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Clouds and Ocean-Atmosphere Interactions

Final Report

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1. Introduction

Predictions of global change based on climate models are influencing both national and international policies on energy and the environment. Existing climate models show some skill in simulating the present climate, but suffer from many widely acknowledged deficiencies. Among the most serious problems is the need to apply "flux corrections" to prevent the models from drifting away from the observed climate in control runs that do not include external perturbing influences such as increased carbon dioxide (CO_2) concentrations. The flux corrections required to prevent climate drift are typically comparable in magnitude to the observed fluxes themselves.

Although there can be many contributing reasons for the climate drift problem, clouds and their effects on the surface energy budget are among the prime suspects. Cess et al. (1990) demonstrated that uncertainties in cloud feedback are capable of explaining much of the three-fold variation in climate sensitivity among the current generation of climate models. Randall et al. (1992) extended this study to investigate the surface energy budgets simulated by the models. Both of these studies are examples of "GCM intercomparisons" conducted under the auspices of the U. S. Department of Energy.

We have conducted a research program designed to investigate global air-sea interaction as it relates to the global warming problem, with special emphasis on the role of clouds. Our research includes model development efforts; application of models to simulation of present and future climates, with comparison to observations wherever possible; and vigorous participation in ongoing efforts to intercompare the present generation of atmospheric general circulation models.

2. A summary of the research conducted under this project

The proposed research consists of leading research activities in both FANGIO and AMIP, and also development of research projects specifically with the Colorado State University (CSU) general circulation model (GCM).

a) *Snow feedback study (FANGIO)*

The effects of snow on the atmospheric general circulation and climate have been the subject of many studies [e.g. Barnett et al. 1989; Dey and Bhanu Kumar 1982; Loth et al 1993; Yasunari et al 1991]. Observations of the seasonal cycle of snow cover were discussed by Robock [1980]. Of particular interest are possible climatic feedbacks involving changes in snow cover in response to externally forced perturbations of the climate system [Robock 1983]. According to Groisman et al. [1994], the annual snow cover in the Northern Hemisphere has in fact declined by about 10% over the past 20 years.

Cess et al. [1991; hereafter "C"] investigated the snow-albedo feedback in seventeen general circulation models [see also the related study by Ingram et al., 1989]. Following the methodology of Cess et al. [1989], each model was run with sea surface temperatures (SSTs) artificially increased by 2 K everywhere over the globe, relative to climatology (the "+2 K" runs), and again with SSTs artificially decreased by 2 K everywhere relative to climatology (the "-2 K" runs). Perpetual April simulations were used, since a pilot study indicated that April represents a good compromise between large Northern Hemisphere snow cover and strong Northern Hemisphere insolation. Each model was used to perform either one or two -2 K runs (see the discussion of "Run Procedures," below) and two +2 K runs. In the first +2 K run, the snow cover was allowed to retreat in response to the prescribed warming of the oceans. In the second +2 K run, the snow cover was held fixed at that obtained in a -2 K run.

For each pair of +2 K and -2 K runs, a "climate sensitivity parameter," λ, was computed from

$$\lambda \equiv \Delta T / G, \qquad (1)$$

where ΔT is the change in the globally averaged surface temperature, and G is the change in the net radiation at the top of the atmosphere. Because λ measures the change in surface temperature per unit change in the net radiation at the top of the atmosphere, it is a measure of climate sensitivity.

The ratio λ/λ_s was interpreted as a measure of the snow feedback; here the subscript s denotes the value of λ obtained in a pair of runs (+2 K, -2 K) for which the snow cover was fixed. For $\lambda/\lambda_s > 1$, the climate sensitivity with variable snow is greater than that with fixed snow, so we can say that changes in snow cover have increased the climate sensitivity. In this sense, λ/λ_s is a measure of the snow feedback.

The main conclusions of C were:

- The snow feedback is negative in some models, and positive in others. Only weak negative feedbacks were obtained by a few models, however, while most models produced positive snow feedbacks, some of them fairly strong.
- The direct snow-albedo feedback is only a portion of the total snow feedback. Numerous indirect snow feedbacks occur, involving changes in the surface temperature and cloudiness. The magnitudes of the various direct and indirect snow feedbacks differ significantly from one model to another.

C's overall conclusion was that even the apparently straightforward snow feedback is difficult to characterize without careful, quantitative consideration of the full complexity of the climate system.

