.5.

In comparison to this direct and indirect observational evidence for a ratio of 1.5, current radiative transfer models, incorporating very little cloud absorption, produce a ratio close to 1. Apparently, the models are depositing too much solar flux at the surface compared to the measurements. Observations suggest that a further 40Wm^{-2} should be absorbed in the model atmosphere.

Solar absorption by clouds in the models is parameterized via the single scattering albedo, which is a function of cloud particle size. One way to correct the models is to adjust this particle size. (Larger particles absorb more radiation than smaller ones.) An effective particle size of 60-70 microns would be needed to achieve the correct absorption, but this is unrealistically large. In practice, for the purpose of the following climate simulations, the increased absorption is introduced by increasing the co-albedo in the visible region and near-infrared region.

Possible mechanisms for the observed enhanced cloud absorption include vapor-droplet 'overlap,' finite cloud effects, continuum absorption, and aerosols.

Implications for accuracy of GCMs

Figure 9.1 shows the solar flux budget of the global annual mean atmosphere without enhanced cloud absorption. Including enhanced cloud absorption by changing the cloud single scattering albedo leads to an increased TOA solar absorption of 12 W/m^2 (Figure 9.2). This reduction in planetary albedo from 0.32 to 0.29 would need to be tuned out in a GCM. Using cloud amount and cloud liquid water path to tune the TOA solar budget back to the control leads to a 40 W/m^2 change in the partitioning of solar flux between the surface and the atmosphere (Figure 9.3). This amounts to roughly half the global mean latent heat flux. Possibly, this large amount of heat flux was missed because in past model runs SST was typically fixed, and many models overestimated surface latent heat flux.

Including the additional cloud absorption had the following effects: latent heat flux decreases by about 25W/m^2 in the tropics, precipitation decreases, solar heating in the atmosphere is roughly doubled, the upper troposphere is warmed by about 6°C, upper tropical easterlies accelerate by about 16 m/s, the troposphere is significantly moistened, total average global cloud cover decreases by 4%, the Hadley cell is slowed down by about 10% (hence, surface winds decrease, consistent with the latent heat decrease). The model with enhanced cloud absorption agrees far better with Ramanathan *et. al.*'s warm pool heat budget discussed above. Incidentally, studies of the warm pool region indicate the need to include aerosol effects to eliminate 20 W/m^2 bias in the surface clear sky flux.

On the whole, the addition of enhanced absorption improves the model's performance in the tropics and degrades it in the extra-tropics. Before enhanced absorption can be included operationally in GCMs, the cause of this absorption should be determined.

On the whole, the addition of enhanced absorption improves the model's performance in the tropics and degrades it in the extra-tropics.

Sensitivity of the CCM Climate to Enhanced Cloud Absorption

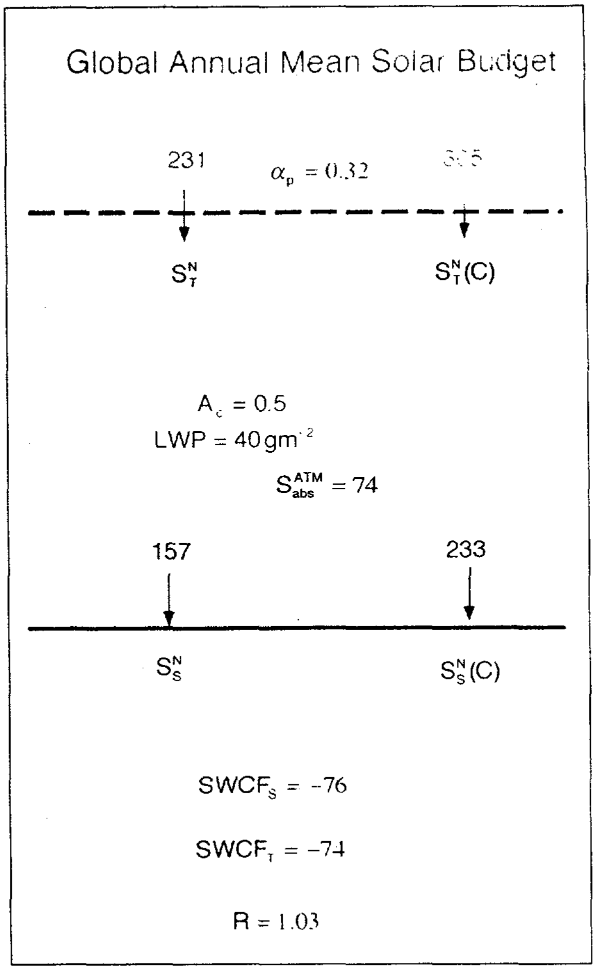

Figure 9.1: Solar flux budget of global annual mean atmosphere without enhanced cloud absorption

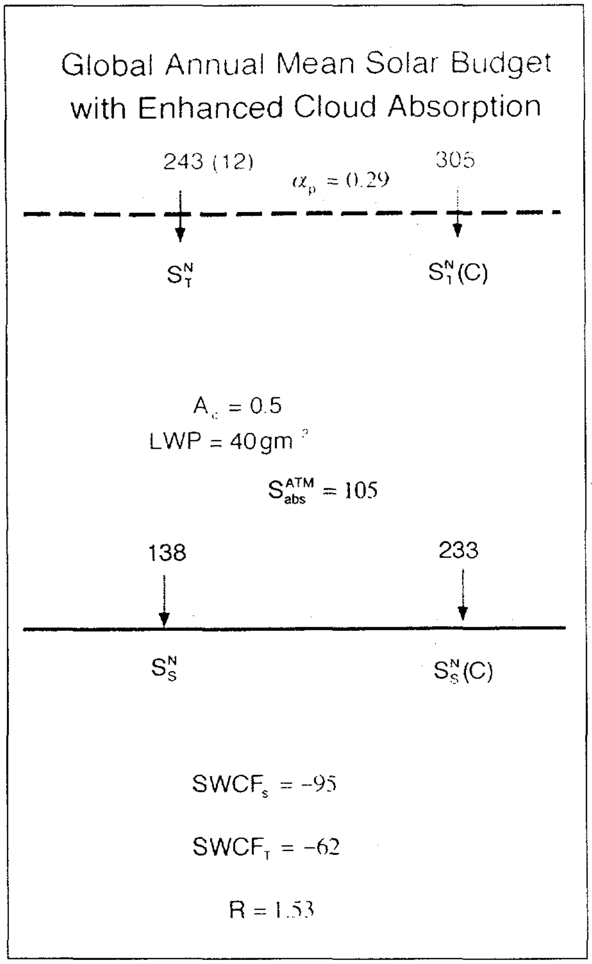

Figure 9.2: As in Figure 1, but with enhanced cloud absorption

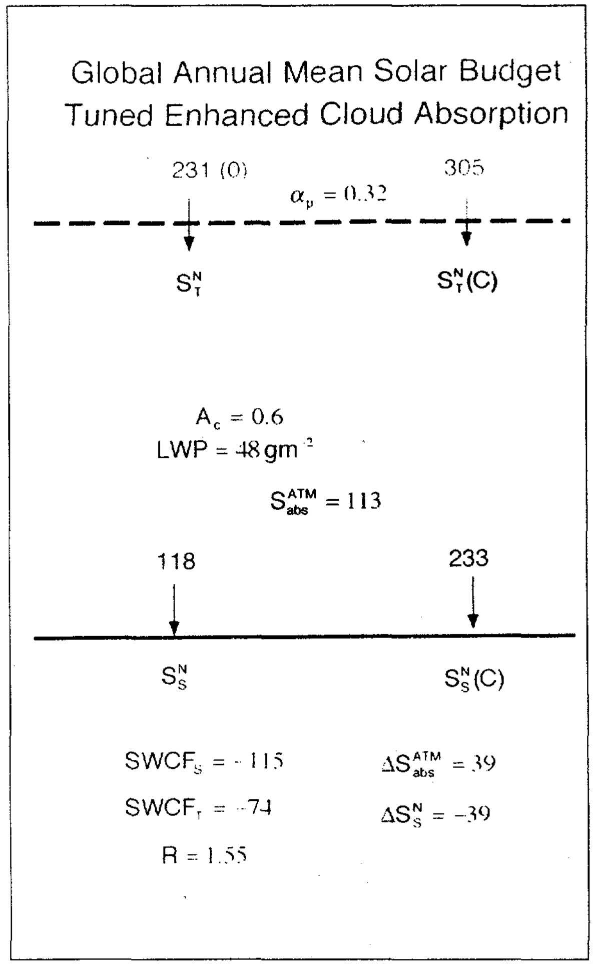

Figure 9.3: As in Figure 2, but including the effect of tuning cloud amount and cloud liquid water path

10 Climatic Implications of Ice Microphysics

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The temperature field perturbed by external radiative forcings, such as greenhouse warming, can alter the composition of ice crystal clouds.

Based on aircraft measurements of mid-latitude cirrus clouds, ice crystal size distribution and ice water content (IWC) are shown to be dependent on temperature (Figure 10.1). This dependence is also evident from the theoretical consideration of ice crystal growth. Using simple models of the diffusion and accretion growth of ice particles, Liou shows that the computed mean ice crystal size and IWC compare reasonably well with the measured mean values. The temperature dependence of ice crystal size and IWC has important climatic implications in that the temperature field perturbed by external radiative forcings, such as greenhouse warming, can alter the composition of ice crystal clouds. Through radiative transfer, ice microphysics can in turn affect the temperature field. Higher IWC would increase cloud solar albedo and infrared emissivity, while for a given IWC, larger crystals would reduce cloud albedo and emissivity. The competing effects produced by greenhouse temperature pertubations via ice microphysics and radiation interactions and feedbacks are assessed by a one-dimensional radiative-convective climate model that includes an advanced radiation parameterization program.

The radiation model includes the delta-four-stream approximation for radiative transfer in nonhomogeneous atmospheres, the correlated k-distribution method for non-gray gaseous absorption, and the scattering and absorption properties of hexagonal ice crystals. The broad band results computed from the delta-four-stream method are found to be about 5% accurate over the full range of zenith angles and optical depths. In comparison, delta-two-stream (or Eddington) calculations, while less computationally expensive, show errors of 20-30% for a number of conditions (Figure 10.2). The correlated k-distribution method is a new technique for computing transfer of radiation involving absorption lines and is superior to the conventional band model approach that is coupled with the scaling and two-parameter approximations. It is exact for a single line and periodic lines, and the absorption coefficients so derived can be directly incorporated in the multiple scattering model for non-homogeneous atmospheres.

The radiation program is driven by the ice water path, the product of IWC and cloud thickness, and mean effective ice crystal size, which are parameterized in terms of temperature based on measured cloud microphysics data. It is important to use the scattering and absorption properties of hexagonal ice crystals in the calculation of solar albedo for ice crystal clouds. Use of equivalent spheres will provide a significant underestimation of solar albedo, because spheres scatter more in forward directions as well as absorb more incident radiation than non-spherical ice particles.

The feedbacks and interactions involving ice crystal diffusion and accretion growth, radiative processes in terms of solar albedo and infrared emissivity, and equilibrium surface temperature are investigated by using a one-dimensional climate model with CO_2 doubling as the climatic forcing. Increasing temperature raises the ice crystal size through diffusion and accretion growth which reduces cloud albedo and emissivity. The combined effect of the feedbacks is to raise the 2 x CO_2 surface temperature increase from a control run of 2.4° to 3.0° C with a net positive temperature-emissivity feedback dominating a net negative temperature-albedo feedback (Figure 10.3). Uncertainty factors, such as the parameterization of ice microphysics as a function of temperature, the radiative properties of small ice crystals and various ice crystal shapes, and the effects of cloud horizontal nonhomogeneity on radiation, require more comprehensive analyses of cloud and radiation data derived from composite field experiments and model simulations.

Increasing temperature raises the ice crystal size through diffusion and accretion growth which reduces cloud albedo and emissivity.

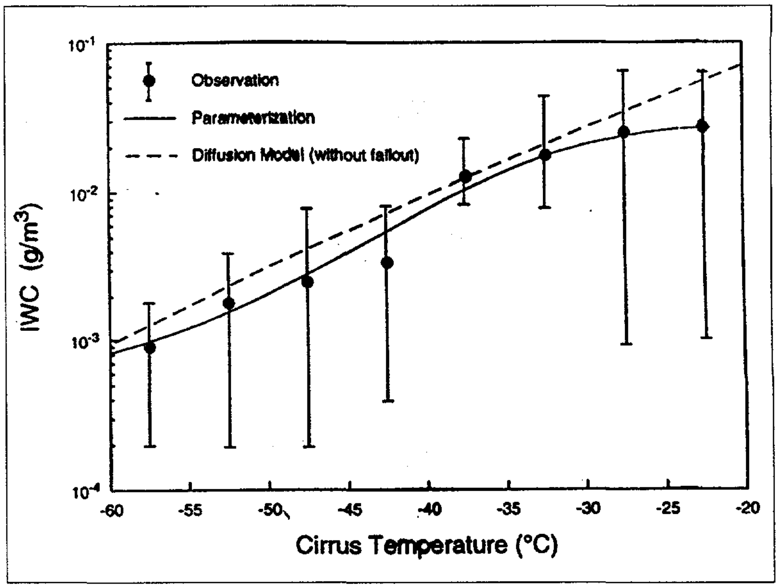

Figure 10.1: Observed and modeled dependence of cirrus ice water content on temperature

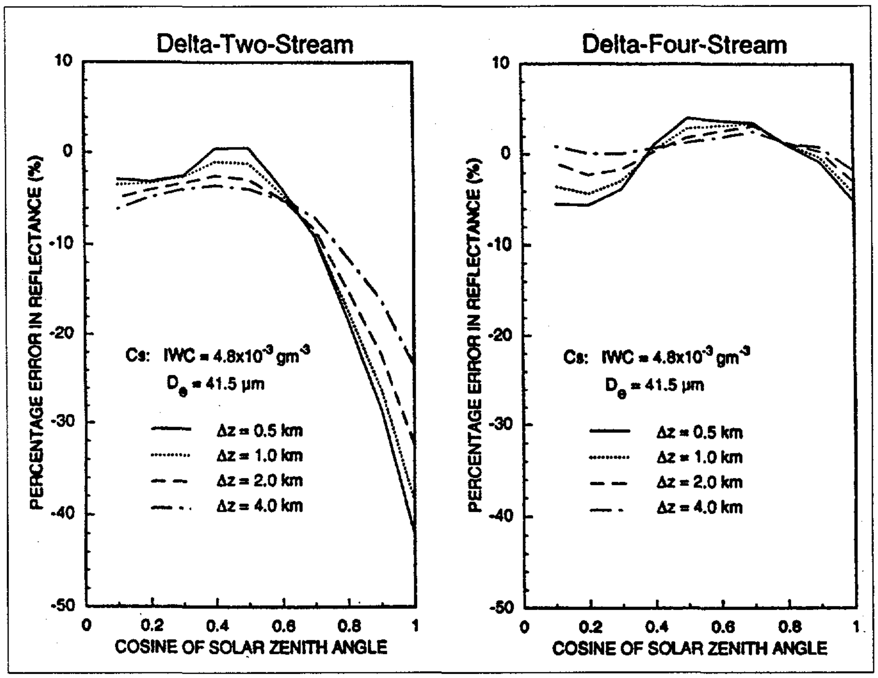

Figure 10.2: Percentage errors in delta-two-stream and delta-four-stream calculations

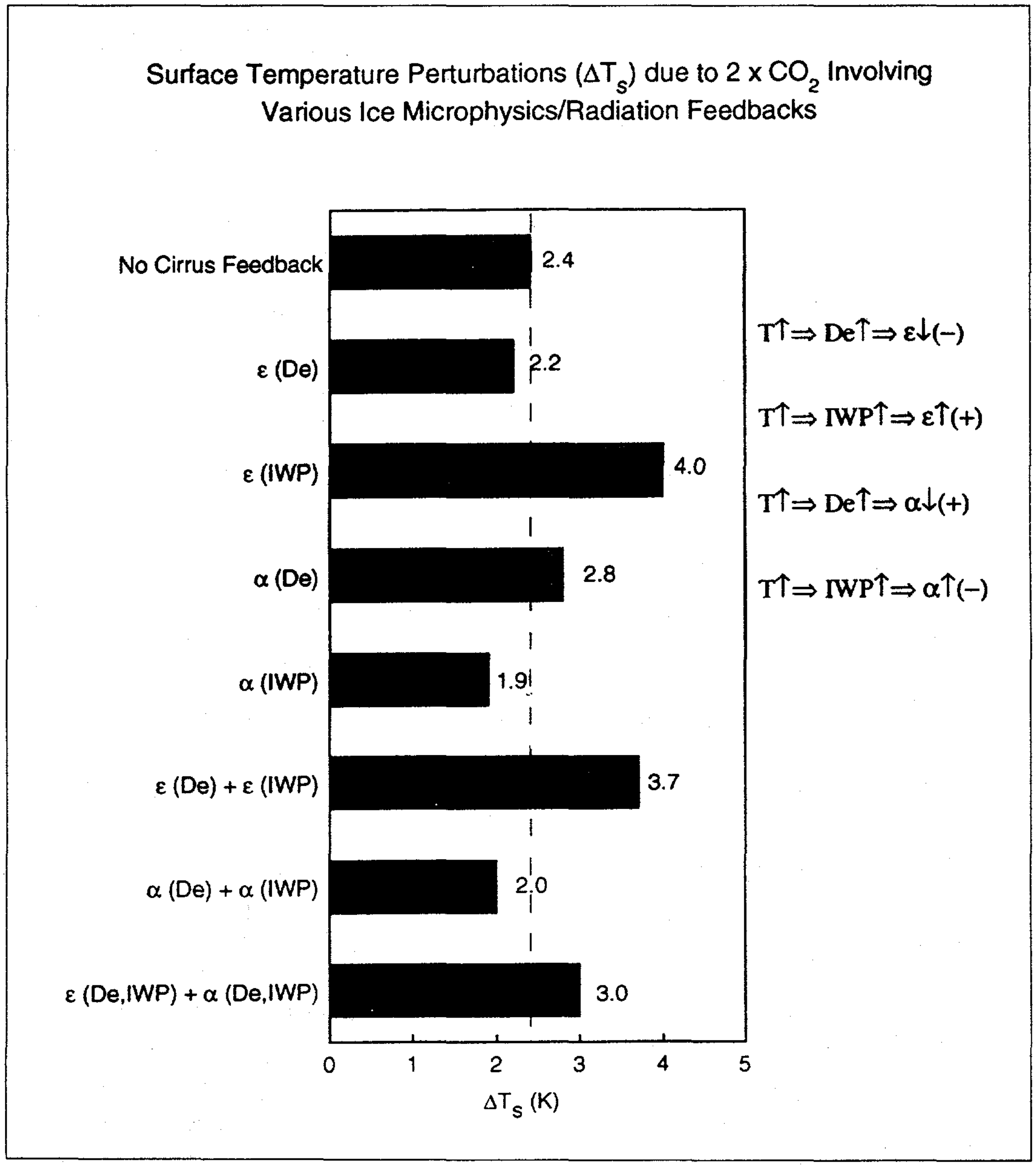

Figure 10.3: Temperature perturbations resulting from doubling carbon dioxide in a one-dimensional model incorporating ice microphysical radiative feedbacks

11 Generalized Scale Invariance, Clouds and Radiative Transfer on Multifractal Clouds

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Recent systematic satellite studies (LANDSAT, AVHRR, METEOSAT) of cloud radiances using (isotropic) energy spectra have displayed excellent scaling from at least about 300m to about 4000km (Figure 11.1), even for individual cloud pictures (Lovejoy et al., 1992). At first sight, this contradicts the observed diversity of cloud morphology, texture and type. Lovejoy and Schertzer (L&S) argue that the explanation of this apparent paradox is that the differences are due to anisotropy, e.g. differential stratification and rotation. A general framework for anisotropic scaling expressed in terms of isotropic self-similar scaling and fractals and multifractals is needed. Schertzer and Lovejoy (1985, 1991) have proposed Generalized Scale Invariance (GSI) in response to this need. In GSI, the statistics of the large and small scales of system can be related to each other by a scale changing operator T_λ which depends only on the scale ratio λ; there is no characteristic size.

In Generalized Scale Invariance, the statistics of the large and small scales of system can be related to each other by a scale changing operator which depends only on the scale ratio; there is no characteristic size.

From this definition it can be concluded that T_λ must obey group properties: $T_\lambda=\lambda^{-G}$ where G is the generator. L&S showed by multifractal simulation how different cloud types and textures can be simulated by varying G. Similarly, they showed how to estimate G from satellite pictures.

L&S then turned to the problem of radiative transfer in fractal clouds (until 1990, with P. Gabriel, A. Davis, and G. L. Austin) and in multifractal clouds (since 1990). The most significant result of the research on monofractal clouds (occupying only a fractal subset of the space) is that two fundamental limits exist: the optically thick and optically thin cases. The bulk transmission and reflection properties, considering periodic boundary conditions and conservative scattering vary for thick clouds as $T=ht^{-\nu}$, $R=1-T$, where $\nu=1$ in plane parallel homogeneous clouds but $\nu<1$ for the fractals. Here, h is a phase function. This means that for sufficiently thick clouds, plane parallel predictions can be seriously inaccurate.

Numerical results from single as well as multiple realizations underscore the dangers and large errors arising from invoking one-to-one relations between cloud parameters (e.g., large scale mean liquid water content) and large scale mean fluxes.

Finally, L&S outlined some recent results of scattering statistics on multifractal clouds (with B. Watson and G. Brosmalen), pointing out the fundamental qualitative difference between clouds with many and few sparse low-density regions; corresponding to the existence (or nonexistence, respectively) of negative statistical moments. Detailed study of the lognormal multifractals allowed L&S to develop a thick cloud formalism for photon transmission statistics (Lovejoy et al., 1992). Due to the near linearity of the photon path moment scaling function, renormalization of the optical density to an "equivalent" plane parallel density was a good approximation in this case. It gave very close agreement with direct simulations on thick lognormal multifractals. It also gave the same result as for the theoretical (one-dimensional) diffusion on lognormal multifractals (joint research with P. Silas). These stochastic radiative transfer results can explain the success of first-order Markov approximations which ignore high-order correlations in scatterings.

References

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These stochastic radiative transfer results can explain the success of first-order Markov approximations which ignore high-order correlations in scatterings.

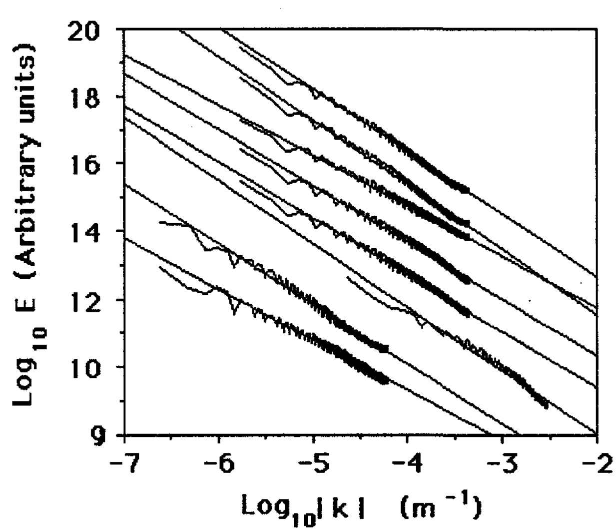

Figure 11.1: Average power spectrum for the satellite images grouped according to the satellite and the frequency range of the images (from bottom to top): LANDSAT (visible) b = 1.7 • GOES (visible) b = 1.4 • GOES (infra red) b = 1.7 • Nimbus-9 (channel 1 to 5) b = 1.67, 1.67, 1.49, 1.91, 1.85 (See Tesier et al., 1992, Lovejoy et al., 1992).

12 Preliminary Investigation of Radiatively Driven Convection in Marine Stratocumulus Clouds

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Marine stratocumulus play an important yet still poorly modeled role in the climate system (Charlson et al., 1987, Roeckner, 1994). These clouds cool the planet, having a large albedo, but little infrared effect. A fundamental question is whether such clouds will exist at a given time and location. Stratocumulus is often formed at higher latitudes as stratus and advected equatorward until it breaks up. Possible mechanisms for cloud breakup include strong subsidence, cloud top entrainment instability (CTEI), drizzle, solar heating and resultant boundary layer decoupling, and surface forcing. The Atlantic Stratocumulus Transition Experiment (ASTEX) was conducted (Açores, June 1992) to investigate these potential cloud breakup mechanisms.

Marine stratocumulus play an important yet still poorly modeled role in the climate system.

A secondary question is the importance of cloud *texture* on the radiative properties of the stratocumulus, and in particular on the cloud albedo. Simple calculations (using the delta-Eddington and independent pixel approximations) were made with a fixed total liquid water content which was distributed in space sinusoidally with varying amplitude. For a mean optical depth of 10, the albedo decreases by ≈15% in going from a homogeneous cloud to one in which the optical depth becomes zero at the troughs of the sinusoid. Hence, the effect of cloud texture is indeed significant.

Convection can be driven in the stratocumulus layer by cloud-top longwave radiative cooling and warming below. This warming may be due to solar heating or to longwave cloud-base warming. This produces a cellular structure in the cloud. The dominance of cloud top cooling leads to closed cells (Getling, 1991; Agee, 1987). A quantitative understanding of radiatively induced convection is thus required, both to correctly estimate the cloud top entrainment rate (and the potential for cloud breakup) and to estimate texture statistics for the albedo calculation.

Norris presented an example of some liquid water and radiative flux data from aircraft during ASTEX. The cloud optical depth was estimated from aircraft profiles of cloud liquid water content and effective radius. A delta-Eddington calculation of the cloud albedo agreed well with the albedo measured during an overflight of the cloud. An interesting result was the observation of significant energy at the scale of ≈600 meters in the cloud albedo spectrum and possibly the liquid water content spectrum. This is thought to be related to radiatively generated convective cells in the cloud. It is planned to use ASTEX data to test modeling efforts underway.

An existing three-dimensional Rayleigh-Bénard code (Hathaway and Somerville, 1986) has been modified to perform simulations of a cloud-topped marine boundary layer. Convection is driven in a virtual cloud layer characterized by an effective differential radiative forcing (top cooling and base warming). The cloud layer is above an initially neutral subcloud layer and below a strong capping inversion. As convection sets in, negatively buoyant cloud top air is mixed down into the top of the neutral subcloud layer and destabilizes it, causing the model to jump to a new steady state with a characteristic profile of convective kinetic energy. Figure 12.1 shows the growth of convective cells in the mid-cloud horizontal plane. Lighter shades indicate upward motion. Clearly the cellular pattern is closed, as is expected for a dominantly top-cooled system. Figure 12.2 shows a vertical slice through the model in three variables. The upper panel shows the potential temperature perturbations generated by convection. The convective cells are clearly visible. The second panel shows that the downdrafts generated at cloud top extend all the way to the surface, thereby forcing the whole boundary layer. Figure 12.3 shows the profiles of horizontally averaged potential temperature, both initially and after the convective steady state is established. This final state is characterized by an unstable surface layer, a near neutral mixed layer, a slightly stable transition layer below cloud, a cloud layer which is unstable, but less so than before convection was established, and a strong capping inversion. All of these features are also found in the actual observed marine boundary layer.

The Rayleigh-Bénard boundary layer model will be used to investigate the amount of convective kinetic energy and cloud top mixing generated as a function of such factors as the strength of radiative forcing (cloud Rayleigh number), the depth of the subcloud layer, and the strength of the capping inversion. Such a study will provide a simple

An interesting result was the observation of significant energy at the scale of ≈600 meters in the cloud albedo spectrum and possibly the liquid water content spectrum. This is thought to be related to radiatively generated convective cells in the cloud.

Preliminary Investigation of Radiatively Driven Convection in Marine Stratocumulus Clouds

An existing three-dimensional Rayleigh-Bénard code has been modified to perform simulations of a cloud-topped marine boundary layer.

dynamical framework for more complicated models including realistic clouds and turbulence. The long-term aim is to make realistic predictions of observed cloud spatial scales and entrainment rates at cloud top and base.

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Mid-Cloud Vertical Velocity

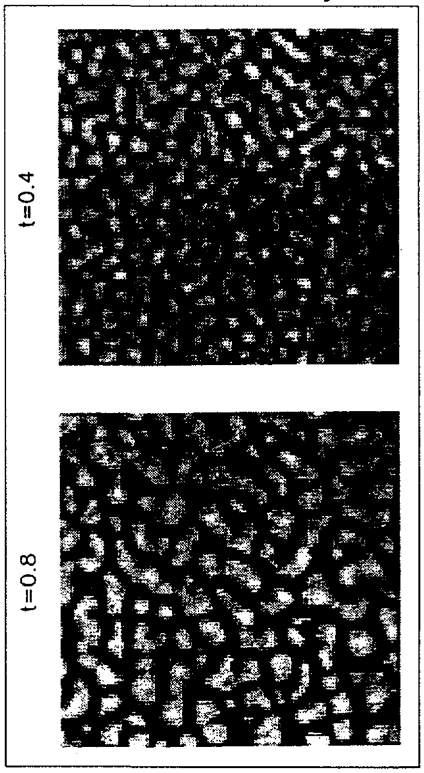

Figure 12.1: Vertical velocity in a mid-cloud horizontal plane at non-dimensional times 0.4 and 0.8. Lighter shades indicate upward motion. Note the closed cellular structure characteristic of dominantly top-cooled systems, and the growth in cell size with time.

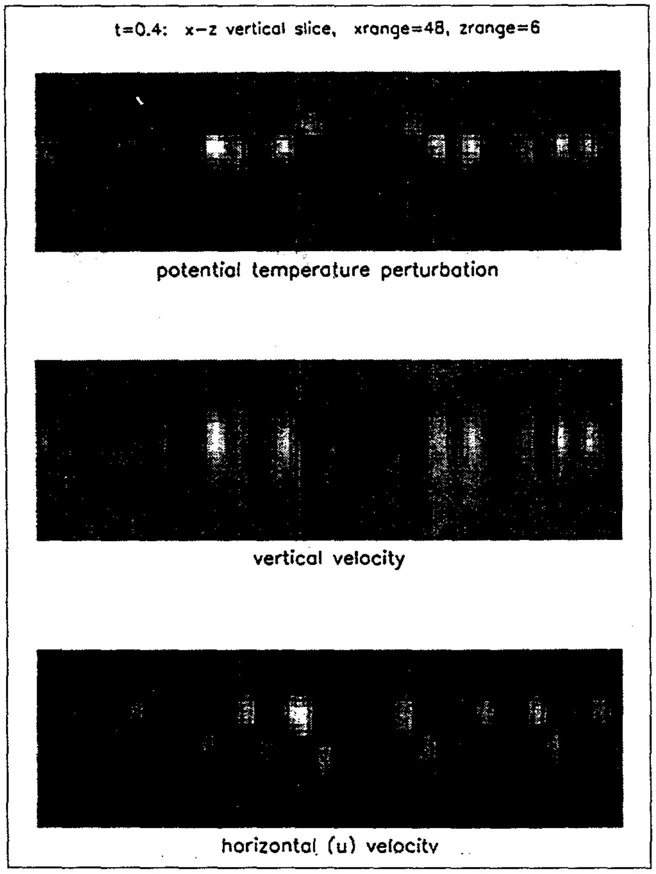

Figure 12.2: Vertical slices through the model domain showing potential temperature perturbation, vertical velocity and horizontal (u) velocity. Note that the cellular structures extend all the way to the surface in the velocity fields.

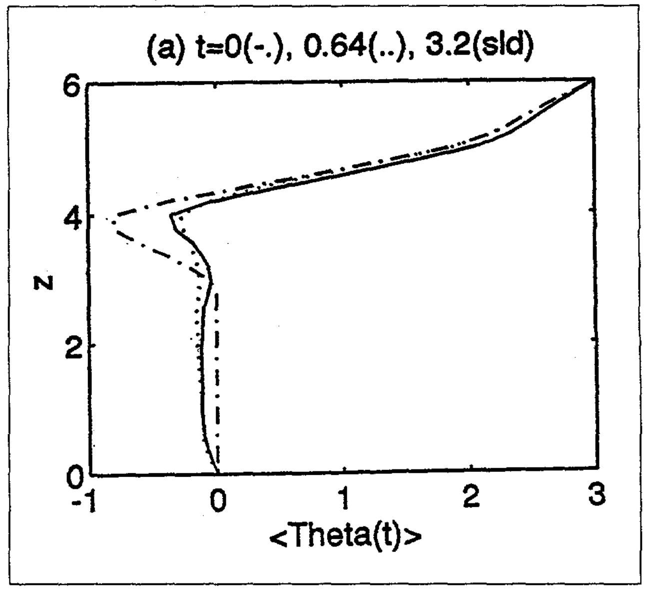

Figure 12.3: Profiles of horizontally averaged potential temperature: t=0 is the initial profile, t=3.2 is a profile typical of the final convective steady state.

13

Preliminary Results of a Three-Dimensional Radiative Transfer Model

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Clouds act as the primary modulator of the Earth's radiation at the top of the atmosphere, within the atmospheric column, and at the Earth's surface. They interact with both shortwave and longwave radiation, but it is primarily in the case of shortwave where most of the uncertainty lies because of the difficulties in treating scattered solar radiation. To understand cloud-radiative interactions, radiative transfer models portray clouds as plane-parallel homogeneous entities to ease the computational physics. Unfortunately, clouds are far from being homogeneous, and large differences between measurement and theory point to a stronger need to understand and model cloud macrophysical properties. In an attempt to better comprehend the role of cloud morphology on the 3-dimensional radiation field, a Monte Carlo model has been developed. This model can simulate broadband shortwave radiation fluxes while incorporating all of the major atmospheric constituents. The model is used to investigate the cloud absorption anomaly where cloud absorption measurements exceed theoretical estimates and to examine the efficacy of ERBE measurements and cloud field experiments.

The Monte Carlo method is essentially a direct simulation of the physical processes involved in radiative transfer, in which the path of a photon is described by probability functions. These functions describe the distance a photon travels before an interaction with an atmospheric particle, if a photon is then absorbed or scattered, and if scattered, the direction the photon is scattered. The Monte Carlo model is designed around a 3-dimensional spatially dynamic structure. This structure provides for large low-variability cells to reduce computations and nested higher-resolution cells to allow the mixing of various spatial scales. Each cell can contain any combination and concentration of gases, aerosols and cloud droplets. The cloud fields used in the model are based on modified multifractal fields of liquid water. Broadband fluxes representing upwelling, downwelling, and absorbed shortwave radiation are derived from a few unique wavelengths

The Monte Carlo method is essentially a direct simulation of the physical processes involved in radiative transfer, in which the path of a photon is described by probability functions.

selected through a principal component analysis and a stepwise regression process.

Results from a tropical scenario with cloud optical depths ranging from 40 to 160 and cloud tops from 1 to 8 kms are displayed in Figure 13.1. The surface downwelling image shows surface fluxes approaching the solar constant from the effect of radiation being reflected from the sides of the towering cumulus. The upwelling fluxes are shown for the top of the cloud and at the top of the atmosphere (TOA). The flux at the TOA is diffused to such an extent that it is difficult to make out features of the cloud. Although ERBE claims to be an estimate of TOA flux, in reality it is a flux derived from TOA radiances where spatial features are easy to distinguish. The absorption image shows the highest column absorption occurs in cloud "valleys" where photons are focused causing enhanced water vapor absorption.

Figure 13.2 is a comparison of the Monte Carlo model results for a stratus cloud and independent pixel results using a plane-parallel model. As shown, higher surface downwelling and lower cloud top upwelling fluxes occur using the Monte Carlo model. Additionally, enhanced atmospheric absorption on the order of 30Wm^{-2} obtained from the Monte Carlo model, suggesting the role of cloud morphology as a possible source for the cloud absorption anomaly. Figure 13.3 displays the difference between calculated atmospheric column absorption using a single-column budget approach and the "measured" absorption derived directly from the Monte Carlo model. As can be readily seen, there are large discrepancies between the two results, caused by the budget approach being unable to account for the redistribution of radiation in the horizontal plane. This result suggests that field experiments which use simultaneous measurements above and below a cloud to compute cloud absorption may produce erroneous results.

The cloud fields used in the model are based on modified multifractal fields of liquid water.

Preliminary Results of a Three-Dimensional Radiative Transfer Model

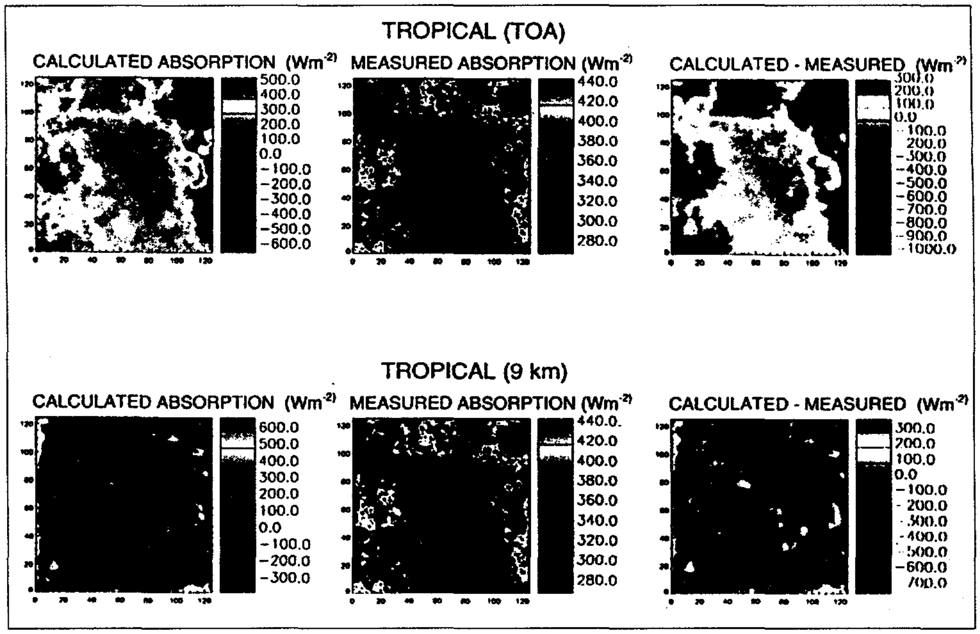

Figure 13.1: Results from a tropical scenario with varying cloud optical depths and cloud top heights

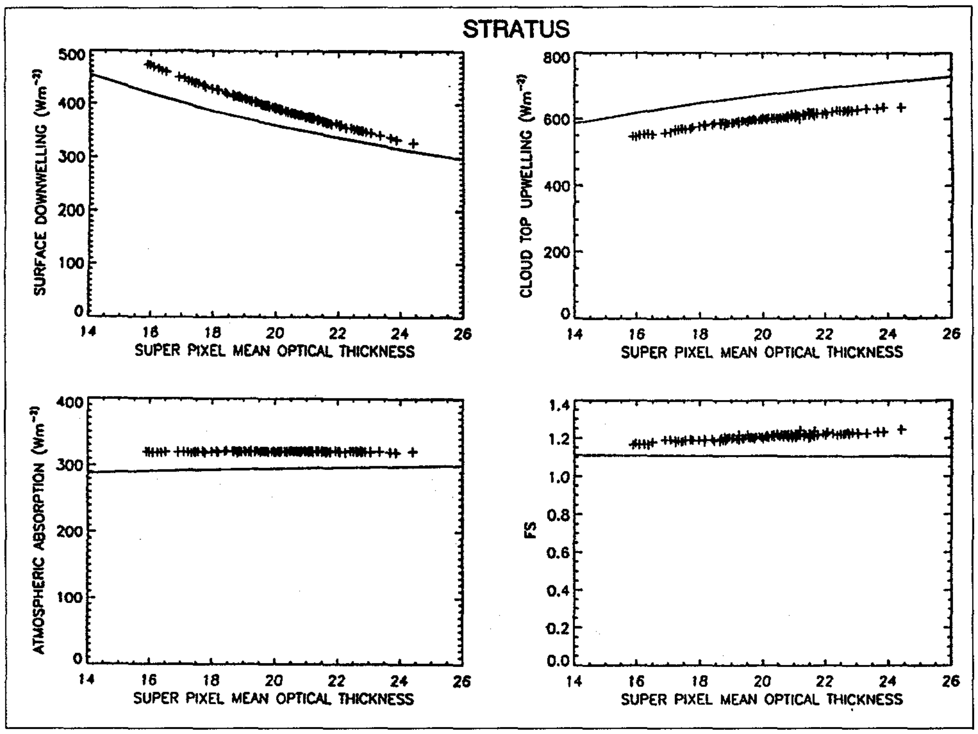

Figure 13.2: Comparison of Monte Carlo results and independent pixel results for stratus clouds

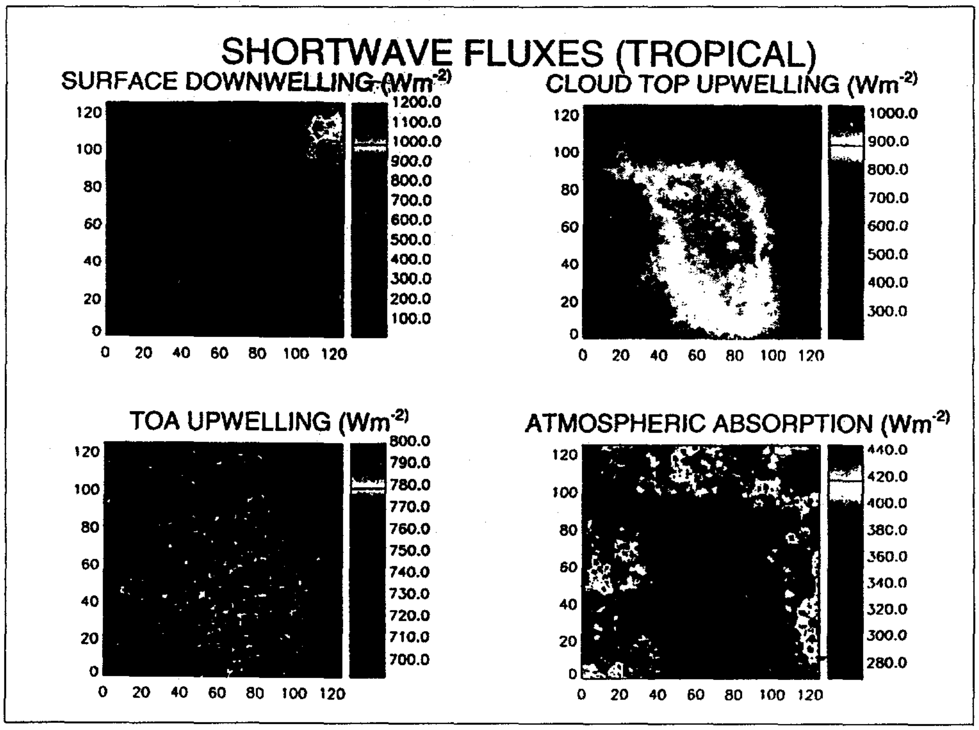

Figure 13.3: Difference between absorption calculated with a single-column budget approach and derived from the Monte Carlo model

14

Parameterization of Clouds and Radiation in Climate Models

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Clouds are a very important, yet poorly modeled element in the climate system. There are many potential cloud feedbacks, including those related to cloud cover, height, water content, phase change, and droplet concentration and size distribution. As a prerequisite to studying the cloud feedback issue, this research reports on the simulation and validation of cloud radiative forcing under present climate conditions using the ECHAM general circulation model and ERBE top-of-atmosphere radiative fluxes.

Model Parameterizations

The ECHAM model carries prognostic cloud water and includes parameterizations of most of the main microphysical cloud processes including droplet coalescence, ice sedimentation, and the evaporation, melting, and freezing of precipitation. Ice and liquid water are partitioned according to temperature.

Cloud droplet optical properties are parameterized as follows: Single scattering properties are calculated from Mie theory as a function of wavelength and effective radius. These values are then averaged over the spectral intervals of the broad-band radiation model used in the GCM and expressed as functions of the effective radius using a least-square method. Ice crystal optical properties are parameterized in the same way but the asymmetry factor is adjusted from Mie theory values (spherical particles) to values consistent with data from FIRE Cirrus. This accounts for the non-sphericity of ice crystals.