In a follow-on to the study of C, we have analyzed snow feedbacks produced by fourteen atmospheric general circulation models (Randall et al. 1994). Included in our analysis was an investigation of the surface energy budgets of the models. Negative or weak positive snow feedbacks occurred in some of the models, while others produced strong positive snow feedbacks. These feedbacks were due not only to melting snow, but also to increases in boundary temperature, changes in air temperature, changes in water vapor, and changes in cloudiness. As a result, the net response of each model was quite complex. We analyzed in detail the responses of one model with a strong positive snow feedback, and another with a weak negative snow feedback. Some of the models include a temperature-dependence of the snow albedo, and this significantly affected the results.

Our results generally support the conclusions of Cess et al. [1991], i.e. that the snow feedback is negative in some models, and positive in others; that the direct snow-albedo feedback is supplemented and to some extent obscured by numerous indirect snow feedbacks involving changes in the surface temperature and cloudiness; and that the magnitudes of the various direct and indirect snow feedbacks differ significantly from one model to another. The main purpose of the present study has been to provide more detail on these results and to give some interpretations as to why the various models responded in such different ways.

The land-surface responds to a prescribed sea surface temperature increase by melting snow, but also by warming the ground, and altering the various components of the surface energy budget in ways that depend strongly on the details of a model's formulation. The darker surface that follows the melting of the snow can lead to more solar energy absorption for a given distribution of clouds. On the other hand, warmer ground can radiate more effectively to space, again for a given distribution of clouds. Of course, cloudiness itself can change in the same regions where snow melt occurs, and the net effect of combined changes of clouds and snow cover on the planetary and surface radiation budgets is not obvious; our results show that it differs drastically from one GCM to another.

b) *CO_2 forcing study (FANGIO)*

The CSU model's results were included in the FANGIO study of CO_2 forcing (Cess et al. 1993). The conclusion of this study is that when a doubling of atmospheric carbon dioxide is imposed, the resulting CO_2 forcing differs substantially among the 15 GCMs used. The largest source of these differences was the carbon dioxide radiation parameterization used in the models. We collectively resolved that in the future simulations of CO_2-altered climates should routinely save the CO_2 forcing as a diagnostic.

c) Seasonal cloud forcing simulations (FANGIO)

It is difficult to devise a practical way to observationally test simulations of the changes in the cloudiness and the CRF that accompany climate changes. We cannot observe the clouds of a future climate until that future arrives; moreover, it seems very difficult to obtain reliable evidence of the cloud distributions characteristic of paleoclimates that we may attempt to simulate with our models.

In an attempt to overcome this problem, Cess et al. (1995) have defined seasonal cloud radiative forcing parameters for both longwave and shortwave radiation, and have compared the results of a dozen or so GCMs with each other and with observations from ERBE. This marks an important step forward for FANGIO, in that this is the first time that a comparison with observations has been included as part of a FANGIO GCM intercomparison study. The comparisons of the model results with observations show that there are several distinct types of errors, and that these errors differ markedly from one model to another, and that some of the models have considerably smaller errors than others.

d) AMIP Subproject on Surface Boundary Fluxes

Gleckler et al. (1994; hereafter G) analyzed the ocean energy transports implied by the ensemble of AGCMs participating in the Atmospheric Model Intercomparison Project (AMIP; Gates 1992). The models were run with prescribed seasonally and interannually varying sea surface temperatures and sea ice distributions, as observed for the years 1979 - 1988.

As the models ran, they produced simulations of the net radiation at the top of the atmosphere and of the net energy flux across the Earth's surface. G determined the ocean meridional energy transport, T_O, implied by the ten-year averages of the implied net surface energy flux, for each AGCM. These are represented by the thin lines in the upper panel of Fig. 1. The heavy lines show observationally derived upper and lower bounds on T_O. See G for details. It is apparent that most of the simulations differ drastically from the observations, particularly in the Southern Hemisphere, where the implied T_O for many of the models is towards the equator.