Effective radius of droplets depends on cloud liquid water, droplet concentration, and a spectral shape constant, which has different values in maritime and continental environments. Currently, the model does not predict droplet concentrations so fixed values are used for maritime and continental clouds. It is planned to introduce a sulfur cycle to predict concentrations of sulfate aerosols. These would then be used to estimate droplet concentration using empirical relationships between sulfate aerosol concentration and cloud droplet

The asymmetry factor is adjusted from Mie theory values (spherical particles) to values consistent with data from FIRE Cirrus. This accounts for the non-sphericity of ice crystals.

concentration. Ice crystal effective radius is parameterized from ice water content according to Heymsfield.

Results

The clear sky, top of the atmosphere (TOA) fluxes agree well with ERBE satellite data and the model has been tuned to reconcile with global mean ERBE cloud radiative forcing. The geographical distribution of longwave cloud forcing in the model shows good agreement with ERBE observations, but there are problems with the shortwave cloud forcing. The model produces insufficient stratiform clouds off the coasts of California and South America, and too much convective cloud in the tropical west Pacific and Indian Ocean. Such regional problems tend to introduce global errors into the model because they bias the tuning process.

As a further means of validation, the model was run with tropical sea surface temperature (SST) anomalies in the equatorial Pacific (Figure 14.1). The model does well in replicating the associated longwave cloud forcing anomalies under these conditions (Figure 14.2). The correct pattern of shortwave cloud forcing is reproduced by the model, but the amplitude is too large by about $20 W/m^2$ (Figure 14.3).

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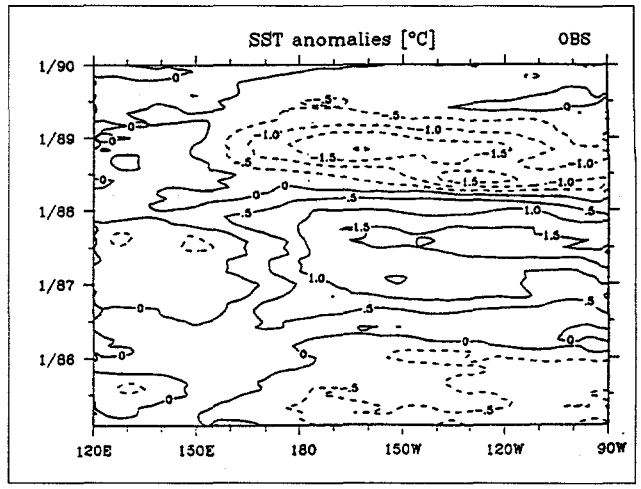

Figure 14.1: Time-longitude (Hovmöller) diagram of sea surface temperature anomalies in the equatorial Pacific averaged over the latitude belt 5° N - 5° S as obtained from the AMIP SST and sea ice dataset.

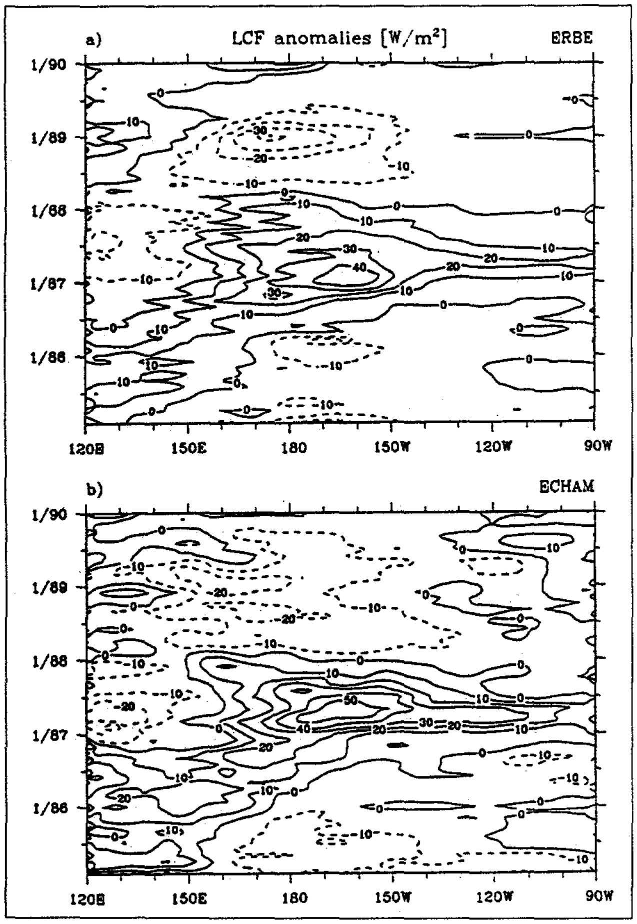

Figure 14.2: Hovmöller diagram of observed (ERBE) and simulated (ECHAM3/T42) anomolies of the longwave cloud forcing (LCF) in the equatorial Pacific, averaged over the latitude belt 5° N - 5° S.

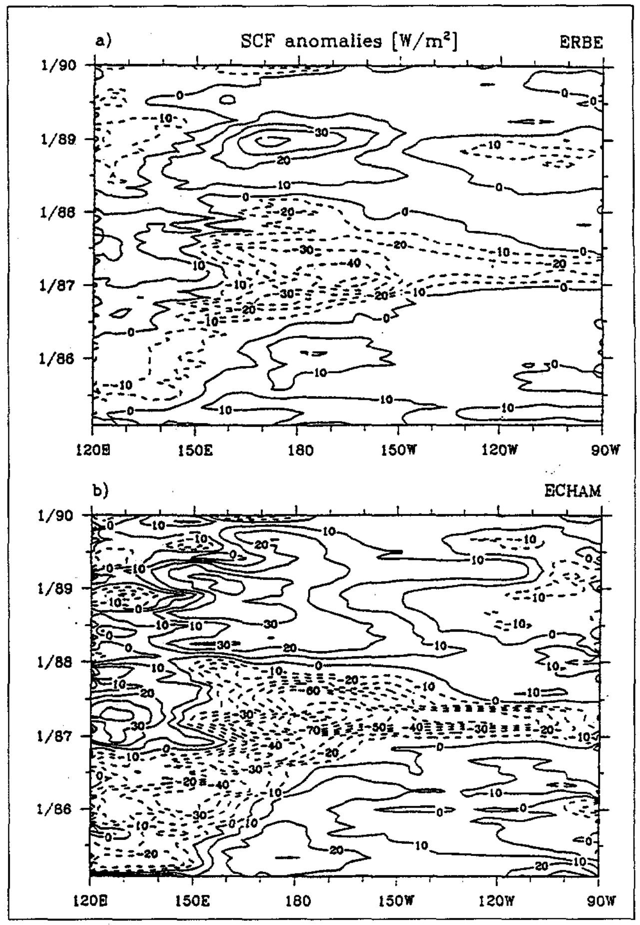

Figure 14.3: As Figure 14.2, except for the anomolies of the shortwave cloud forcing (SCF).

15 Classical and Advanced Stochastic Multifractals in Geophysics: Lie Cascades and Multifractal Phase Transitions

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Multifractal techniques and notions are increasingly widely recognized as the most appropriate and straightforward framework within which to analyze and simulate not only the scale dependence of geophysical observables, but also their extreme variability over a wide range of scales.

Multifractal techniques and notions are increasingly widely recognized as the most appropriate and straightforward framework within which to analyze and simulate not only the scale dependence of geophysical observables, but also their extreme variability over a wide range of scales. This is particularly the case for cloud fields and their radiative properties. Schertzer first recalled the original scalar framework of turbulent cascades, especially for the modeling and analysis of passive clouds, based on multifractal developments of the Corrsin-Obukhov spectral scaling of scalar variance (Schertzer and Lovejoy, 1987; Pecknold et al. 1993). These developments are based on the scaling symmetries of the dynamical equations of both the velocity and liquid water density fields. He emphasized the power of straightforward simulation methods based on these physical arguments. Schertzer showed a video (Brenier et al. 1990) displaying a time evolution of multifractal cloud in the framework of universal multifractals. He insisted that with the aid of these tools, there is no real need to look for constructs such as bounded cascades.

There are two rather recent developments in stochastic multifractals that are of particular interest. On the one hand, as a wide variety of possible multifractal behaviors exists, ranging from extremely "soft" to "hard," there is a need to understand their differences qualitatively, as well as the transitions from one type of behavior to another. Different behaviors correspond to multifractal analogues of phases, with two types of phase transitions between them. High- or low-temperature second-order transitions naturally arise from finite sample sizes and are only representative of these limitations. By contrast, low-temperature first-order transitions are consequences of the scale and dimension of the observations, which are no longer able to smooth away the most extreme small-scale fluctuations by building up larger-scale structures. The latter is a generic stochastic route to a non-classical self-organized criticality, since it occurs in high-dimensional stochastic multifractal processes with non-vanishing input (e.g. flux of turbulent energy). The origin of these transitions, as well as their implications, were discussed. There are many practical and drastic consequences of the "divergence of moments" associated with self-organized criticality, e.g. the breakdown of laws of large numbers and the related standard statistical estimates, the loss of ergodicity, the existence of very large fluctuations related to the "zoology" of structures, and the overwhelming contribution of catastrophic events.

On the other hand, the present situation is somewhat paradoxical: classical methods, such as those used in GCM research or direct simulations, deal easily and explicitly with this vector interaction, but only over a very limited range of scales, whereas scaling models deal easily with an infinite range of scales but avoid treating this vector interaction. For instance, multifractal modeling of clouds has relied until now on the simplifying hypothesis that the interaction between the cloud and the environmental dynamics can be reduced to a scalar relationship (namely between their respective fluxes). On the theoretical side, there now exists a rather general framework of "Lie cascades" which has been recently developed to analyze and generate multiplicative processes for vector and tensor fields, and more generally rather abstract fields admitting a Lie group of symmetries. This framework opens up a very appealing alternative to GCM techniques, since we then may consider the generator of the (scaling) multi-component field describing atmospheric states (e.g. dynamics, temperature, water concentration, radiative fields, etc.).

In conclusion, Schertzer briefly emphasized that these aspects of new developments of multifractals are potentially very powerful techniques which may allow us to simulate and analyze both qualitatively and quantitatively a wide variety of geophysical fields and interactions, well beyond conventional deterministic frameworks. In the future, these tools should be useful for evaluating and assessing many aspects of global change.

Multifractal modeling of clouds has relied until now on the simplifying hypothesis that the interaction between the cloud and the environmental dynamics can be reduced to a scalar relationship.

Classical and Advanced Stochastic Multifractals in Geophysics: Lie Cascades and Multifractal Phase Transitions

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16 Influence of Sea Surface Temperature on the Tropical Atmosphere: Scale Dependent Feedbacks

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La Jolla, CA 02093-0221

Total deep cloud cover in the tropics may not be not sensitive to the underlying SST field, but its spatial distribution seems to be strongly sensitive to the SST distribution. This would make the stability of the ocean-atmosphere system to SST perturbations, and the important mechanisms for maintaining stability, dependent on the spatial arrangement of the perturbation.

Total deep cloud cover in the tropics may not be sensitive to the underlying SST field, but its spatial distribution seems to be strongly sensitive to the SST distribution.

Observational Support

Monthly averaged ERBE observations of cloud longwave radiative forcing (CRF) during the 1985-89 period, and Reynolds' analyses of SST during the same period, can each be broken down into four components. Those SST components which average to zero over a large area are associated with large shifts of CRF toward the higher SSTs, of 20-25 $W/m^2/K$. These include the annual component of the seasonal cycle and the time average distribution within the Pacific warm pool region. Conversely, components involving mean SST changes over large areas (areas that include most deep convective activity) are not associated with significant changes in CRF. These components include El Niño, La Niña, and the biannual component of the seasonal cycle (see Figure 16.1). This does not prove that overall cloudiness is insensitive to SST, however, since it is influenced also by non-local events such as the Asian monsoon.

Model Support

A simple box model of the tropics is presented which is based on energy and moisture conservation, and simple dynamics. The model has two locations, representing convective and non-convective regions, and two layers (Figure 16.2). It is forced by SST as a boundary condition. This model fails to show a large change in cloud cover when the SST in either region is changed. However, when the model is reduced in size to cover two halves of the convecting region only, it shows sensitivity to SST redistribution within this region on the same order as the observed sensitivity to zero-mean

SST shifts. The lack of sensitivity of the total cloud cover is tentatively explained as a result of the energy conservation requirement in the upper layer, assuming a direct proportionality between CRF and convective heating.

The model results (still preliminary) suggest that cloud shortwave forcing by deep clouds is the dominant negative feedback damping SST heterogeneities within convecting regions, but surface fluxes could be the dominant mechanism in stabilizing overall SST changes throughout convective regions. Neither of these mechanisms is very effective in stabilizing the model to tropical mean SST changes. In reality, cloud optical properties or lifetimes (which are constant in the model) might allow clouds to provide feedbacks for these overall perturbations.

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Influence of Sea Surface Temperature on the Tropical Atmosphere: Scale Dependent Feedbacks

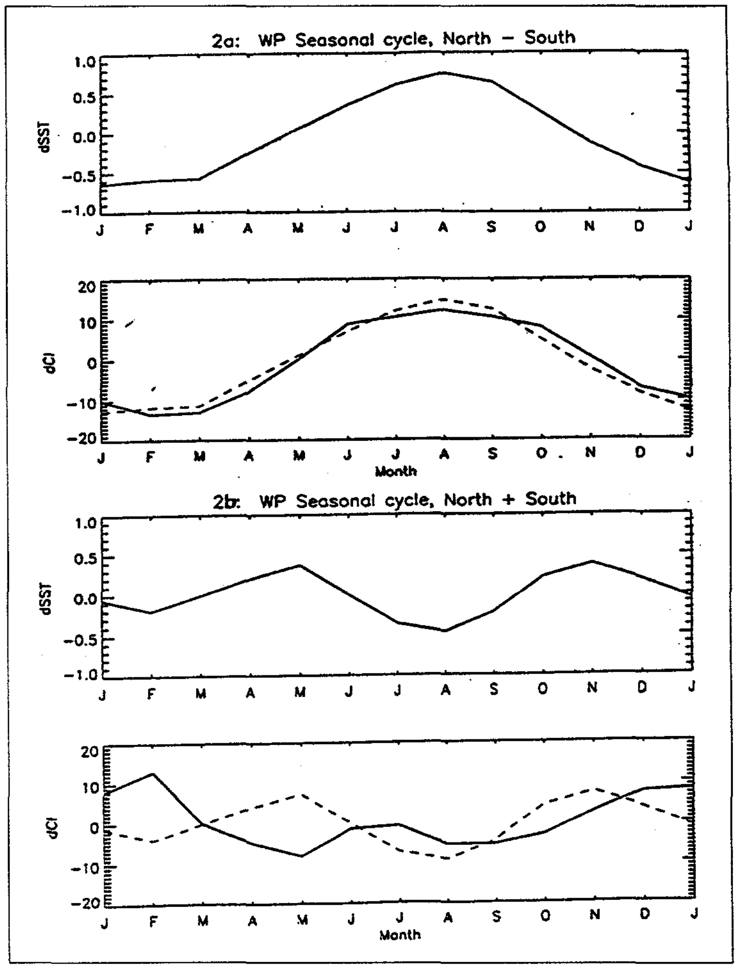

Figure 16.1: Observational components of cloud radiative forcing and SST

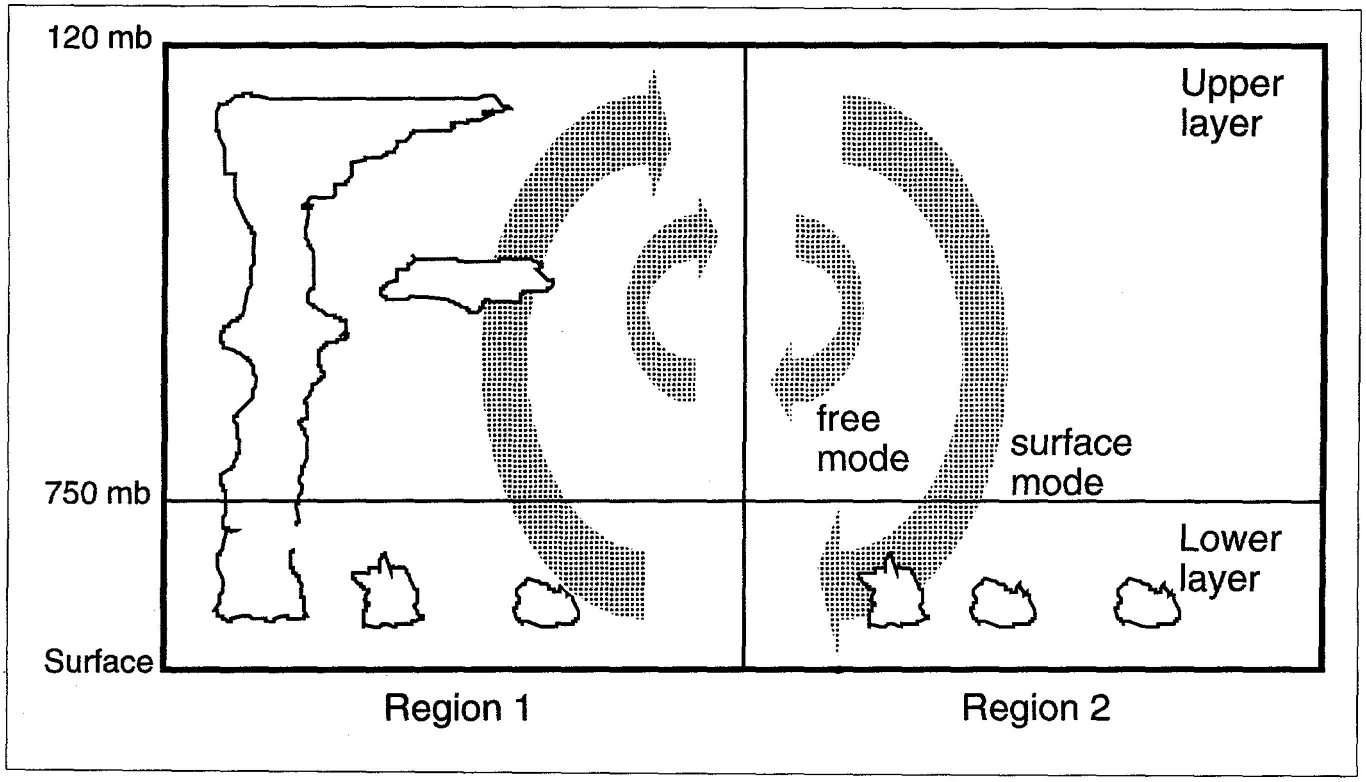

Figure 16.2: Schematic description of the model

17 Observational & Modeling Analysis of Surface Heat and Moisture Fluxes

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Four sensible heat flux closure schemes currently being used in GCMs were then evaluated against the FIFE observations. Results indicate that the methods by which closure models are calibrated lead to exceedingly large errors when the schemes are applied to variable boundary layer conditions.

An observational and modeling study was conducted to help assess how well current GCMs are predicting surface fluxes under the highly variable cloudiness and flow conditions characteristic of the real atmosphere. The observational data base for the study was obtained from a network of surface flux stations operated during the First ISLSCP Field Experiment (FIFE). The study included examination of a surface-driven secondary circulation in the boundary layer resulting from a persistent cross-site gradient in soil moisture, to demonstrate the sensitivity of boundary layer dynamics to heterogeneous surface fluxes. The performance of a biosphere model in reproducing the measured surface fluxes was evaluated with and without the use of satellite retrieval of three key canopy variables with RMS uncertainties commensurate with those of the measurements themselves. Four sensible heat flux closure schemes currently being used in GCMs were then evaluated against the FIFE observations. Results indicate that the methods by which closure models are calibrated lead to exceedingly large errors when the schemes are applied to variable boundary layer conditions.

The FIFE study-area was a 15 km by 15 km region of semi-complex terrain in central Kansas containing the Konza Prairie Natural Area. Twenty-two sites across the study-area were selected in an attempt to sample the natural inhomogeneity in terrain and phenology influencing the fluxes. The region was studied for 143 days in 1987 and 21 days in 1989. Annual, intraseasonal, synoptic, and diurnal time scales are the four predominant temporal scales over which the fluxes were observed to vary. Cloudiness was found to be the dominant control on flux magnitudes. Precipitation and its resultant effects on soil moisture distribution was found to be the dominant control on evaporative fraction or Bowen ratio.

The effects of burn treatment, grazing conditions, topography, and cloudiness on radiative, sensible heat, and moisture fluxes were examined for both growing season and senescent periods.

Cloudiness was the far more dominant control on variations in available heating than phenology or topography, and thus was the dominant control on the modulation of sensible and latent heat fluxes. For sensible heat, the amplitude of the effect of cloudiness was largest during the senescent period, while for latent heat, it was largest during the growing season. The RMS uncertainties in the measured fluxes were estimated to be approximately 30 Wm^{-2}.

During 1989, a persistent gradient of soil moisture was observed across the site throughout the 21-day study period. This was due to the irregular distribution of antecedent rainfall in the 2 months prior to the experimental period. The soil moisture gradient was independently observed through gravimetric, L-band microwave, and gamma-ray soil moisture measurements. Even though the cloudiness variability tended to remove any site heterogeneity in available heating, the gradient in soil moisture maintained a gradient in evaporative fraction and thus a cross-site difference in sensible heating of the boundary layer. A resulting ABL secondary circulation was established with daytime vertical velocities approaching one cm s^{-1}; Smith *et al.* (1994)

A biosphere model was then evaluated using the FIFE data. The model is driven in a top-down scheme by standard surface meteorological variables produced in any GCM scheme at every time step; these are precipitation, temperature, relative humidity, pressure, winds, and the downwelling short- and long-wave radiative fluxes; Smith *et al.* (1993). In the model performance calculations, these 8 variables were obtained from actual measurements. The model allows for fractional vegetation cover, has several vertical layers in the canopy for purposes of radiative transfer, and three soil layers which are thermally and hydrologically prognosed. To be closed, the model requires three additional variables: canopy albedo, leaf area index (LAI), and stomatal resistance. These three slowly changing variables must be measured, arbitrarily specified, or retrieved from satellite measurements for the purpose of integrating the model over a time period. In contrast to simple heat transfer closure models and bucket evaporation models, a biosphere model provides more realistic treatment of transpiring vegetation and the canopy-soil interface, some vital checks and balances which prevent the occurrence of pathological fluxes, and a more detailed treatment of water transfer and phase change in the canopy and solid. The modeled and measured latent heat fluxes show good agreement with a bias of 8 Wm^{-2} and an RMS uncertainty of ~40

Cloudiness was the far more dominant control on variations in available heating than phenology or topography, and thus was the dominant control on the modulation of sensible and latent heat fluxes.

In contrast to simple heat transfer closure models and bucket evaporation models, a biosphere model provides more realistic treatment of transpiring vegetation and the canopy-soil interface, some vital checks and balances which prevent the occurrence of pathological fluxes, and a more detailed treatment of water transfer and phase change in the canopy and solid.

Wm^{-2} for the growing season.

A pair of numerical experiments were conducted in which a control run was first compared to a "satellite run", in which the three slow canopy variables were obtained by satellite-derived parameters, retrieved from AVHRR measurements during clear-sky periods and linearly interpolated during cloudy periods, and then to a "synthetic run" in which the canopy albedo and LAI were specified by measurements but the stomatal resistance by an independent formula (Crosson *et al.*, 1993). The control run itself was based on use of measured canopy albedo, LAI, and stomatal resistance. All three runs produced small biases; the RMS differences were approximately 35 Wm^{-2} for the control run, 45 Wm^{-2} for the satellite run, and 55 Wm^{-2} for the synthetic run (see Figure 17.1).

Finally, four popular closure schemes used in a number of limited area and large scale models (including 19 GCMs) for calculation of sensible heat flux were evaluated (Wai and Smith, 1994). The schemes consist of (1) the bulk aerodynamic method of Laval *et al.* (1981); (2) the stability adjusted parametric scheme based on bulk Richardson number of Louis (1979); the modified parametric scheme of Louis *et al.* (1981); and the two-level turbulent closure scheme of Mellor & Yamada (1982). All four schemes involve empirical coefficients; such constants for the first two schemes were obtained from fitting measured flux data obtained for idealized boundary layer conditions, by tuning 10-day ECMWF forecasts in the case of the Louis-81 scheme, and from laboratory data in the case of the Level-2 closure scheme.

For the 1989 FIFE data, the Louis, and Mellor and Yamada schemes perform best and worst, respectively, but these differences are overshadowed by the overall errors found for all four schemes (see Figure 17.2). All schemes significantly overestimate sensible heat fluxes, particularly under unstable conditions, with RMS uncertainties exceeding 100 Wm^{-2} up to 160 Wm^{-2} for the noon period. The uncertainties of the

Louis-79 and Level-2 schemes could be reduced to levels consistent with uncertainties in the measured data by recalibration with the FIFE data itself.

It appears that a number of closure schemes currently being used in GCMs are simply too idealized to handle the diverse set of flow and cloudiness situations found in the real boundary layer, representing turbulence conditions for which the closure schemes were never calibrated. Biosphere models are generally more adaptable to non-idealized boundary layers and may be able to yield significant improvement in flux accuracy as well as increased understanding of GCM behavior. However, the design of biosphere models should be reduced to a level of complexity consistent with the scales at which GCMs are operated to avoid the problem of having to specify too many biophysical parameters in an *ad hoc* fashion.

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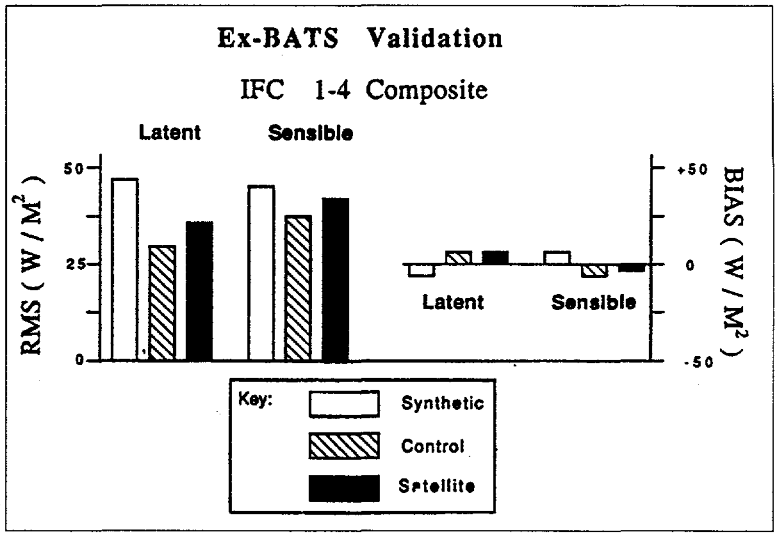

Figure 17.1: Biases from three versions of the model

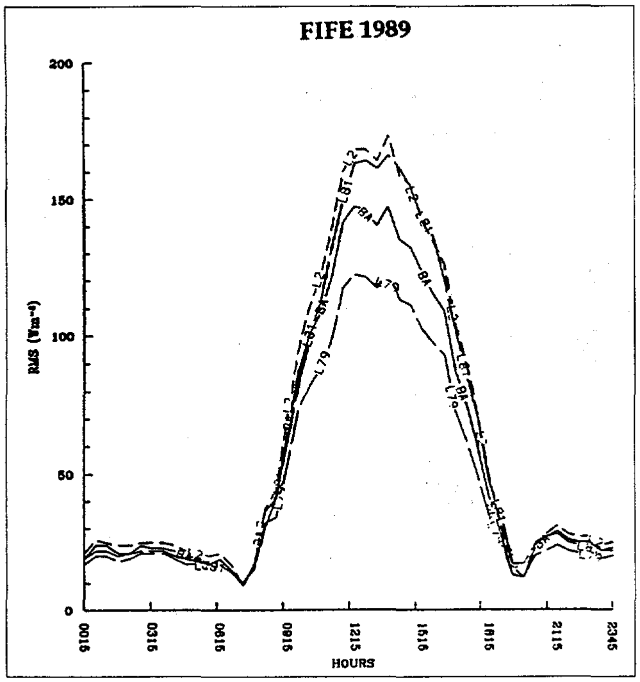

Figure 17.2: Sensible heat fluxes calculated by four closure schemes:

BA Bulk Aerodynamics Method

L 79 LOUIS 79 scheme

L 81 LOUIS 81 scheme

L 2 Mellor and Yamada

18

Parameterization of Cirrus Optical Depth and Cloud Fraction

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This research illustrates the utility of combining satellite observations and operational analysis for the evaluation of parameterizations. A parameterization based on ice water path (IWP) captures the observed spatial patterns of tropical cirrus optical depth. The strong temperature dependence of cirrus ice water path in both the observations and the parameterization is probably responsible for the good correlation where it exists. Poorer agreement is found in Southern Hemisphere mid-latitudes where the temperature dependence breaks down. Uncertainties in effective radius limit quantitative validation of the parameterization (and its inclusion into GCMs). Also, it is found that monthly mean cloud cover can be predicted within an RMS error of 10% using ECMWF relative humidity corrected by TOVS Upper Troposphere Humidity.

A parameterization based on ice water path captures the observed spatial patterns of tropical cirrus optical depth.

Parameterization of cirrus optical properties

A parameterization is developed to predict the optical depth of cirrus clouds formed by large scale lifting. The routine is used in locations where cirrus is *a priori* known to exist. IWP is calculated as an equilibrium between deposition (from large scale lifting) and sedimentation of crystals. By reconstructing parcel trajectory the IWP can be specified as a function of only four parameters: temperature, pressure, vertical velocity, and lapse rate.

Operationally, ECMWF analyses are used to provide these four input parameters, and the ISCCP retrievals are used to find the occurrence of cirrus and its optical depth. In this way, the input to the parameterization and the optical depth against which it is validated are both obtained from observational sources. This allows the parameterization to be validated in isolation. Exact quantitative validation of the parameterization is not possible due to the large uncertainty in cirrus ice crystal size. Instead, optical depth *patterns* are studied. Spatial correlations between the observed and predicted optical depths are typically greater than 0.7 for the tropics and Northern Hemisphere mid-latitudes (Figure 18.1). The good spatial agreement largely stems from the strong dependence of the ice water path upon the temperature of the environment in which the clouds form.

Poorer correlations (r~0.3) are noted over the Southern Hemisphere mid-latitudes, suggesting that additional processes not accounted for by the parameterization may be important there. One potential source of error is a possible cold bias in the ECMWF analysis for the Southern Hemisphere upper troposphere. Improved correlations in the Southern Hemisphere and tropical regions are obtained by using global mean "cirrus" values of pressure, vertical velocity, and lapse rate, and allowing regional variations in temperature only (Figure 18.2). This may be due to errors in ECMWF vertical velocity, sub-grid variability in vertical velocity, and oversimplifications in the parameterization.

Quantitative evaluation of the parameterization is hindered by the present uncertainty in the size distribution of cirrus ice particles. Consequently, it is difficult to determine if discrepancies between the observed and predicted optical properties are attributable to errors in the parameterized ice water path or to geographic variations in effective radii.

Parameterizability of cirrus cloud cover

An empirical relationship between cloud cover and relative humidity is produced for high clouds. ECMWF relative humidity is used as input and output cloud cover is validated against ISCCP cloud cover. The relationship is optimized for one day of data and used to test monthly average agreement. While the agreement is generally good, there is a systematic underprediction of cloud fraction in the Inter Topical Convergence Zone and a systematic overprediction in subtropical descending regions. These discrepancies are probably due to errors in the ECMWF upper troposphere and can be partially corrected using the TOVS satellite Upper Troposphere Humidity. With this correction, monthly mean high cloud cover can be predicted within an RMS error of 10%. The agreement is poorer on a daily basis because there is no strong correlation between cloud cover and relative humidity on this time scale.

Reference

Soden, B.J. and L.J. Donner, Evaluation of a GCM Cirrus Parameterization Using Satellite Observations, *J. Geo. Res.*, July 1994.

It is difficult to determine if discrepancies between the observed and predicted optical properties are attributable to errors in the parameterized ice water path or to geographic variations in effective radii.

Parameterization of Cirrus Optical Depth and Cloud Fraction

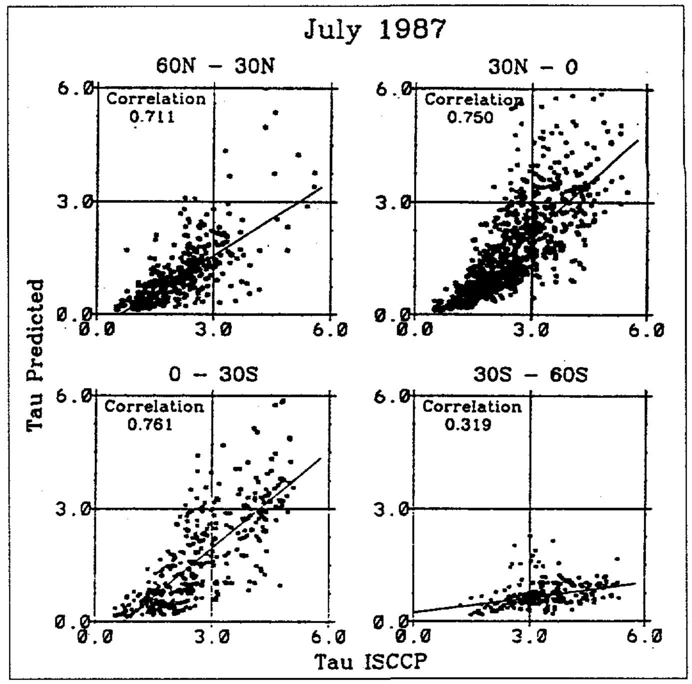

Figure 18.1: Spatial correlation between observed and predicted cloud optical depths

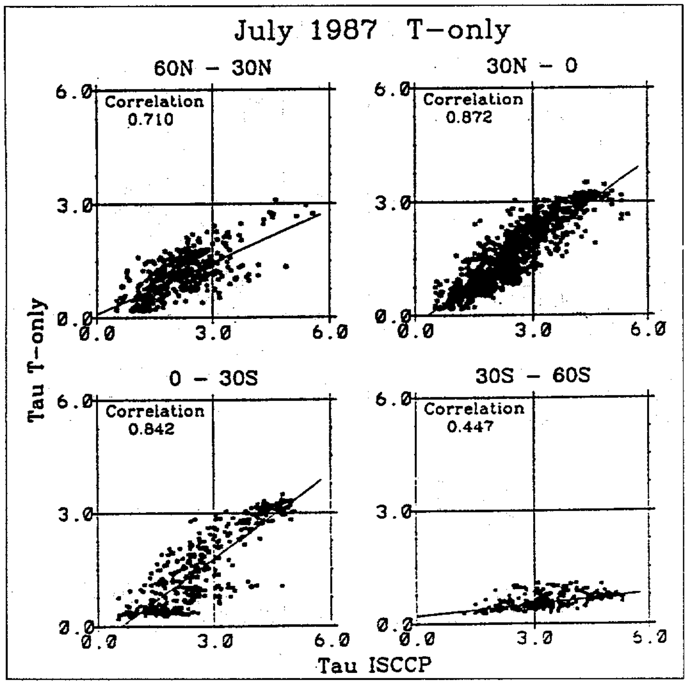

Figure 18.2: As in Figure 1, but allowing regional variations in temperature only

19 Testing Cloud-Radiation Algorithms in GCMs and Single-Column Models

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Our poor understanding of cloud processes limits our ability to make realistic climate change predictions. Part of the problem is that we have too many cloud parameterizations and too few observations. Lack of contact between observationalists and modelers exacerbates this problem.

The principle behind the single-column model is that the horizontal convergence of heat, momentum, and moisture is specified from observations.

Somerville and Sam Iacobellis have developed a diagnostic model in the form of a single-column version of a general circulation model (GCM), which is used to test the various available parameterizations. The principle behind the single-column model is that the horizontal convergence of heat, momentum, and moisture is *specified* from observations (typically, analyzed fields, such as numerical weather prediction data), allowing diagnostic prediction of model profiles of temperature and humidity from local sources and sinks of heat and water; plug-compatible parameterizations are used to calculate the sources and sinks.

The single-column model is currently being applied to a 200-kilometer by 200-kilometer region centered on the Oklahoma ARM site. Initial tests have shown that significantly different cloud fractions are predicted using three different cloud parameterizations (a relative humidity model and two prognostic cloud liquid water models) (Figure 19.1). There is a need to compare the parameterizations using variables which are readily measurable observationally. One such variable is the net solar flux at the surface which also shows significant differences when the various cloud parameterizations are used.

The parameterizations are also being tested using the CCM-2 GCM running on a workstation (Figure 19.2). This eliminates the limitation of externally specifying horizontal convergence. When a liquid water budget is included in the model, some high tropical clouds are underpredicted. All versions predict a strong temperature increase in the upper troposphere. This is because a large vertical transport of heat is produced by the CCM2 mass flux convective scheme, regardless of the cloud parameterization used.

The combination of well-thought-out field programs, diagnostic modeling, (as with single-column GCMs), and the increased accessibility of GCMs to the university community (by making them available on workstations), should lead to more rapid progress in validating parameterizations.

Reference

Iacobellis, Sam F. and Richard C.J. Somerville, Diagnostic Modeling of the Indian Monsoon Onset. Part I: Model Description and Validation, *J. Atmos. Sci.*, **48**, pp.1948-1959, (1991)

Iacobellis, Sam F. and Richard C.J. Somerville, Diagnostic Modeling of the Indian Monsoon Onset. Part II: Budget and Sensitivity Studies, *J. Atmos. Sci.*, **48**, pp. 1960-1971, (1991).

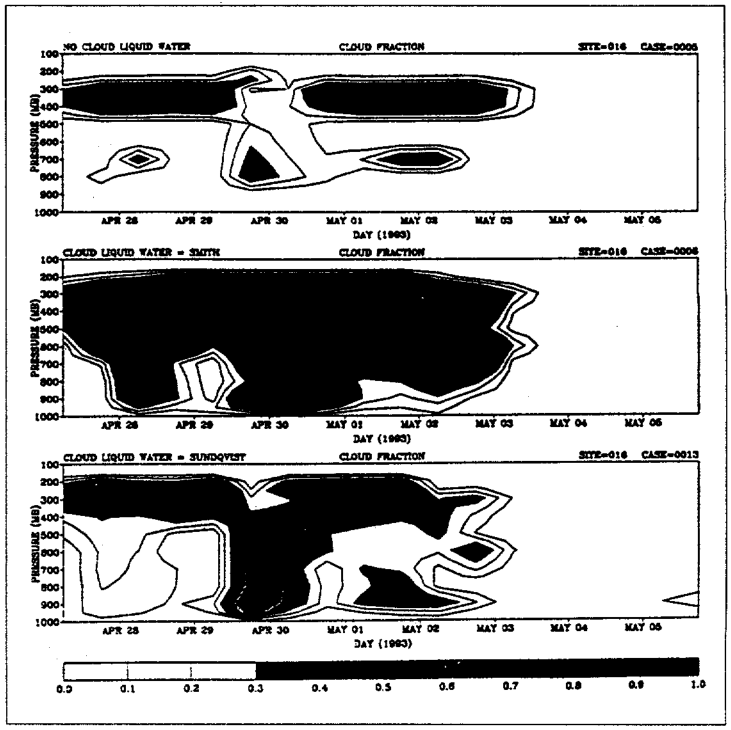

Figure 19.1: Ten-day simulations of cloud fraction over the Oklahoma ARM site using the single-column GCM. Three different cloud parameterizations (a relative humidity model and two different prognostic cloud liquid water models by Smith (UKMO) and by Sündqvist) yield significantly different results.

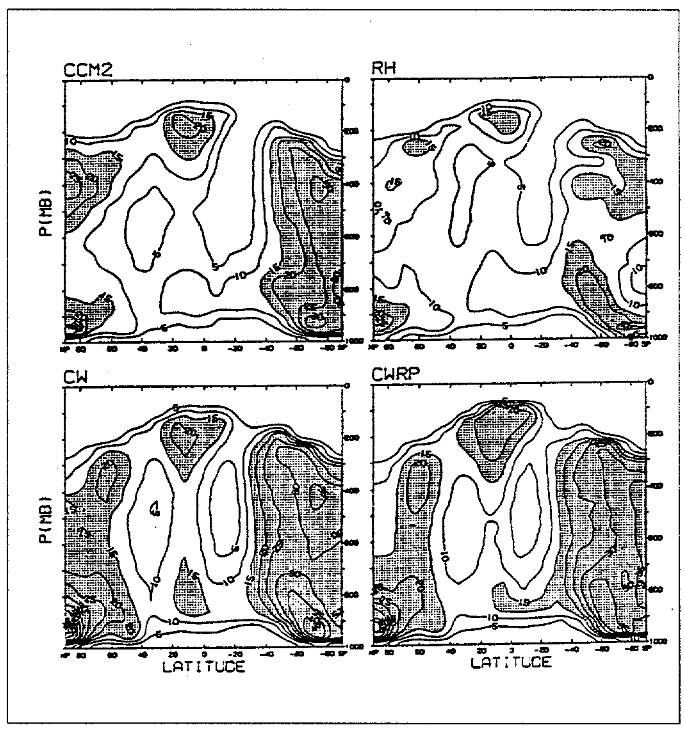

Figure 19.2: Latitude height distributions of cloud fraction predicted by four versions of CCM2:
CCM2: standard model
RH: cloud amount derived from relative humidity distribution
CW: parameterized prognostic cloud water budget
CWRP: cloud radiative properties derived from prognostic cloud water

20 The ARM Unpiloted Aerospace Vehicle (UAV) Program

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Unmanned aerospace vehicles (UAVs) are an important complement to the DOE's Atmospheric Radiation Measurement (ARM) Program. ARM is primarily a ground-based program designed to extensively quantify the radiometric and meteorological properties of an atmospheric column. There is a need for airborne measurements of radiative profiles, especially flux at the tropopause, cloud properties, and upper troposphere water vapor. There is also a need for multi-day measurements at the tropopause; for example, in the tropics, at 20 km for over 24 hours. UAVs offer the greatest potential for long endurance at high altitudes and may be less expensive than piloted flights.

There is a need for airborne measurements of radiative profiles, especially flux at the tropopause, cloud properties, and upper troposphere water vapor.

The ARM-UAV program strategy has three major phases with increasing capability. The first phase, now complete, was a one-year demonstration stage which served to acquire early scientific results and UAV operational experience, using existing UAVs and instruments. The second phase, meant to develop interim capability over the next 2-3 years, will be characterized by sustained operations and near-term UAV construction and use (14+ km for over 24 hours), using existing and near-term instruments. The third, or full capability phase, in years 3 and 4, will be characterized by sustained/autonomous operations, full capability UAVs (20 km, multi-day, 200 kg payloads), and full instrument capability.

The UAV demonstration flights focused on clear-sky flux profiling, flying straight level runs at multiple altitudes. Multi-plane flight patterns with UAVs may be a possibility in the future. The FAA is still considering how it will regulate UAV flights.

Figure 20.1 shows a preliminary comparison between the UAV longwave flux observations and line-by-line model calculations. Figure 20.2 shows the difference between observed and calculated downward flux divergence in two layers. Differences are mostly within 5%.

The program has four new instruments under development: HONER, a novel net flux radiometer, MPIR, a multi-spectral cloud imaging radiometer, CDL , a cloud detection lidar, and UAV-AERI, an IR interferometer. HONER will be able to simultaneously measure upward and downward fluxes and flux divergence. Additional new instruments may also be developed. All flights include a standard meteorological package to measure temperature, pressure, and relative humidity.

Three UAV flight activities are planned: a cloudy skies satellite calibration mission at 14 km in Sept./Oct. 1994 in the U.S.; a sustained operations mission for multi-day coverage, with 2 UAVs flying simultaneously, in the U.S. in the Spring of 1995; and a tropical cirrus mission at 20 km in the tropical Pacific in the Winter of 1995-96.

UAVs offer the greatest potential for long endurance at high altitudes and may be less expensive than piloted flights.