Next, G determined the total meridional energy transport by the atmosphere and ocean combined, denoted by T_{A+O}, by using the simulated ten-year averages of the top-of-the-atmosphere net radiation, for each model. They then determined the simulated atmospheric energy transport, T_A, from

$$T_A = T_{A+O} - T_O. \tag{1}$$

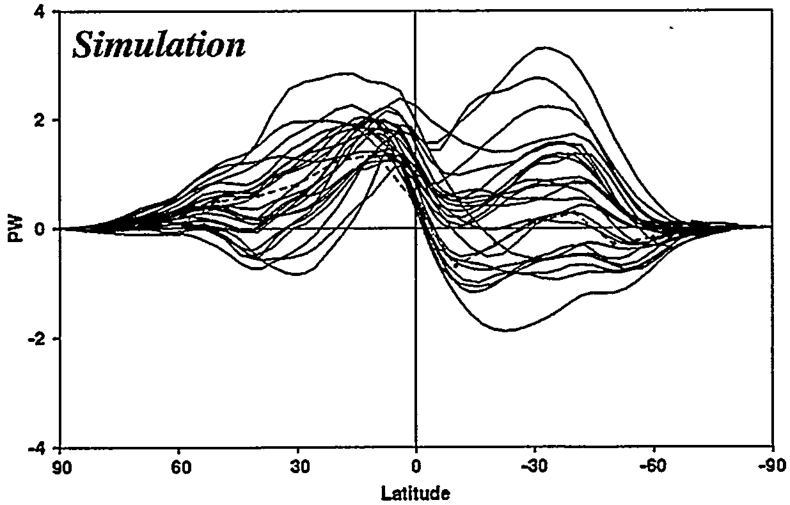
Finally, G obtained a "hybrid" value of T_O, denoted by $(T_O)_{hybrid}$, by using

$$(T_O)_{hybrid} = (T_{A+O})_{ERBE} - T_A. \tag{2}$$

Here $(T_{A+O})_{ERBE}$ is the total meridional energy transport implied by the net to-of-the-atmosphere radiation, as observed by ERBE. Thus $(T_O)_{hybrid}$ is a "hybrid" in the sense that it combines the simulated T_A with the observed T_O. The results for $(T_O)_{hybrid}$ are shown in the lower panel of Fig. 1. It is clear that, on the whole, the various $(T_O)_{hybrid}$ bear a much closer resemblance to the observations than the simulated T_{A+O} curves do.

G gave the following interpretation of the results shown in Fig. 1, based in part on the results of further calculations, which are shown in their paper but are omitted here for brevity. The top-of-the-atmosphere radiation simulated by many of the models is seriously in error compared with ERBE, largely as a result of deficiencies in the simulated cloud radiative forcing.

Implied Ocean Meridional Energy Transport



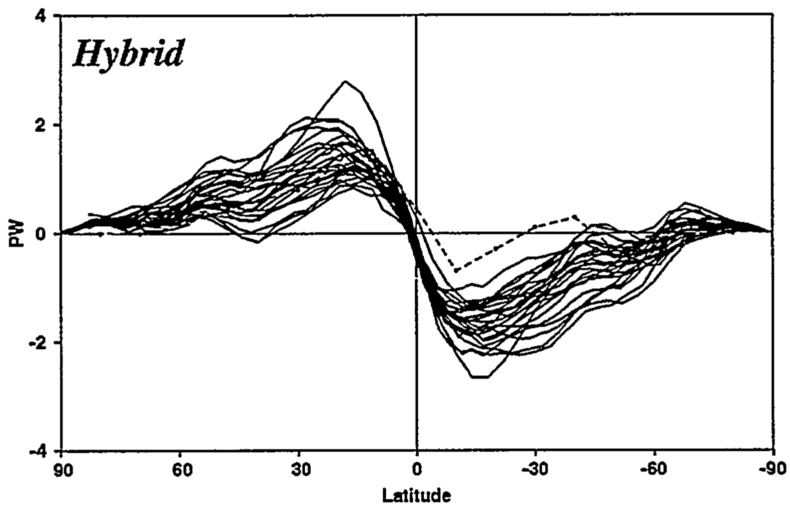


Figure 1: a) The thin lines show the ocean meridional energy transport, T_O, implied by the ten-year averages of the implied net surface energy flux, for each AGCM. The gray shading shows the observational bounds on T_O. The dashed line shows the results obtained by Semtner and Chervin (1992) in a numerical simulation of the general circulation of the oceans, forced with the observed atmospheric climate. b) As in panel a, except that the thin lines show $(T_O)_{hybrid}$. See text for details.