The ARM Unpiloted Aerospace Vehicle (UAV) Program

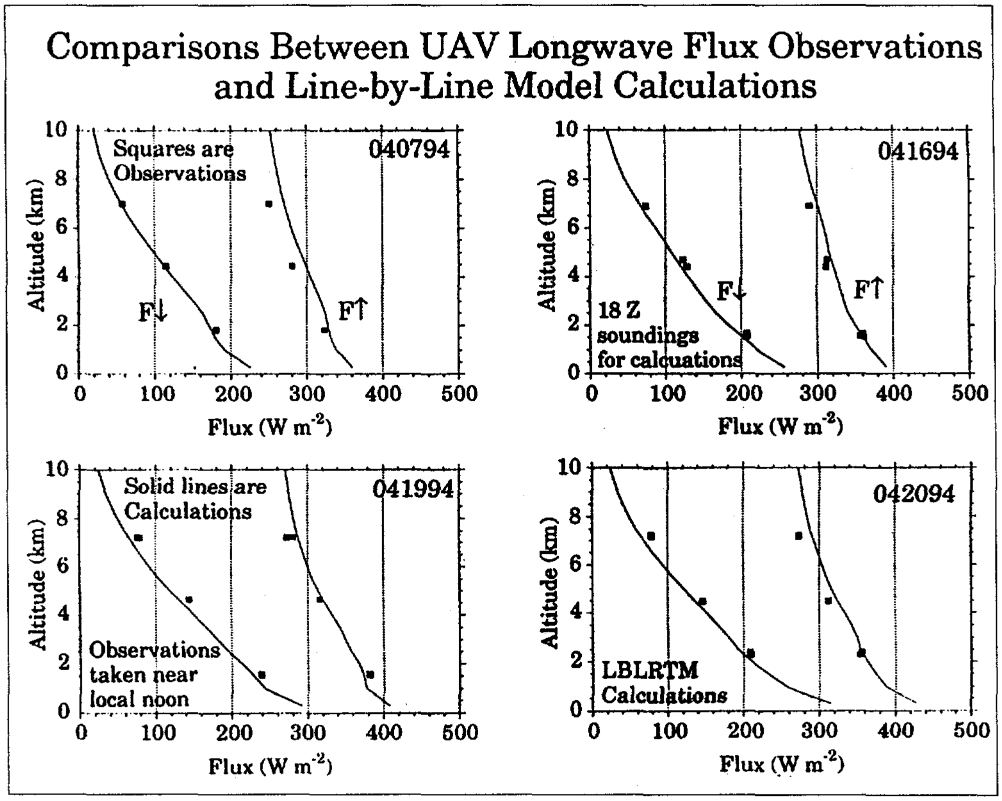

Figure 20.1: Comparison between UAV long-wave flux observations and model calculations

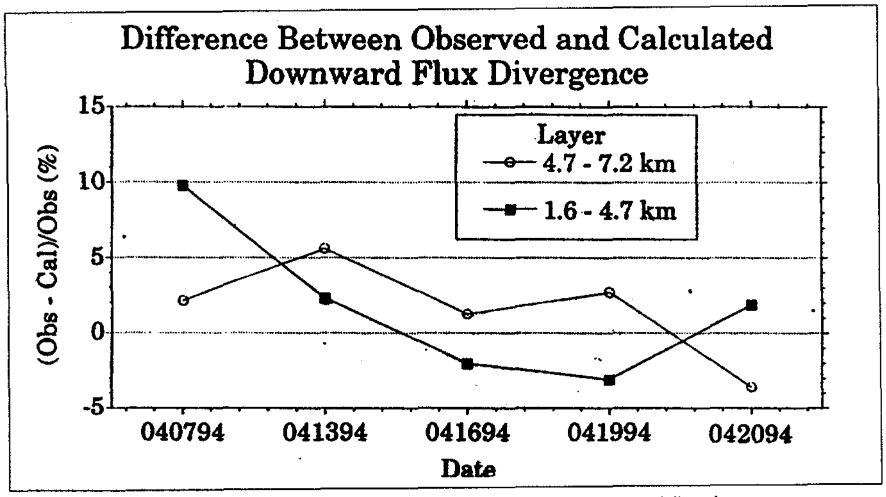

Figure 20.2: Difference between Observed and calculated downward flux divergence

21 Cloud Microphysics and Surface Properties in Climate

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For medium thick clouds a 10 % increase in drop size yields a surface warming of 1.5°C, which is the same as that due to a doubling of carbon dioxide.

Cloud optical thickness is determined from ground-based measurements of broadband incoming solar irradiance using a radiation model in which the cloud optical depth is adjusted until computed irradiance agrees with the measured value. From spectral measurements it would be feasible to determine both optical thickness and mean drop size, which apart from cloud structure and morphology, are the most important climatic parameters of clouds. A radiative convective model is used to study the sensitivity of climate to cloud liquid water amount and cloud drop size. This is illustrated in Figure 21.1 which shows that for medium thick clouds a 10 % increase in drop size yields a surface warming of 1.5°C, which is the same as that due to a doubling of carbon dioxide. For thick clouds, a 5% decrease in drop size is sufficient to offset the warming due to doubling of carbon dioxide. A radiative transfer model for the coupled atmosphere/sea ice/ocean system is used to study the partitioning of radiative energy between the three strata, and the potential for testing such a model in terms of planned experiments in the Arctic is discussed.

The determination of cloud optical properties at the ground in the Arctic relies on the use of broadband surface albedo and solar irradiance measurements from the NOAA/CMDL station in Barrow, Alaska. The absorption of cloud drops increases with drop size, leading to decreased transmission, while the forward scattering increases, leading to enhanced transmission. The net effect is that the transmittance is insensitive to drop size. But the cloud optical depth can be determined by simply comparing the measured irradiance with radiative transfer computations in which the measured surface albedo is used. Then the cloud optical depth is adjusted until the computed irradiance agrees with the measured one. The seasonal variation in cloud optical thickness at Barrow, Alaska derived using this approach for the period April 1988 through August 1988 is shown in Figure 21.2. The potential for deriving optical depth from narrowband measurements and mean drop size from bispectral transmittance measurements is explored in terms of the channels available in the Multi-Filter Shadowband Radiometer (MFRSR) deployed in the ARM program. The optical depth can be reliably inferred from the 862 nm channel (which is less influenced by atmospheric aerosols than channels at shorter wavelengths), while the mean size could be determined from a combination of measurements in the 862 nm channel and a channel centered at 2.2 microns. The latter channel is currently not available, but would be a valuable addition to narrowband instruments such as the MFRSR.

A radiative convective model with accurate treatment of radiative transfer including clouds is used to study the climate sensitivity to changes in mean drop size and optical thickness. The cloud optical properties are parameterized in terms of cloud liquid water content and equivalent radius throughout the solar and infrared portion of the spectrum. It is found that the infrared properties of clouds are sensitive to cloud scattering, which implies that clouds should not be treated as black bodies in climate models (Figures 21.3 and 21.4).

A radiative transfer model for the coupled atmosphere/sea ice/ocean system is used to study the disposition of solar energy throughout the system. The effects of clouds, snow on ice, and sea ice properties and thickness are quantified. The potential for testing this model in terms of planned experiments in the Arctic in the near future are briefly discussed. These experiments include the North Slope of Alaska site to be established through DOE's Atmospheric Radiation Measurements (ARM) Program, the Surface Heat and Energy Budget of the Arctic Ocean (SHEBA) experiment led by NSF and ONR, as well as the FIRE Phase III experiment, which is an interagency experiment led by NASA. It is concluded that the opportunities for all three efforts to benefit from close collaboration are great, but that the challenges in experimental design are equally great. In spite of these challenges, even broader interagency and international participation would be helpful.

The infrared properties of clouds are sensitive to cloud scattering, which implies that clouds should not be treated as black bodies in climate models.

References

Leontieva, E. N., and K. Stamnes, Estimations of cloud optical properties from ground-based measurements of incoming solar radiation in the Arctic, *J. Climate*, **7**, 566-578, 1994.

Hu, Y.-X., and K. Stamnes, An accurate parameterization of the radiative properties of water clouds suitable for use in climate models, *J. Climate*, **6**, 728-742, 1993.

Hu, Y.-X., A Study of the Link between Cloud Microphysics and ClimateChange, Ph.D. thesis, University of Alaska, 1994.

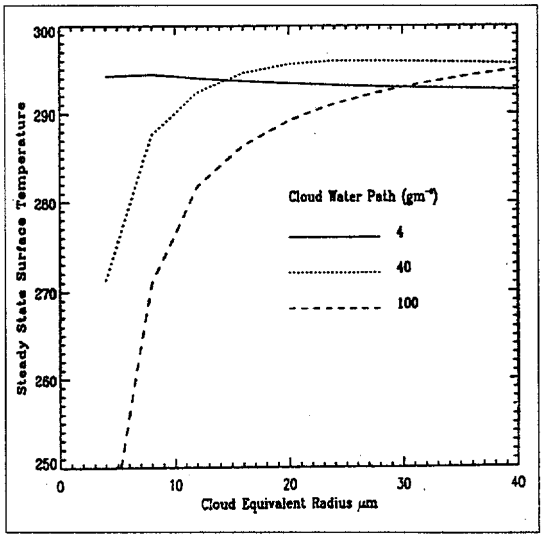

Figure 21.1: Equilibrium state surface temperature with different cloud equivalent radius. Cloud amount 50%. Cloud top height 3 km. Surface albedo for solar radiation 1.0. Radiative convective model results of dependence of surface temperature on cloud equivalent radius for various cloud water paths.

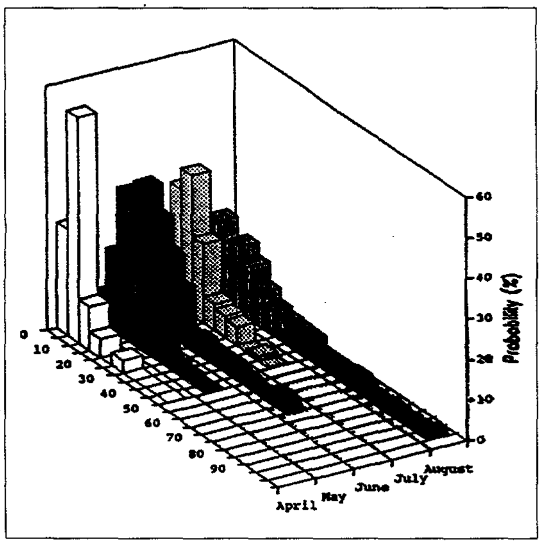

Figure 21.2: Estimated values of cloud optical thickness at Barrow Alaska, during April-August 1988

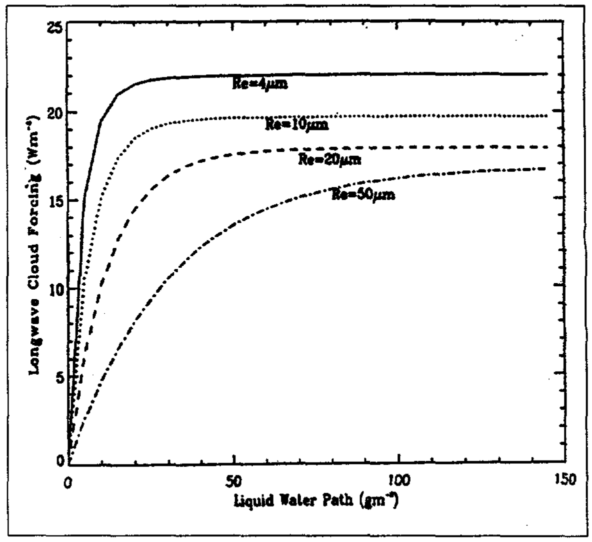

Figure 21.3: Clouds become black for longwave radiation (outgoing longwave radiation does not change when the liquid water increases) when cloud liquid water reaches about 20 gm^{-2}, if the cloud droplet is small (equivalent radius around 4 μm). When the equivalent radius increases to about 50 μm, the outgoing longwave radiation increases with the cloud water path until the cloud become very thick (cloud liquid water path around 50 gm^{-2}). So the cloud greenhouse gas effect is sensitive to the scattering of longwave radiation.

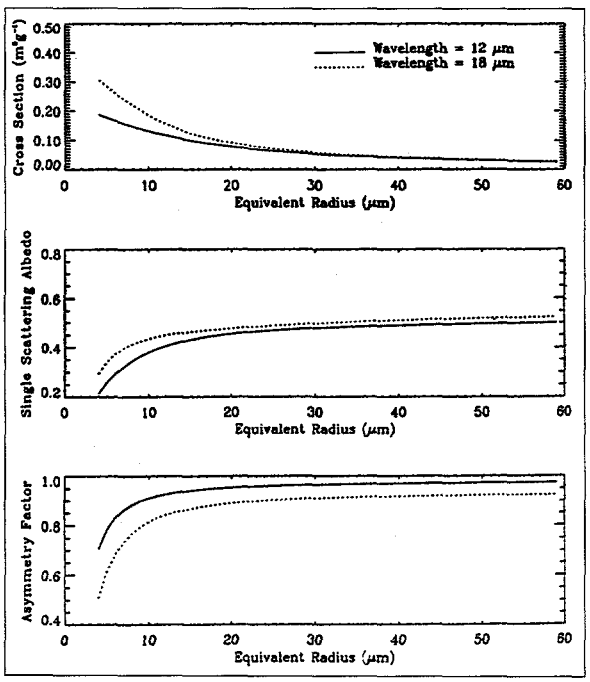

Figure 21.4: The longwave cloud radiative effect for optically thick clouds is not only determined by the cloud top temperature, but also is related to the cloud equivalent radius. This figure explains why there is more outgoing radiation (less longwave cloud radiative forcing) for thick cloud with bigger equivalent radius: the difference comes from the scattering. The scattering of longwave radiation is stronger if R_e is larger. The middle panel of this figure shows that the single scattering albedo and the asymmetry factor increases with R_e. This means the outgoing longwave radiation because of the scattering increases with R_e and thus the cloud radiative forcing decreases with the increase of R_e.

22

Cloud Physics Considerations in Global Climate Change Studies

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In order for relative humidity to remain constant, the liquid water content must be proportional to the cube root of the saturation vapor pressure, and it is difficult to explain why this should be true.

Introduction

In predicting the global warming due to a doubling of CO_2, it is important not to only evaluate the net effect of all the known feedback mechanisms, but to estimate the sensitivity to each. In other words, the partial derivatives as well as the total derivatives should be estimated. For instance, we might conclude that

$$\frac{\partial \overline{T}}{\partial \ln[CO_2]} = +1.5K$$

$$\frac{\partial \overline{T}}{\partial \ln[H_2O_{(vap)}]} = +12.5K$$

indicating that the climate is more sensitive to changes in water vapor which may occur as a result of CO_2 greenhouse warming, than to the CO_2 induced warming itself.

Precipitation

In a simple model, water vapor is injected at a rate proportional to the saturation vapor pressure, and rained out at an equal rate. The rate of precipitation (according to Berry) is proportional to the cube of LWC, since droplet coalescence is a highly nonlinear process. (In this sense, it is not the average LWC that matters for precipitation, but the extreme values in a cloud). In order for relative humidity to remain constant, the LWC must be proportional to the cube root of the saturation vapor pressure, and it is difficult to explain why this should be true. Consequently, there needs to be a better justification for making climate predictions which assume constant relative humidity.

Infrared Radiation

The treatment of clouds as black bodies is only an approximation. In fact, the extinction and absorption properties of cloud drops are quite sensitive to droplet size for the sizes typically found in clouds. Detailed calculations of the infrared "seeing" distances in clouds indicate that continental (polluted) air masses produce clouds with significantly smaller seeing distances than do maritime air masses (Figure 22.1). This effectively means that cloud top cooling will occur over a smaller depth in continental clouds, producing a more intense response (smaller time constant).

Shortwave Radiation

It is important to quantify the influence of cloud absorption. Figure 22.2 shows isolines of reflectance in the absorption/ droplet concentration plane. Reflectance strongly depends on droplet concentration, but only weakly on absorption until the absorption becomes large (which is one reason that cloud absorption is so poorly determined at present). The important point is that reflectance can either increase or decrease with increasing droplet concentration depending on the way in which absorption increases with droplet concentration.

Shiptrack experiments help to quantify the effect of air pollution on clouds. Shiptracks are found to be twice as bright as cloud surrounding the tracks, implying a factor of 8 increase in droplet concentration, and consequently a halving of mean radius in order to conserve liquid water content. Results by Platnick (1991) add weight to this conclusion.

Three scenarios were considered for particles in a CO_2 doubled atmosphere: (1) the aerosol loading would double, (2) the aerosol concentration would remain constant, but aerosol mass would increase, and (3) the coagulating mass flux would double. These three scenarios lead to a spread in climatic responses, (1) almost doubling the droplet concentration, (2) increasing it by only 20%, and (3) being in between. The climate sensitivities (see introduction) are, respectively, -2.8K, -0.7K and -1.5K. The point is that these sensitivities are as big as the direct CO_2 doubling effect, so that our uncertainty about which scenario is most realistic has important implications for our global change predictions.

Conclusion

The approximate treatment of precipitation and infrared transmission in clouds together with uncertainties in the effect of a warmer climate on the global aerosol loading introduce potentially significant sources of error into current global change predictions.

The point is that these sensitivities [to particles] are as big as the direct CO_2 doubling effect, so that our uncertainty about which scenario is most realistic has important implications for our global change predictions.

CUMULATIVE	RANGE (m)	
	Ocean	Continental / Polluted
.10	1.1	~0.3
.20	3.5	1.1
.40	8.7	2.8
.60	17.0	5.3
.80	34.0	10.0
.99	100.0	29.0

Figure 22.1: "Seeing" distances in the 8-12 μm IR Window as influenced by pollution/microphysics

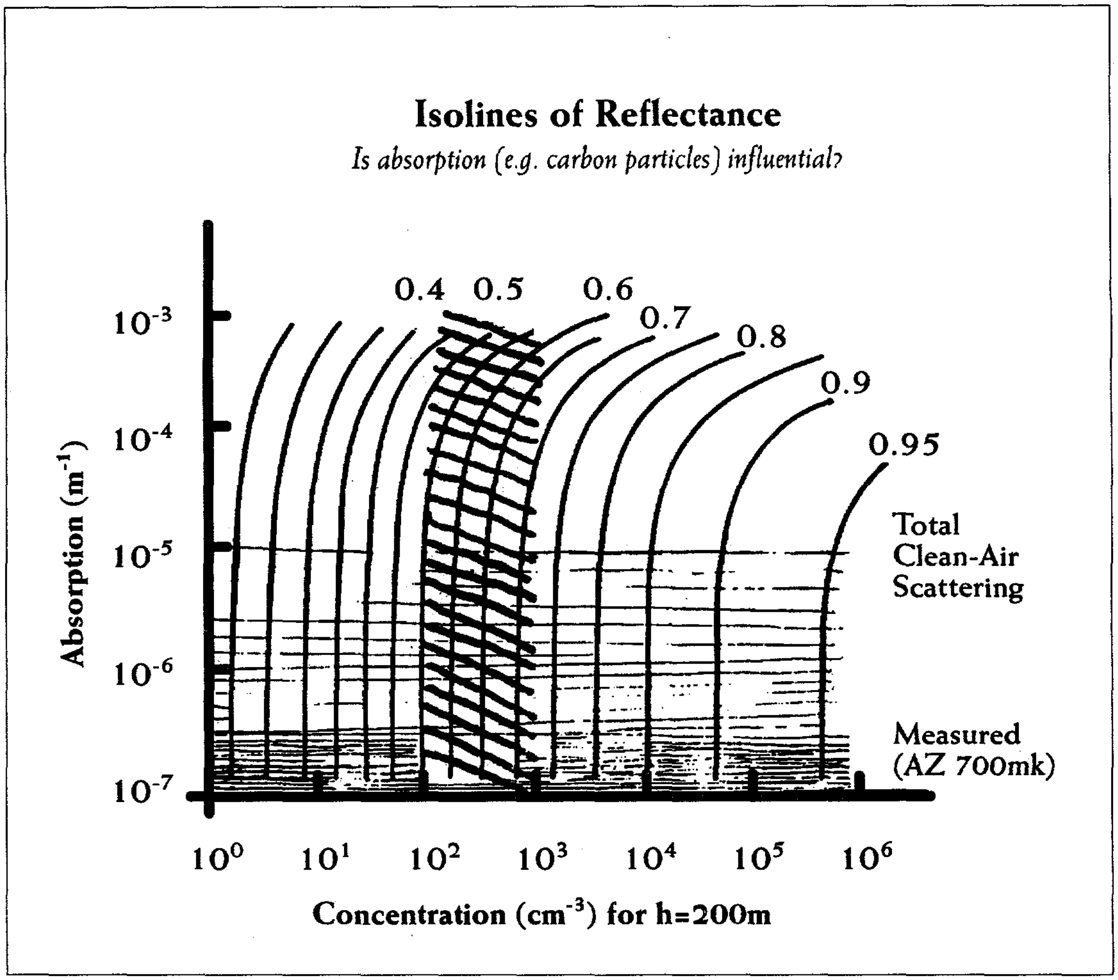

Figure 22.2: Isolines of reflectance in the absorption, droplet concentration plane

23

Clouds and Relative Humidity in Climate Models; or What Really Regulates Cloud Cover?

Chris Walcek

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State University of New York at Albany
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Relative humidity is the best single indicator of cloud coverage. However, if there is a relationship between cloud coverage and relative humidity, our current models and observations are inadequate to reveal exactly what that relationship is.

The response and impact of clouds remains one of the largest outstanding questions in GCMs. Clouds are not homogeneous, though they are treated as such in the models. When averaged over areas typically used as numerical grid elements by GCMs, observations suggest that there are some clouds at all relative humidities. Fractional cloud cover at 100% relative humidity is rarely 100%, and totally clear skies rarely occur, even for low relative humidities (see Figure 23.1). Relative humidity is the best *single* indicator of cloud coverage. However, if there is a relationship between cloud coverage and relative humidity, our current models and observations are inadequate to reveal exactly what that relationship is. It does appear that cloud coverage decreases exponentially as humidity falls below 100%.

Climate change predictions are extremely sensitive to modeled cloud cover estimates. There are numerous methods for predicting cloud cover from relative humidity, yet none of them are firmly grounded in observation. The intent of this research is to study the relationship between cloud cover and relative humidity using available observations.