Nevertheless, the simulated atmospheric general circulations, and in particular the simulated atmospheric meridional energy transports, are fairly realistic in most cases. This is possible because the distribution of sea surface temperature is prescribed from observations, and acts as a very strong constraint on the atmospheric general circulation. The errors in the top-of-the-atmosphere radiation simulations are thus "buried" in the ocean. These errors become evident only when the net surface energy flux and the implied ocean meridional energy transport are evaluated, as in the upper panel of Fig. 1, or in fact when the AGCMs are coupled with ocean GCMs.

G concluded that future coupled ocean-atmosphere models will require improved simulations of the effects of clouds on the radiation budget. For this, we need improved cloudiness parameterizations.

The obvious follow-up to the work of G, besides a further publication giving more details of the model results, is an in-depth analysis of the errors in particular models. We have begun such an analysis for the CSU GCM. Some early results are discussed below.

e) Analysis of AMIP results produced with the CSU GCM

The Colorado State University (CSU) AGCM is one of the models that participated in AMIP and in the study of G, as described above. The model has been derived from the 1982 version of the UCLA GCM, developed by A. Arakawa and colleagues. Numerous changes have been made since the model was taken from UCLA. The version of the model used in AMIP and by G was described by Randall et al. (1991) and references therein. The AMIP simulation with the CSU AGCM, as used by G, was performed in 1991, and is referred to below as "CSU91."

Since 1991, the model has undergone many modifications, three of which are particularly important. First, the cumulus parameterization was revised following the approach of Randall and Pan (1993), who introduced a prognostic cumulus kinetic energy. Second, SiB2, the land-surface parameterization described by Sellers et al. (1995 a, b) and Randall et al. (1995 a), was incorporated into the model. Finally, the model was endowed with an improved parameterization of stratiform cloudiness developed and tested by Fowler et al. (1995) and Fowler and Randall (1995).

Tests have shown that, of the three changes listed above, the improved parameterization of stratiform cloudiness has by far the greatest effect on the results presented below, and so we briefly describe it here. The old stratiform cloudiness parameterization is purely diagnostic and follows the methods described by Harshvardhan et al. (1989). Fowler et al. (1995) introduced new prognostic variables to represent the mass of cloud water, cloud ice, rain, and snow. Cumulus detrainment acts as a source of cloud ice and cloud water, which can also form through large-scale saturation. Snow and rain are produced through autoconversion and collection. The various microphysical processes are parameterized following Rutledge and Hobbs (1983) and Lin et al. (1983). The radiative properties of the stratiform clouds are parameterized in terms of the predicted distributions of cloud mass. As discussed by Fowler and Randall (1995), the new cloudiness parameterization leads to major improvements in the model's simulation of the Earth's radiation budget. Large changes also occur in the simulated hydrologic cycle, including the distribution of cumulus precipitation, even though Fowler et al. (1995) made no change to the model's cumulus parameterization. For further discussion, see the papers by Fowler et al. (1995) and Fowler and Randall (1995).

We have recently completed an AMIP simulation using the new model, which incorporates all three of the revisions listed above. The results of the first nine years of the run, denoted hereafter by "CSU94," have been used to make the figures discussed below; it is expected that inclusion of the tenth year would have very little effect on these results because the quantities under discussion show little interannual variability during the first nine simulated years.

Fig. 2 shows T_O as simulated by CSU91 and CSU94. The CSU91 results show equatorward transport in the Southern Hemisphere, and are strongly at odds with the observationally based estimates. The CSU94 results are considerably improved, although they still differ significantly from the observations.