In Walcek's research, U. S. Air Force 3DNEPH cloud data is correlated with relative humidity fields produced by assimilating radiosonde observations using a mesoscale meteorology model. This produces a scatter diagram of cloud cover versus relative humidity, the gross features of which are summarized in Figure 1. Clearly, in contrast to current GCM methodologies, clouds exist over a wide range of relative humidities, rather than disappearing below some arbitrarily defined threshold, typically 60-80%, depending on height in the atmosphere.

The purpose of current models of climate change is to attempt to discern how small changes in temperature and humidity will affect cloud cover and climate. But current models are unable to respond subtly. In going from 85% to 80% relative humidity, some models go from 100% cloud cover to 0%.

Not withstanding the current uncertainties inherent in observations of both cloud cover and relative humidity, the best fit to the data appears to be an exponential decrease in cloud cover with falling relative humidity.

$$\text{cloud cover fraction} = f_{100} \exp\left[-\frac{(1-Rh)}{(1-Rh_e)}\right]$$

Of all atmospheric layers, the lower boundary layer is by far the most sensitive to changes in relative humidity. For example, a 1% change in relative humidity is associated with a 4-6% change in cloud cover in the lower boundary layer (Figure 23.2). This means that if relative humidity increased from 82% to 84%, cloud cover would increase 15%, which according to Slingo (1990), would be enough to offset the temperature rise that could result from a doubling of CO_2.

Reference

Slingo, A., 1990: Sensitivity of the earth radiation budget to changes in low cloud amount. *Nature*, **343**, 49-51.

Walcek, C. J., 1994: Cloud cover and its relationship to relative humidity during a springtime mid-latitude cyclone. *Monthly Weather Review*, **122**, 1021-1035.

Not withstanding the current uncertainties inherent in observations of both cloud cover and relative humidity, the best fit to the data appears to be an exponential decrease in cloud cover with falling relative humidity.

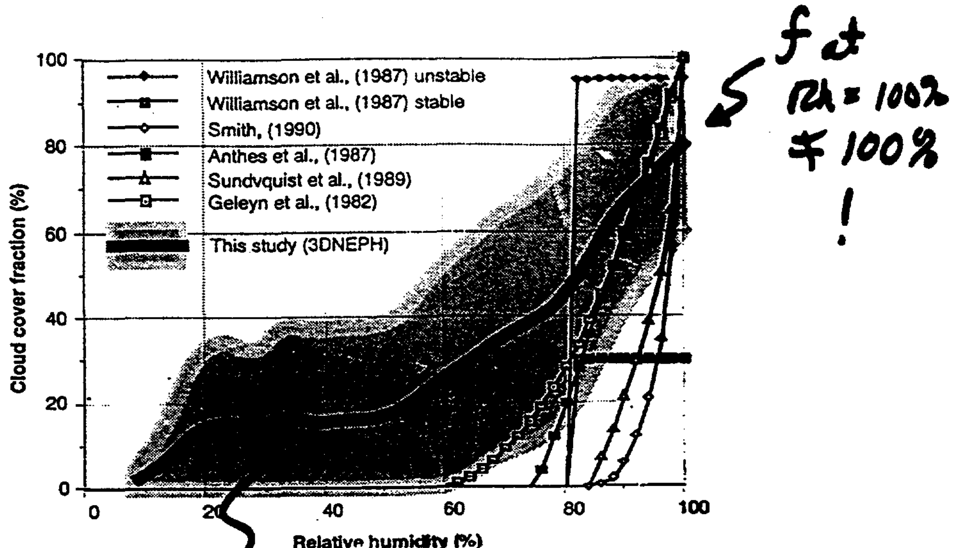

Figure 4: Fractional cloud coverage as a function of relative humidity at 800 mb according to various formulations used by meso- and global-scale atmospheric models. Shaded curve and area shows mean ±standard deviation of 3DNEPH cloud cover at specified relative humidity during five noon periods during 20-24 April 1981.

f ≠ 0 !

Figure 23.1

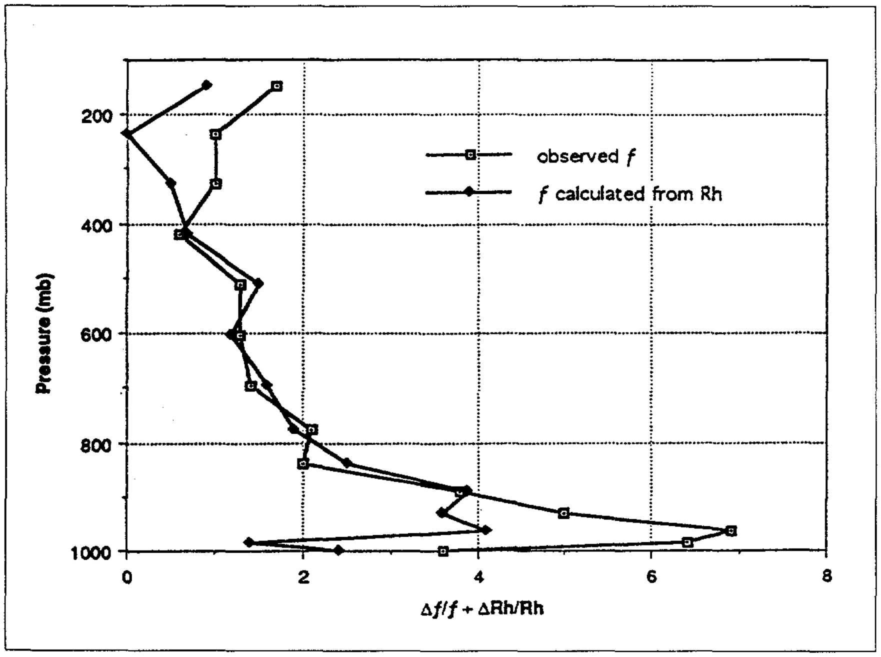

Figure 23.2: Observed and calculated vertical dependence of normalized changes in cloud fraction and relative humidity.

24 A New Conceptual Model of Convection

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Cumulus clouds can be reasonably simulated by assuming that buoyant plumes detrain mass as they rise through the atmosphere.

Classical cumulus parameterizations assume that cumulus clouds are *entraining* plumes of hot air rising through the atmosphere. However, ample evidence shows that clouds cannot be simulated using this approach. Dr. Walcek suggests that cumulus clouds can be reasonably simulated by assuming that buoyant plumes *detrain* mass as they rise through the atmosphere. Walcek successfully simulates measurements of tropical convection using this detraining model of cumulus convection. Comparisons with measurements suggest that buoyant plumes encounter resistance to upward movement as they pass through dry layers in the atmosphere. This probably results from turbulent mixing and evaporation of cloud water, which generates negatively buoyant mixtures which detrain from the upward moving plume. This mass flux model of detraining plumes is considerably simpler than existing mass flux models, yet reproduces many of the measured effects associated with convective activity. Figure 24.1 compares this "modern" conceptual model with the classical one.

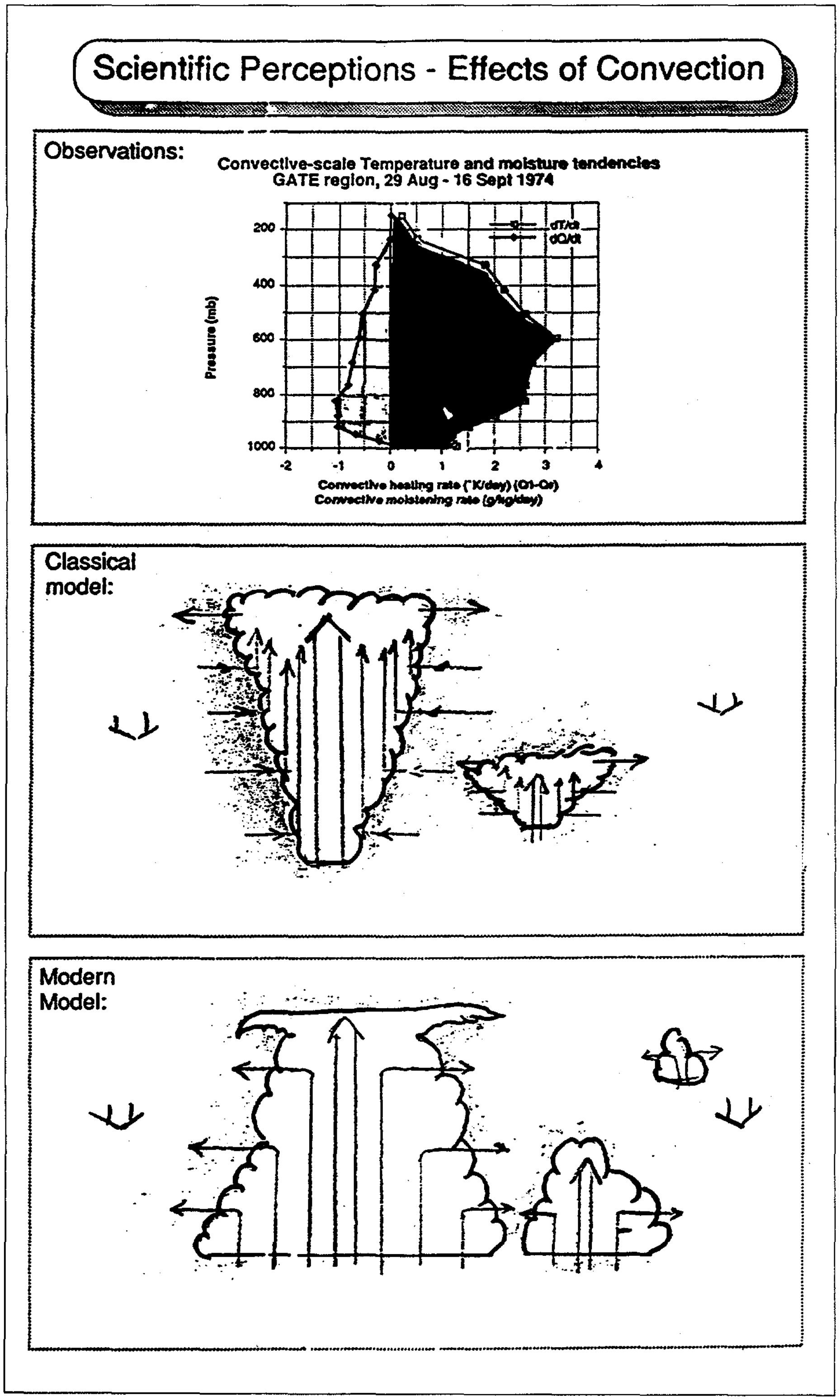

Figure 24.1

This figure compares Walcek's conceptual model of convection with the classical one.

25

Global Cloud Climatology from Surface Observations

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A threshold level of illuminance was determined, above which the clouds are apparently detected adequately. This threshold corresponds to light from a full moon at an elevation angle of 6°.

Surface weather observations from stations on land and ships in the ocean are used to obtain the global distribution, at 5°x5° latitude-longitude resolution, of total cloud cover and the average amounts of the different cloud types: cumulus, cumulonimbus, stratus, stratocumulus, nimbostratus, altostratus, altocumulus, cirrus, cirrostratus, cirrocumulus, and fog. Diurnal and seasonal variations are derived, as well as interannual variations and multi-year trends.

Two climatic atlases have been published (a) using 50 million ship observations for the 30-year period 1952-1981, and (b) using 130 million land station observations for the 11-year period 1971-1981. Two additional atlases have been published on the probabilities of co-occurrence of the different cloud types. Recently an additional ten years (1982-1991) of land and ocean data have been analyzed with greater accuracy at night by use of a moonlight criterion.

Visual observations of cloud cover are hindered at night due to inadequate illumination of the clouds. This usually leads to an underestimation of the average cloud cover at night, especially for the amounts of middle and high clouds, in climatologies based on surface observations. The diurnal cycles of cloud amounts, if based on all the surface observations, are therefore in error, but can be obtained more accurately if nighttime observations are screened to select those made under sufficient moonlight.

Ten years of nighttime weather observations from the northern hemisphere in December were classified according to the illuminance of moonlight or twilight on the cloud tops, and a threshold level of illuminance was determined, above which the clouds are apparently detected adequately. This threshold corresponds to light from a full moon at an elevation angle of 6° or from a partial moon at higher elevation, or twilight from the sun less than 9° below the horizon. It permits the use of about 38% of the observations made with the sun below the horizon.

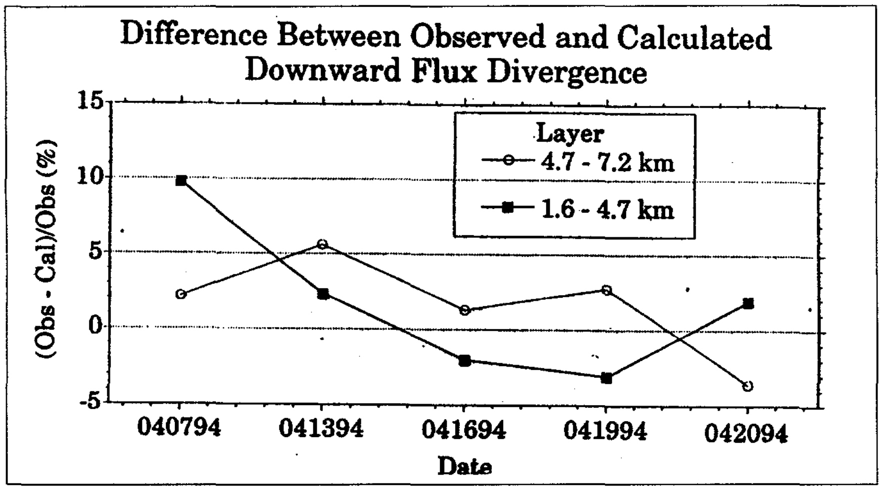

Figure 20.2: Difference between Observed and calculated downward flux divergence

21

Cloud Microphysics and Surface Properties in Climate

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For medium thick clouds a 10 % increase in drop size yields a surface warming of 1.5°C, which is the same as that due to a doubling of carbon dioxide.

Cloud optical thickness is determined from ground-based measurements of broadband incoming solar irradiance using a radiation model in which the cloud optical depth is adjusted until computed irradiance agrees with the measured value. From spectral measurements it would be feasible to determine both optical thickness and mean drop size, which apart from cloud structure and morphology, are the most important climatic parameters of clouds. A radiative convective model is used to study the sensitivity of climate to cloud liquid water amount and cloud drop size. This is illustrated in Figure 21.1 which shows that for medium thick clouds a 10 % increase in drop size yields a surface warming of 1.5°C, which is the same as that due to a doubling of carbon dioxide. For thick clouds, a 5% decrease in drop size is sufficient to offset the warming due to doubling of carbon dioxide. A radiative transfer model for the coupled atmosphere/sea ice/ocean system is used to study the partitioning of radiative energy between the three strata, and the potential for testing such a model in terms of planned experiments in the Arctic is discussed.

The determination of cloud optical properties at the ground in the Arctic relies on the use of broadband surface albedo and solar irradiance measurements from the NOAA/CMDL station in Barrow, Alaska. The absorption of cloud drops increases with drop size, leading to decreased transmission, while the forward scattering increases, leading to enhanced transmission. The net effect is that the transmittance is insensitive to drop size. But the cloud optical depth can be determined by simply comparing the measured irradiance with radiative transfer computations in which the measured surface albedo is used. Then the cloud optical depth is adjusted until the computed irradiance agrees with the measured one. The seasonal variation in cloud optical thickness at Barrow, Alaska derived using this approach for the period April 1988 through August 1988 is shown in Figure 21.2. The potential for deriving optical depth from narrowband measurements and mean drop size from bispectral transmittance measurements is explored in terms of the channels available in the Multi-Filter Shadowband Radiometer (MFRSR) deployed in the ARM program. The optical depth can be reliably inferred from the 862 nm channel (which is less influenced by atmospheric aerosols than channels at shorter wavelengths), while the mean size could be determined from a combination of measurements in the 862 nm channel and a channel centered at 2.2 microns. The latter channel is currently not available, but would be a valuable addition to narrowband instruments such as the MFRSR.

A radiative convective model with accurate treatment of radiative transfer including clouds is used to study the climate sensitivity to changes in mean drop size and optical thickness. The cloud optical properties are parameterized in terms of cloud liquid water content and equivalent radius throughout the solar and infrared portion of the spectrum. It is found that the infrared properties of clouds are sensitive to cloud scattering, which implies that clouds should not be treated as black bodies in climate models (Figures 21.3 and 21.4).

A radiative transfer model for the coupled atmosphere/sea ice/ocean system is used to study the disposition of solar energy throughout the system. The effects of clouds, snow on ice, and sea ice properties and thickness are quantified. The potential for testing this model in terms of planned experiments in the Arctic in the near future are briefly discussed. These experiments include the North Slope of Alaska site to be established through DOE's Atmospheric Radiation Measurements (ARM) Program, the Surface Heat and Energy Budget of the Arctic Ocean (SHEBA) experiment led by NSF and ONR, as well as the FIRE Phase III experiment, which is an interagency experiment led by NASA. It is concluded that the opportunities for all three efforts to benefit from close collaboration are great, but that the challenges in experimental design are equally great. In spite of these challenges, even broader interagency and international participation would be helpful.

The infrared properties of clouds are sensitive to cloud scattering, which implies that clouds should not be treated as black bodies in climate models.

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Leontieva, E. N., and K. Stamnes, Estimations of cloud optical properties from ground-based measurements of incoming solar radiation in the Arctic, *J. Climate*, **7**, 566-578, 1994.

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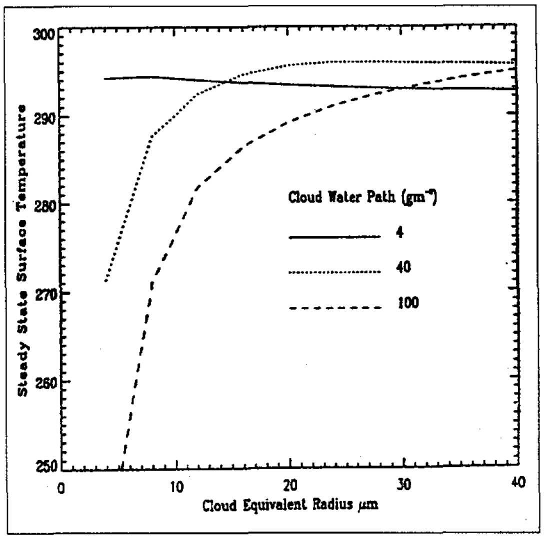

Figure 21.1: Equilibrium state surface temperature with different cloud equivalent radius. Cloud amount 50%. Cloud top height 3 km. Surface albedo for solar radiation 1.0. Radiative convective model results of dependence of surface temperature on cloud equivalent radius for various cloud water paths.

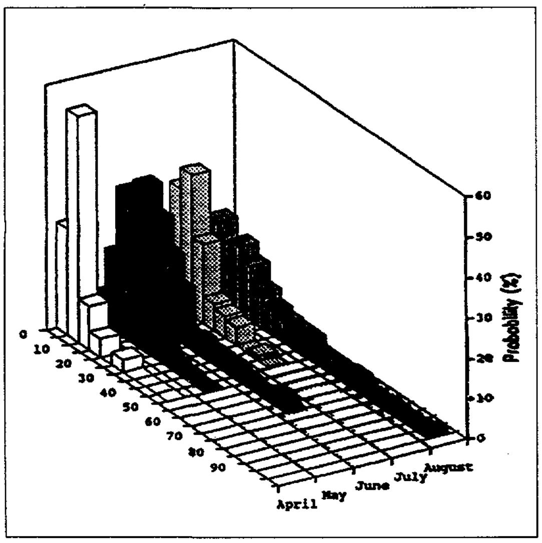

Figure 21.2: Estimated values of cloud optical thickness at Barrow Alaska, during April-August 1988

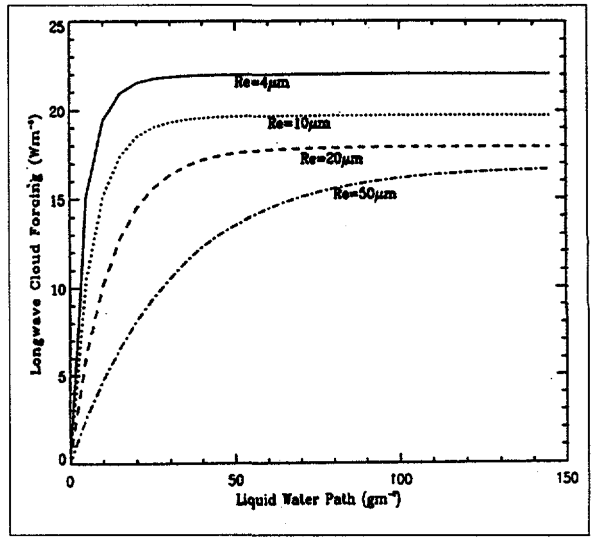

Figure 21.3: Clouds become black for longwave radiation (outgoing longwave radiation does not change when the liquid water increases) when cloud liquid water reaches about 20 gm^{-2}, if the cloud droplet is small (equivalent radius around 4 µm). When the equivalent radius increases to about 50 µm, the outgoing longwave radiation increases with the cloud water path until the cloud become very thick (cloud liquid water path around 50 gm^{-2}). So the cloud greenhouse gas effect is sensitive to the scattering of longwave radiation.

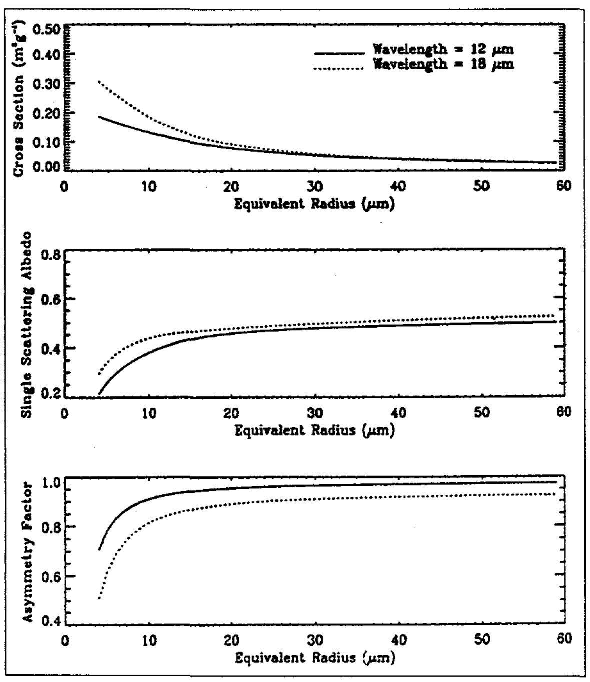

Figure 21.4: The longwave cloud radiative effect for optically thick clouds is not only determined by the cloud top temperature, but also is related to the cloud equivalent radius. This figure explains why there is more outgoing radiation (less longwave cloud radiative forcing) for thick cloud with bigger equivalent radius: the difference comes from the scattering. The scattering of longwave radiation is stronger if R_e is larger. The middle panel of this figure shows that the single scattering albedo and the asymmetry factor increases with R_e. This means the outgoing longwave radiation because of the scattering increases with R_e and thus the cloud radiative forcing decreases with the increase of R_e.