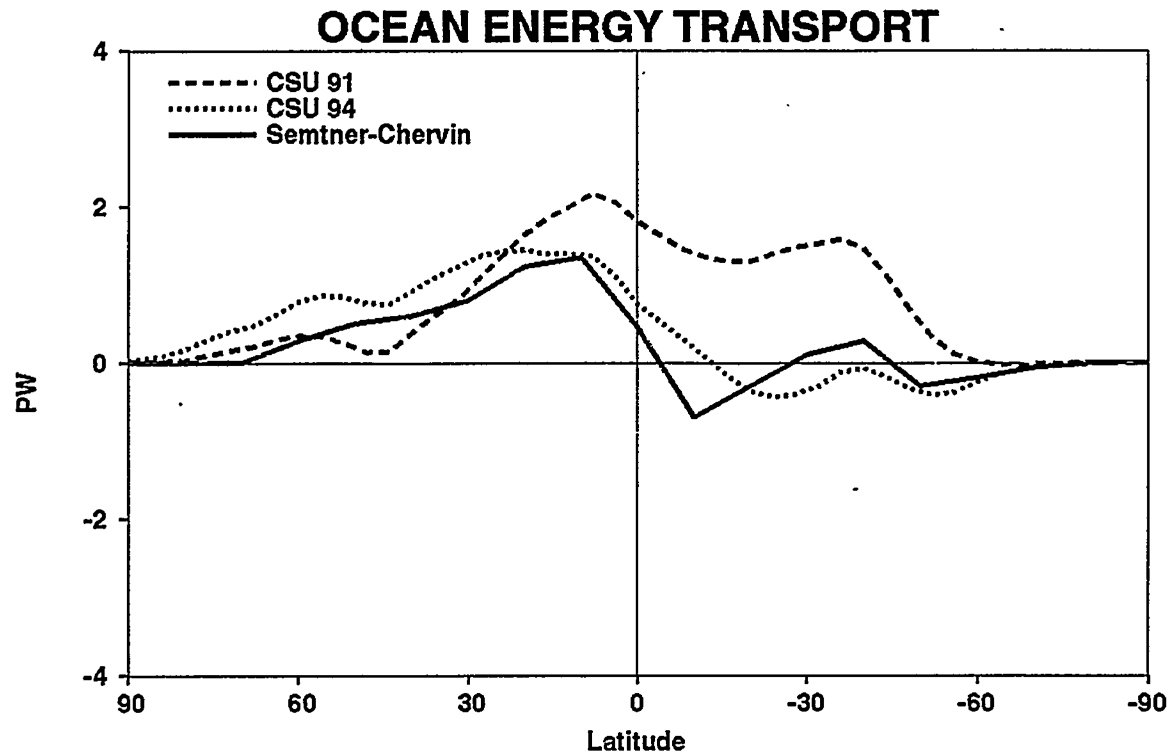


Figure 2: **The implied zonally integrated ocean meridional energy transport as obtained from the net surface energy fluxes produced in CSU91 (dashed line) and CSU94 (solid line). The gray shading shows the observational bounds on T_O. The solid line shows the results obtained by Semtner and Chervin (1992) in a numerical simulation of the general circulation of the oceans, forced with the observed atmospheric climate.**

Fig. 3 shows the simulated net surface energy flux for both runs. The correspondence with the results shown in Fig. 2 is clear. CSU94 increases the net energy flux into the tropical oceans, which takes particularly large values in the southern tropics, and this favors an increased poleward ocean energy transport, which shows up primarily as an increased southward transport in the Southern Hemisphere.

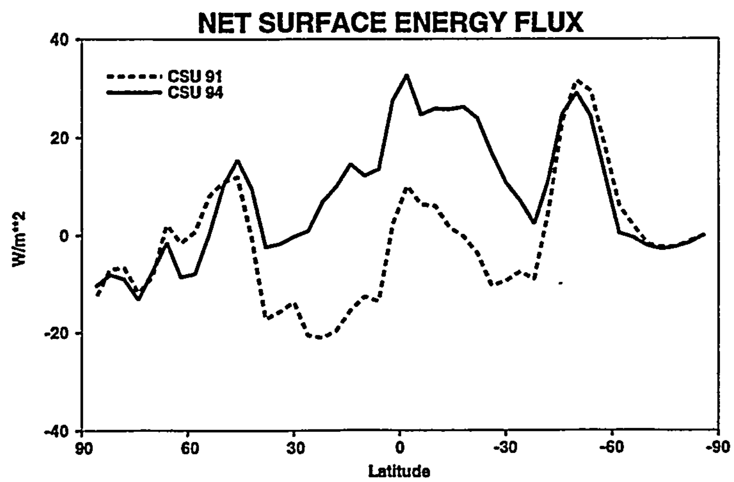
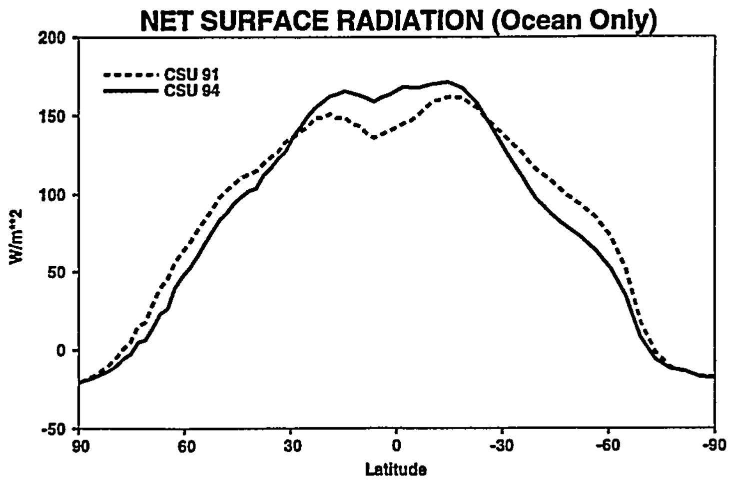