22

Cloud Physics Considerations in Global Climate Change Studies

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In order for relative humidity to remain constant, the liquid water content must be proportional to the cube root of the saturation vapor pressure, and it is difficult to explain why this should be true.

Introduction

In predicting the global warming due to a doubling of CO_2, it is important not to only evaluate the net effect of all the known feedback mechanisms, but to estimate the sensitivity to each. In other words, the partial derivatives as well as the total derivatives should be estimated. For instance, we might conclude that

$$\frac{\partial \overline{T}}{\partial \ln[CO_2]} = +1.5K$$

$$\frac{\partial \overline{T}}{\partial \ln[H_2O_{(vap)}]} = +12.5K$$

indicating that the climate is more sensitive to changes in water vapor which may occur as a result of CO_2 greenhouse warming, than to the CO_2 induced warming itself.

Precipitation

In a simple model, water vapor is injected at a rate proportional to the saturation vapor pressure, and rained out at an equal rate. The rate of precipitation (according to Berry) is proportional to the cube of LWC, since droplet coalescence is a highly nonlinear process. (In this sense, it is not the average LWC that matters for precipitation, but the extreme values in a cloud). In order for relative humidity to remain constant, the LWC must be proportional to the cube root of the saturation vapor pressure, and it is difficult to explain why this should be true. Consequently, there needs to be a better justification for making climate predictions which assume constant relative humidity.

Infrared Radiation

The treatment of clouds as black bodies is only an approximation. In fact, the extinction and absorption properties of cloud drops are quite sensitive to droplet size for the sizes typically found in clouds. Detailed calculations of the infrared "seeing" distances in clouds indicate that continental (polluted) air masses produce clouds with significantly smaller seeing distances than do maritime air masses (Figure 22.1). This effectively means that cloud top cooling will occur over a smaller depth in continental clouds, producing a more intense response (smaller time constant).

Shortwave Radiation

It is important to quantify the influence of cloud absorption. Figure 22.2 shows isolines of reflectance in the absorption/droplet concentration plane. Reflectance strongly depends on droplet concentration, but only weakly on absorption until the absorption becomes large (which is one reason that cloud absorption is so poorly determined at present). The important point is that reflectance can either increase or decrease with increasing droplet concentration depending on the way in which absorption increases with droplet concentration.

Shiptrack experiments help to quantify the effect of air pollution on clouds. Shiptracks are found to be twice as bright as cloud surrounding the tracks, implying a factor of 8 increase in droplet concentration, and consequently a halving of mean radius in order to conserve liquid water content. Results by Platnick (1991) add weight to this conclusion.

Three scenarios were considered for particles in a CO_2 doubled atmosphere: (1) the aerosol loading would double, (2) the aerosol concentration would remain constant, but aerosol mass would increase, and (3) the coagulating mass flux would double. These three scenarios lead to a spread in climatic responses, (1) almost doubling the droplet concentration, (2) increasing it by only 20%, and (3) being in between. The climate sensitivities (see introduction) are, respectively, -2.8K, -0.7K and -1.5K. The point is that these sensitivities are as big as the direct CO_2 doubling effect, so that our uncertainty about which scenario is most realistic has important implications for our global change predictions.

Conclusion

The approximate treatment of precipitation and infrared transmission in clouds together with uncertainties in the effect of a warmer climate on the global aerosol loading introduce potentially significant sources of error into current global change predictions.

The point is that these sensitivities [to particles] are as big as the direct CO_2 doubling effect, so that our uncertainty about which scenario is most realistic has important implications for our global change predictions.

CUMULATIVE	RANGE (m)	
	Ocean	Continental / Polluted
.10	1.1	~0.3
.20	3.5	1.1
.40	8.7	2.8
.60	17.0	5.3
.80	34.0	10.0
.99	100.0	29.0

Figure 22.1: "Seeing" distances in the 8-12 µm IR Window as influenced by pollution/microphysics

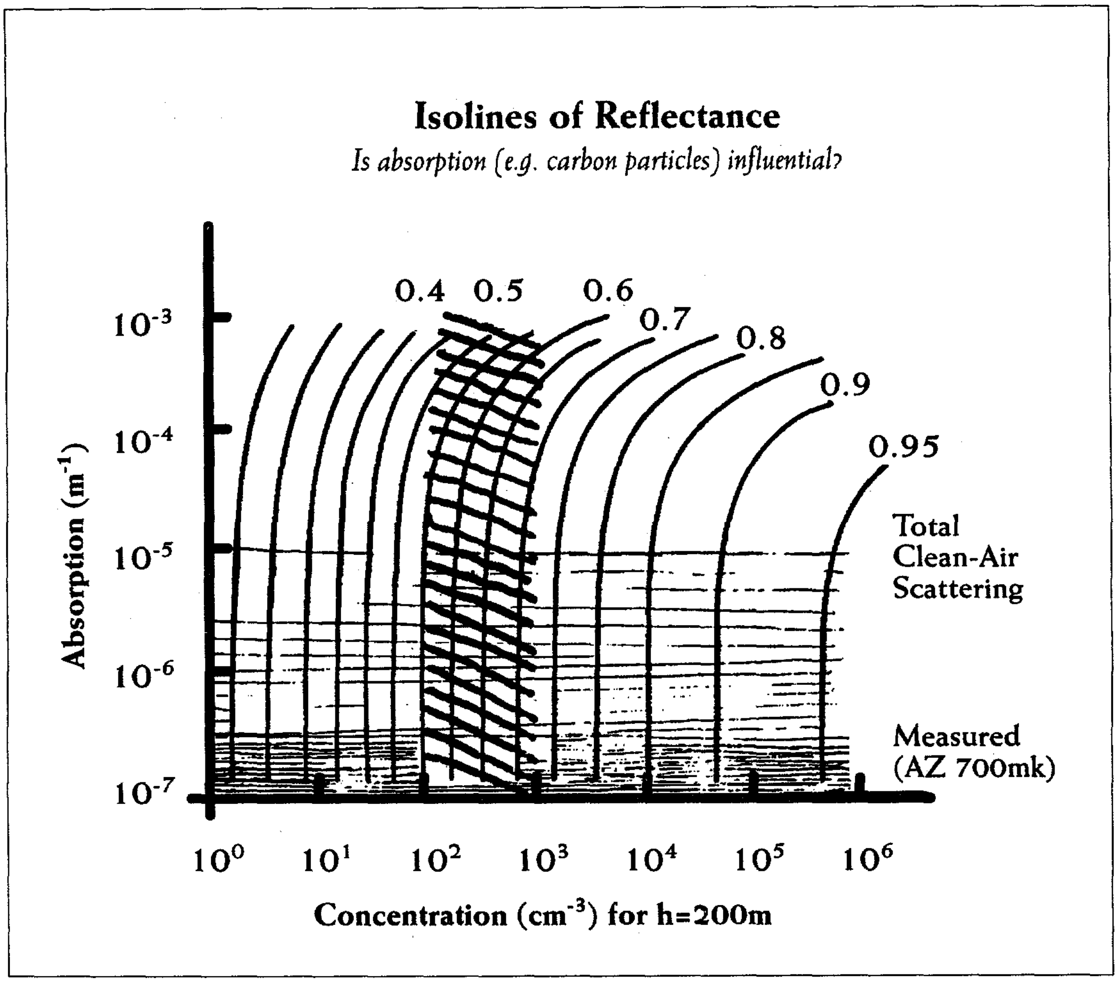

Figure 22.2: Isolines of reflectance in the absorption, droplet concentration plane

23

Clouds and Relative Humidity in Climate Models; or What Really Regulates Cloud Cover?

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The response and impact of clouds remains one of the largest outstanding questions in GCMs. Clouds are not homogeneous, though they are treated as such in the models. When averaged over areas typically used as numerical grid elements by GCMs, observations suggest that there are some clouds at all relative humidities. Fractional cloud cover at 100% relative humidity is rarely 100%, and totally clear skies rarely occur, even for low relative humidities (see Figure 23.1). Relative humidity is the best *single* indicator of cloud coverage. However, if there is a relationship between cloud coverage and relative humidity, our current models and observations are inadequate to reveal exactly what that relationship is. It does appear that cloud coverage decreases exponentially as humidity falls below 100%.

Relative humidity is the best single indicator of cloud coverage. However, if there is a relationship between cloud coverage and relative humidity, our current models and observations are inadequate to reveal exactly what that relationship is.

Climate change predictions are extremely sensitive to modeled cloud cover estimates. There are numerous methods for predicting cloud cover from relative humidity, yet none of them are firmly grounded in observation. The intent of this research is to study the relationship between cloud cover and relative humidity using available observations.

In Walcek's research, U. S. Air Force 3DNEPH cloud data is correlated with relative humidity fields produced by assimilating radiosonde observations using a mesoscale meteorology model. This produces a scatter diagram of cloud cover versus relative humidity, the gross features of which are summarized in Figure 1. Clearly, in contrast to current GCM methodologies, clouds exist over a wide range of relative humidities, rather than disappearing below some arbitrarily defined threshold, typically 60-80%, depending on height in the atmosphere.

The purpose of current models of climate change is to attempt to discern how small changes in temperature and humidity will affect cloud cover and climate. But current models are unable to respond subtly. In going from 85% to 80% relative humidity, some models go from 100% cloud cover to 0%.

Not withstanding the current uncertainties inherent in observations of both cloud cover and relative humidity, the best fit to the data appears to be an exponential decrease in cloud cover with falling relative humidity.

$$\text{cloud cover fraction} = f_{100} \exp\left[-\frac{(1-Rh)}{(1-Rh_e)}\right]$$

Of all atmospheric layers, the lower boundary layer is by far the most sensitive to changes in relative humidity. For example, a 1% change in relative humidity is associated with a 4-6% change in cloud cover in the lower boundary layer (Figure 23.2). This means that if relative humidity increased from 82% to 84%, cloud cover would increase 15%, which according to Slingo (1990), would be enough to offset the temperature rise that could result from a doubling of CO_2.

Reference

Slingo, A., 1990: Sensitivity of the earth radiation budget to changes in low cloud amount. *Nature*, **343**, 49-51.

Walcek, C. J., 1994: Cloud cover and its relationship to relative humidity during a springtime mid-latitude cyclone. *Monthly Weather Review*, **122**, 1021-1035.

Not withstanding the current uncertainties inherent in observations of both cloud cover and relative humidity, the best fit to the data appears to be an exponential decrease in cloud cover with falling relative humidity.

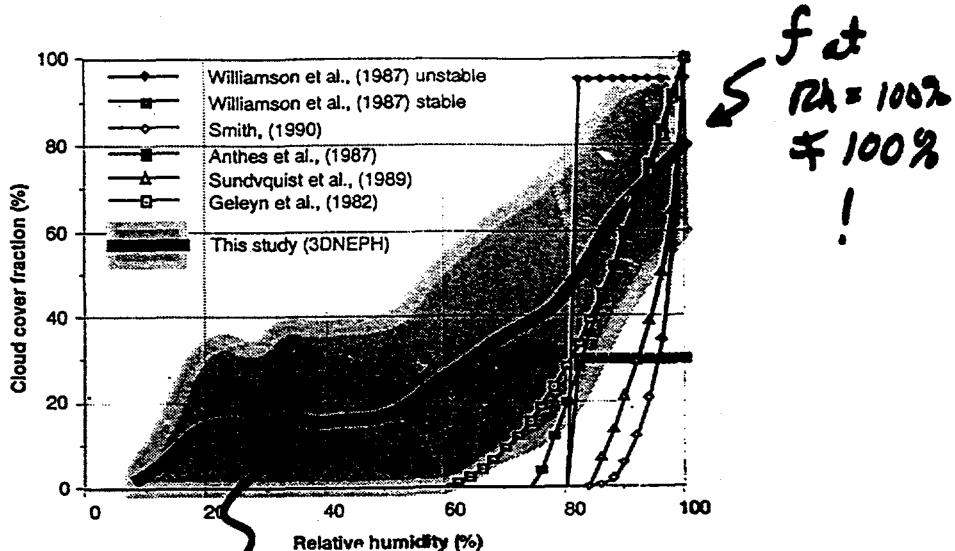

Figure 4: Fractional cloud coverage as a function of relative humidity at 800 mb according to various formulations used by meso- and global-scale atmospheric models. Shaded curve and area shows mean ±standard deviation of 3DNEPH cloud cover at specified relative humidity during five noon periods during 20-24 April 1981.

f ≠ 0 !

Figure 23.1

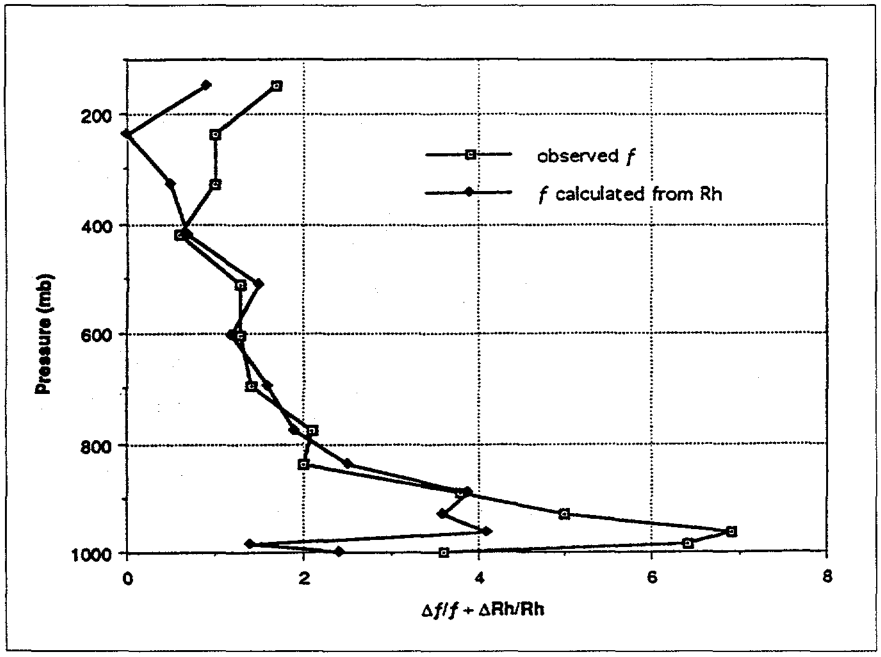

Figure 23.2: Observed and calculated vertical dependence of normalized changes in cloud fraction and relative humidity.

24 A New Conceptual Model of Convection

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Albany, NY 12205

Classical cumulus parameterizations assume that cumulus clouds are *entraining* plumes of hot air rising through the atmosphere. However, ample evidence shows that clouds cannot be simulated using this approach. Dr. Walcek suggests that cumulus clouds can be reasonably simulated by assuming that buoyant plumes *detrain* mass as they rise through the atmosphere. Walcek successfully simulates measurements of tropical convection using this detraining model of cumulus convection. Comparisons with measurements suggest that buoyant plumes encounter resistance to upward movement as they pass through dry layers in the atmosphere. This probably results from turbulent mixing and evaporation of cloud water, which generates negatively buoyant mixtures which detrain from the upward moving plume. This mass flux model of detraining plumes is considerably simpler than existing mass flux models, yet reproduces many of the measured effects associated with convective activity. Figure 24.1 compares this "modern" conceptual model with the classical one.

Cumulus clouds can be reasonably simulated by assuming that buoyant plumes detrain mass as they rise through the atmosphere.

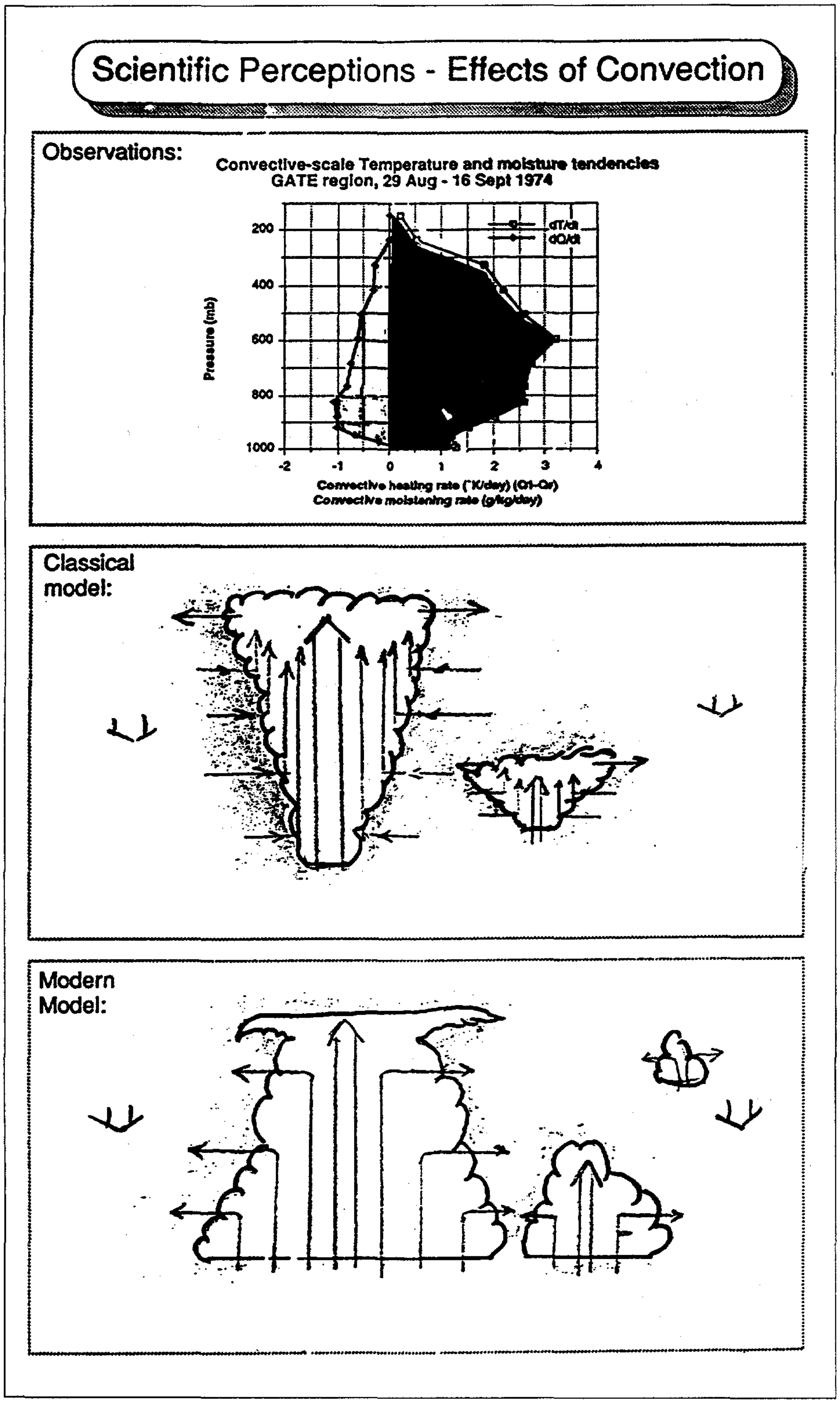

Figure 24.1

This figure compares Walcek's conceptual model of convection with the classical one.

25

Global Cloud Climatology from Surface Observations

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Seattle, WA 98195

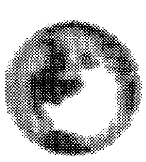
A threshold level of illuminance was determined, above which the clouds are apparently detected adequately. This threshold corresponds to light from a full moon at an elevation angle of 6°.

Surface weather observations from stations on land and ships in the ocean are used to obtain the global distribution, at 5°x5° latitude-longitude resolution, of total cloud cover and the average amounts of the different cloud types: cumulus, cumulonimbus, stratus, stratocumulus, nimbostratus, altostratus, altocumulus, cirrus, cirrostratus, cirrocumulus, and fog. Diurnal and seasonal variations are derived, as well as interannual variations and multi-year trends.

Two climatic atlases have been published (a) using 50 million ship observations for the 30-year period 1952-1981, and (b) using 130 million land station observations for the 11-year period 1971-1981. Two additional atlases have been published on the probabilities of co-occurrence of the different cloud types. Recently an additional ten years (1982-1991) of land and ocean data have been analyzed with greater accuracy at night by use of a moonlight criterion.

Visual observations of cloud cover are hindered at night due to inadequate illumination of the clouds. This usually leads to an underestimation of the average cloud cover at night, especially for the amounts of middle and high clouds, in climatologies based on surface observations. The diurnal cycles of cloud amounts, if based on all the surface observations, are therefore in error, but can be obtained more accurately if nighttime observations are screened to select those made under sufficient moonlight.

Ten years of nighttime weather observations from the northern hemisphere in December were classified according to the illuminance of moonlight or twilight on the cloud tops, and a threshold level of illuminance was determined, above which the clouds are apparently detected adequately. This threshold corresponds to light from a full moon at an elevation angle of 6° or from a partial moon at higher elevation, or twilight from the sun less than 9° below the horizon. It permits the use of about 38% of the observations made with the sun below the horizon.



The computed diurnal cycles of total cloud cover are altered considerably when this moonlight criterion is imposed. Maximum cloud cover over much of the ocean is now found to be at night or in the morning, whereas in the published atlases without the moonlight criterion the computed time of maximum was obtained as noon or early afternoon in many regions (Figure 25.1). The diurnal cycles of total cloud cover obtained are compared with those of ISCCP for a few regions; they are generally in better agreement if the moonlight criterion is imposed on the surface observations. The average cloud cover is found to be greater during the day than at night by 3.3% over land but by only 0.3% over the ocean. Cloud cover is greater at night than during the day over the open oceans far from the continents, particularly in summer (Figure 25.2).

Using the moonlight criterion, ten years (1982-1991) of surface weather observations over land and ocean, worldwide, have been analyzed for total cloud cover and for the frequency of occurrence of clear sky, fog, and precipitation. The global average cloud cover (average of day and night) is about 2% higher if the moonlight criterion is imposed than if we use all observations (see Figure 25.3). The difference is greater in winter than in summer, because of the fewer hours of darkness in summer. The amplitude of the *annual* cycle of total cloud cover in the Arctic Ocean and at the South Pole is diminished by a few percent when the moonlight criterion is imposed.

The average cloud cover for 1982-1991 is found to be 54% for northern hemisphere land, 53% for southern hemisphere land, 66% for northern hemisphere ocean, and 70% for southern hemisphere ocean, giving a global average of 64%. The global average for daytime is 64.6% and for nighttime, 63.3%.

The 1982-1991 data have not yet been analyzed for cloud types. However, an archive of edited individual cloud reports has been prepared, so that a user can develop a climatology for any particular type for any geographical region and any spatial and temporal resolution desired. The information in the weather reports relating to clouds, including the present weather information, was extracted and put through a series of quality control checks. Reports not meeting certain quality control standards were rejected. Minor correctable inconsistencies within reports were edited for consistency. Cases of "sky obscured" were interpreted by reference to the present weather code as to whether they indicated fog, rain, snow, or thunderstorm. Special coding is added to indicate probable nimbostratus clouds

The global average cloud cover (average of day and night) is about 2% higher if the moonlight criterion is imposed than if we use all observations.

which are not specifically coded for in the synoptic code. This "edited cloud report" also includes the amounts, either inferred or directly reported, of low, middle and high clouds, both overlapped and non-overlapped. The relative lunar illuminance and solar zenith angle are also given.

An archive of edited individual cloud reports has been prepared, so that a user can develop a climatology for any particular type for any geographical region and any spatial and temporal resolution desired.

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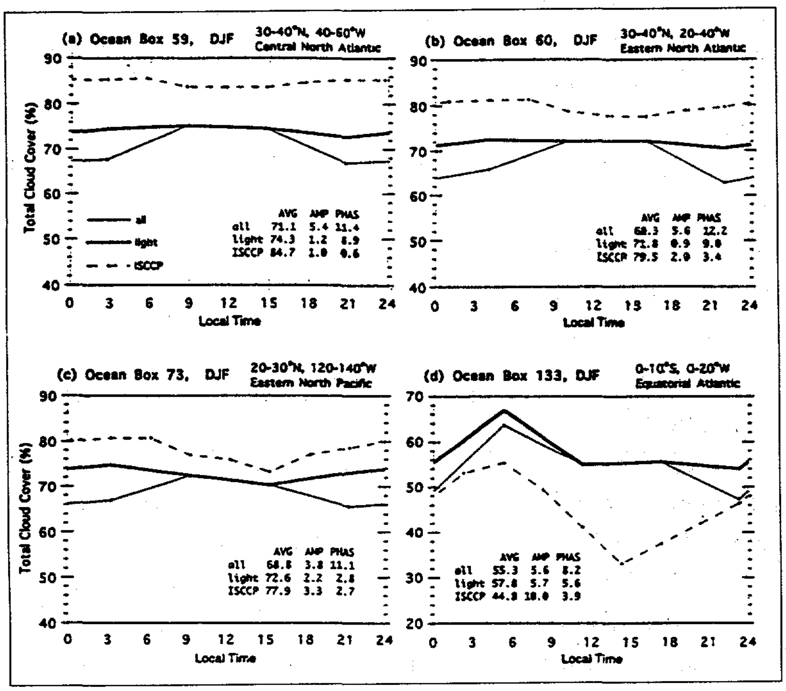

Figure 25.1: Diurnal variation of total cloud cover for various locations

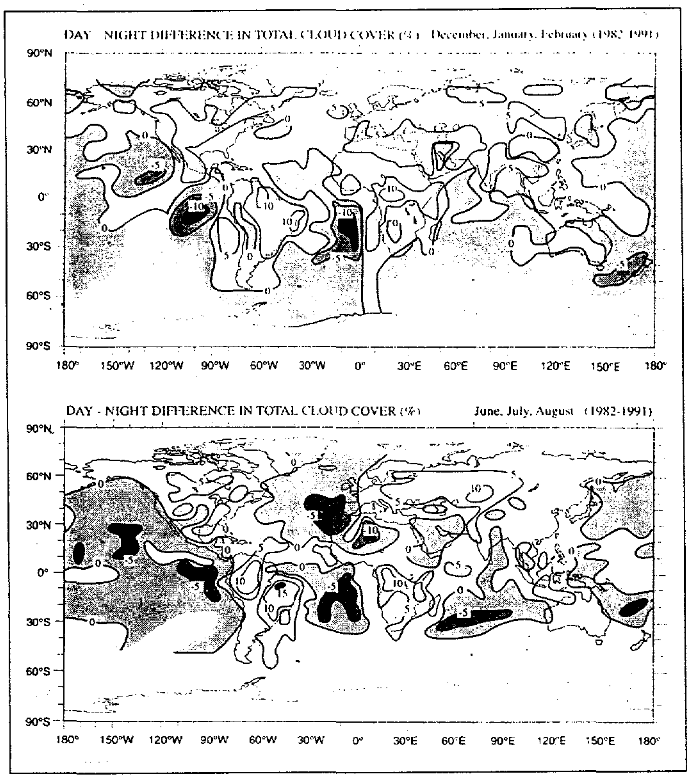

Figure 25.2: Day-night differences in total cloud cover

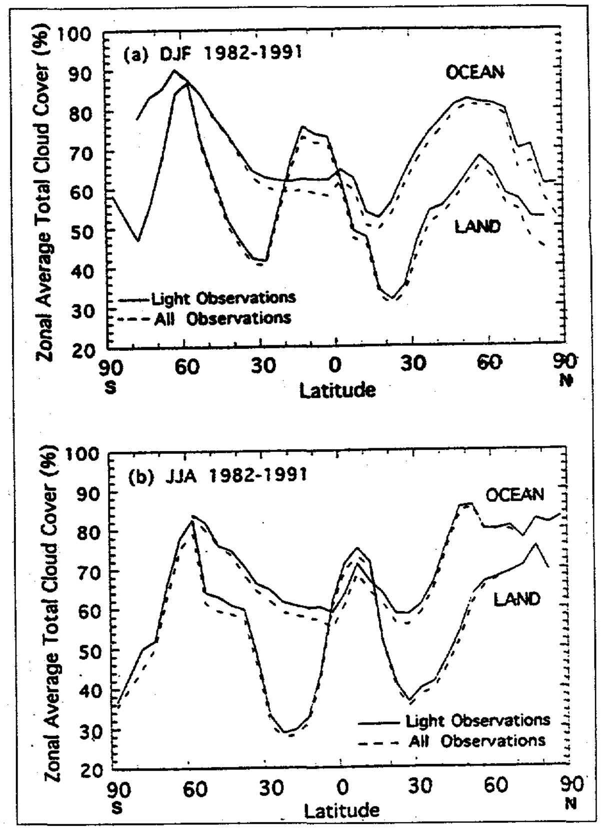

Figure 25.3: Latitudinal dependence of zonal average cloud cover with and without a moonlight criterion

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Dimethyl Sulfide as a Source of Cloud Condensation Nuclei

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Marine biogenic sulfur may be an important factor in determining the Earth's climate.

Cloud condensation nuclei (CCN) are predominantly sulfate particles, and over the oceans the major source of sulfur for these particles appears to be dimethyl sulfide, a gas produced by marine biota (see Figure 26.1). The reflection of sunlight by marine stratiform clouds is a major feature of the Earth's radiation budget, and these clouds will reflect more sunlight if their liquid water is distributed among more CCN, thus forming more (and smaller) droplets. These facts form the basis of a proposal that marine biogenic sulfur may be an important factor in determining the Earth's climate. Key implications of this proposal are (1) the possibility of a biota-climate feedback loop if the production of biogenic sulfur is sensitive to changes in climate, (2) the possibility that anthropogenic sulfur emissions may be altering the global climate through this cloud-mediated mechanism, and (3) the possibility that anthropogenic pollution could alter climate by perturbing the sulfur-producing marine organisms.

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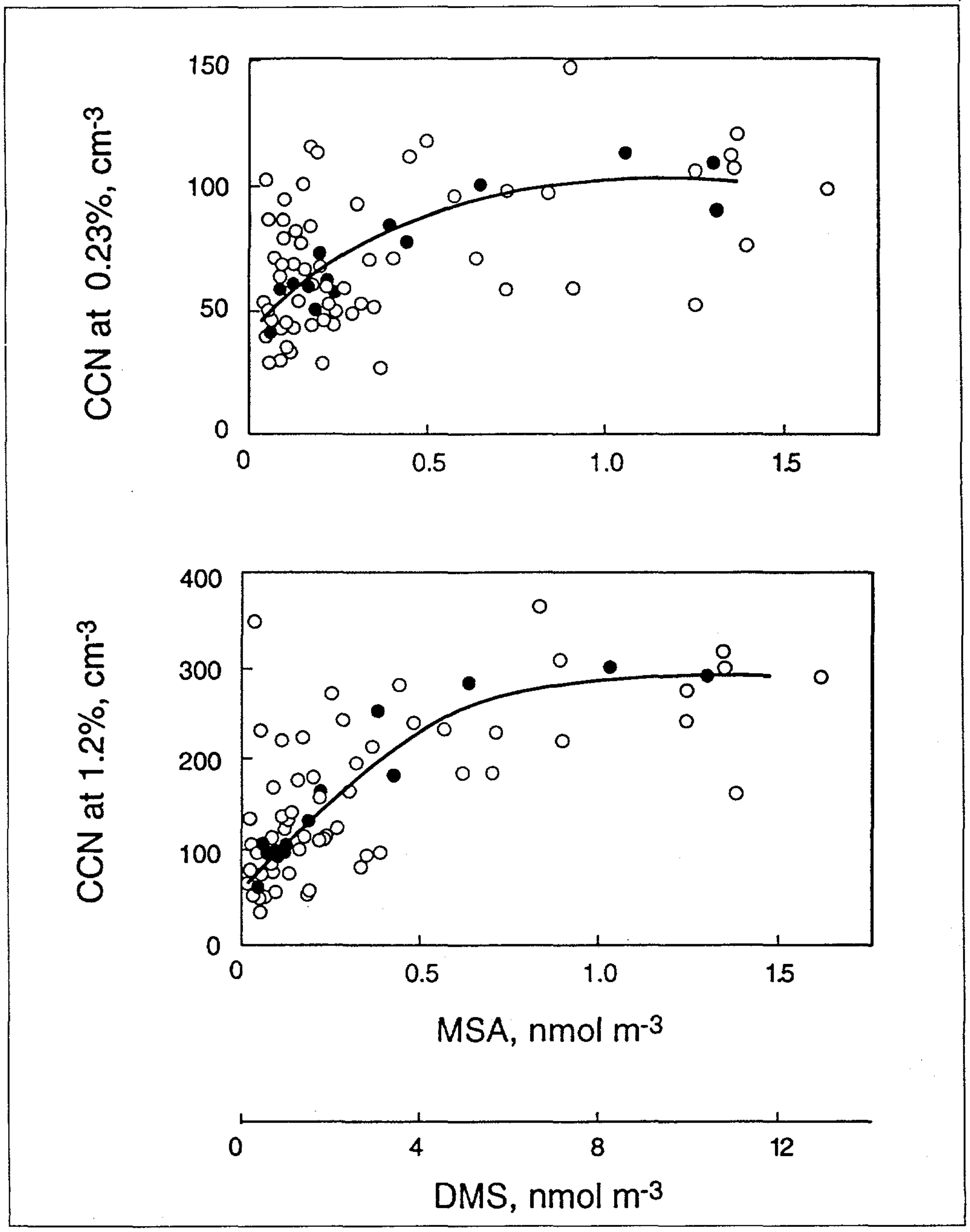

Figure 26.1: Measured cloud condensation nucleus concentration (cm^{-3}) at 0.23 and 1.2% supersaturation versus near simultaneously measured aerosol methane sulfonate (MSA). Surrogate axis for dimethylsulfide (DMS) is from other simultaneous observation of DMS and MSA (Adapted from Ayers and Gras, 1991).

Reference for this figure: Charlson, R. J., 1993: Gas-to-particle conversion and CCN production. International Symposium on Dimethylsulphide: Oceans, Atmosphere and Climate (eds. G. Restelli and G. Angeletti), Kluwer, Dordrecht, (275-268)

27 Modeling of Cloud Liquid Water Structure and the Associated Radiation Field

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A 0.5°C global warming should result from every 1% decrease in global albedo. It is therefore necessary to accurately quantify the cloud radiation interaction. Most radiation calculations are one-dimensional and attempt to deal with horizontal variability using a horizontally-averaged optical depth. This study presents detailed scale-by-scale statistical analysis of the cloud liquid water content (LWC) field. The aim is to use this information to provide radiation calculations with more adequate information about inhomogeneity in cloud fields. The radiation community needs to carefully specify the minimum requirements which GCMs must include in order to treat cloud-radiation interaction correctly. This may involve GCMs predicting not only mean cloud quantities but also cloud variability.

The radiation community needs to carefully specify the minimum requirements which GCMs must include in order to treat cloud-radiation interaction correctly. This may involve GCMs predicting not only mean cloud quantities but also cloud variability.

The radiative properties of clouds are typically treated using the plane parallel approximation but this is known to be inadequate for dealing with inhomogeneity in clouds. The next simplest description of cloud variability is provided by fractal analysis. Clouds have been shown to exhibit fractal structure over a large range of scales (30 meters to 1000 kilometers). Fractal clouds reflect about 5-10% less than their homogeneous equivalents (Figure 27.1).

There are a number of ways to measure cloud LWC. Aircraft have traditionally used hot wire probes (Johnson-Williams or King probes). The FSSP, which optically samples individual drops, is extensively used to obtain cloud droplet spectra. Large sample times are required to obtain adequate statistics, especially for higher order moments of droplet size such as LWC. A new optical probe, the Gerber probe, has a significantly larger sampling volume and promises to provide high quality LWC and effective radius measurements at much improved rates. There is also a possibility of using tomography to map the LWC field. From the surface, microwave radiometers provide a good estimate of cloud liquid water path.

Almost all records of LWC show intermittent dry patches (as distinct from equipment glitches).

While different records appear quite distinct in terms of the amount of variability, the power spectra are generally very similar, with slopes between 1.3 and 1.7 over a wide range of scales. This naturally suggests a fractal approach to analysis. Interestingly, the ASTEX data shows an unexplained scale break around 60 meters (Figure 27.2).

Fractal analysis of the LWC record proceeds as follows: the Hurst exponent, H_1, a measure of non-stationarity (or roughness), is obtained by structure function analysis. A second exponent, C_1, which determines the intermittency of the data, is obtained through singular measure analysis. Different data records (FIRE, ASTEX, ARM, and differing synoptic regimes therein) can be represented by points on the (C_1, H_1) plane, the so-called "mean" multi-fractal plane (Figure 27.3). The scatter of points is large enough to suggest that a more complete multi-fractal description is required.

There are several methods which can be used to generate a fractal LWC field with both intermittency and non-stationarity. Among these are the Bounded Cascade model, and the Fractionally-Integrated Cascade. These LWC fields can be used to determine the dependence of cloud radiative properties on the fractal characteristics of the clouds, and how the independent pixel approximation (plane parallel at each pixel) can be improved, or corrected, to account for realistic cloud structure.

The radiative properties of clouds are typically treated using the plane parallel approximation but this is known to be inadequate for dealing with inhomogeneity in clouds. The next simplest description of cloud variability is provided by fractal analysis.

Modeling of Cloud Liquid Water Structure and the Associated Radiation Field

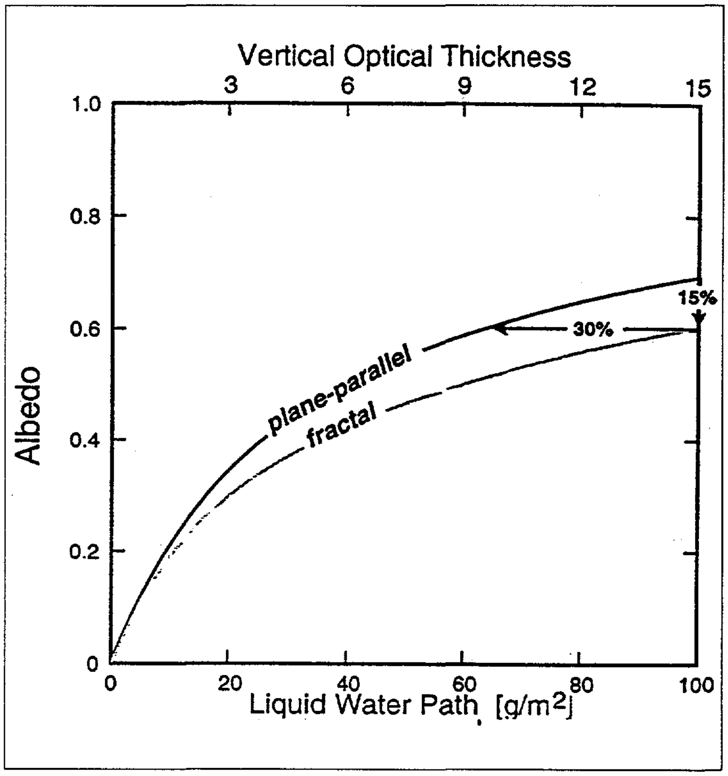

Figure 27.1: Dependence of albedo on optical thickness and liquid water path, for fractal and plane-parallel clouds

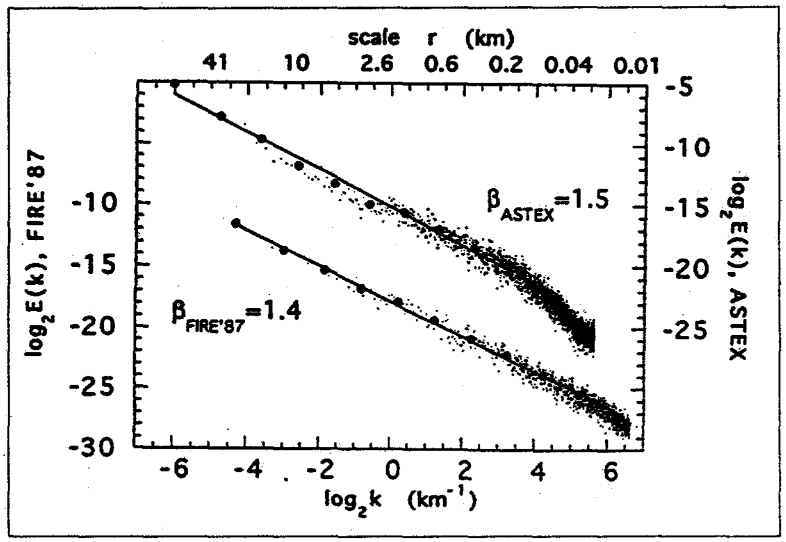

Figure 27.2: Scale dependence of ASTEX and FIRE liquid water data

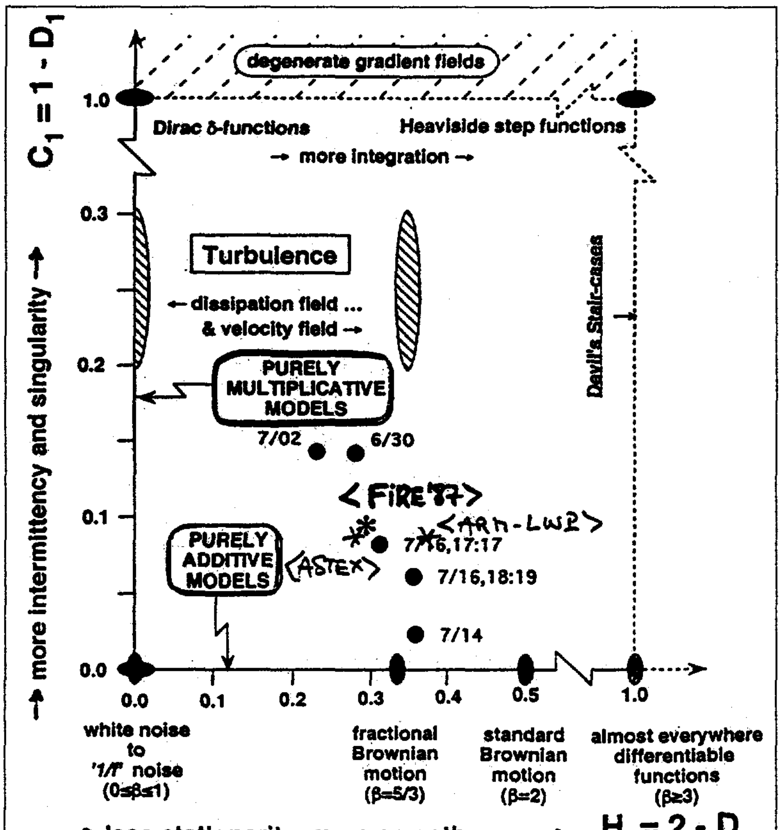

Figure 27.3: The "mean" multi-fractal plane

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Participant List

ASPEN GLOBAL CHANGE INSTITUTE 1994 SUMMER SESSION 1

July 10 to July 23 1994

Climate-Radiation Feedbacks: The Current State of the Science

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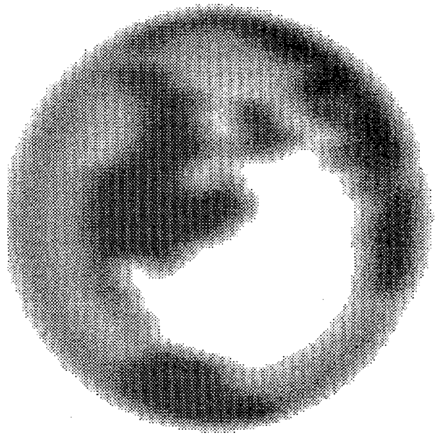

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