Figure 3: The annually averaged net surface energy flux, zonally averaged for the oceans only, as simulated in CSU91 (dashed line) and CSU94 (solid line).

Of course, the net surface energy flux shown in Fig. 3 is a combination of the net surface radiation (solar and terrestrial) with the surface latent heat flux (quite important) and the surface sensible heat flux (generally not so important). Fig. 4 shows the annually averaged net surface radiation and surface latent heat flux from both runs. Both quantities have been significantly altered. The net radiation into the tropical oceans has increased, while the nat radiation into higher latitudes of both hemispheres has decreased. This obviously favors increased poleward energy transport in both hemispheres. The surface latent heat flux over the oceans has decreased, primarily in the Southern Hemisphere subtropics and middle latitudes. This favors reduced poleward energy transport. The changes in the net surface energy flux are thus not merely due to changes in the surface radiation, which might be expected as a response to a change in the stratiform cloudiness parameterization, but also from changes in the surface latent heat flux, whose relation to the stratiform cloudiness parameterization is much less obvious. The changes in net surface radiation dominate those of the latent heat flux.

It is nevertheless important to understand why the latent heat flux differs so systematically between the two runs. As discussed by Stephens and Webster (1979), the radiatively active upper tropospheric clouds associated with deep convection tend to warm the atmosphere by trapping



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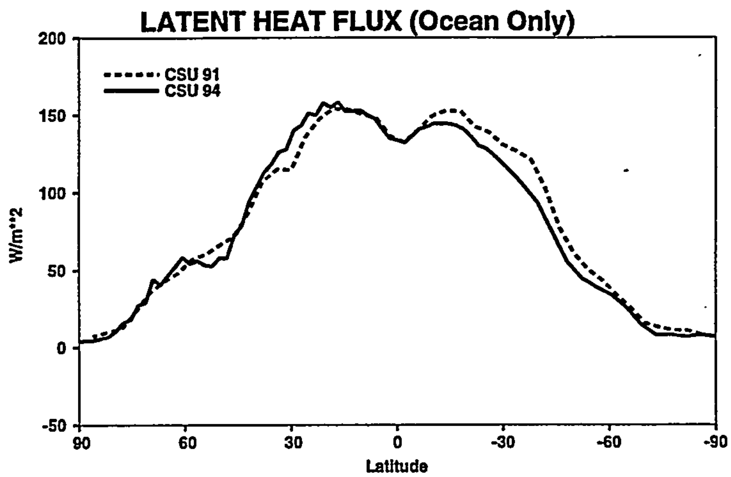


b

Figure 4: a) The annually averaged net surface radiation, zonally averaged for the oceans only, as simulated by CSU91 and CSU94. b) As in panel a, but for the surface latent heat flux.

longwave radiation which would otherwise escape to space. Randall et al. (1989) presented the results of numerical experiments with the CSU AGCM demonstrating that the radiatively induced warming favors large-scale rising motion, low-level moisture convergence, stronger surface winds which produce stronger surface evaporation, and so inevitably stronger convection. The convectively produced upper tropospheric stratiform clouds thus effectively drive further convection and so perpetuate themselves. This is a positive feedback between convection and stratiform cloudiness. The feedback has the effect of making the hydrologic cycle run faster than it otherwise would. The feedback due to interactions among deep convection, the radiative effects of the stratiform clouds produced by convective detrainment, and the effects of the radiative and convective heating on the large-scale circulation of the atmosphere. It can be described as a "Radiative-Dynamical-Convective (RDC) Feedback," and is schematically illustrated in Fig. 5. Slingo and Slingo (1988) found the signature of essentially the same feedback, using a drastically

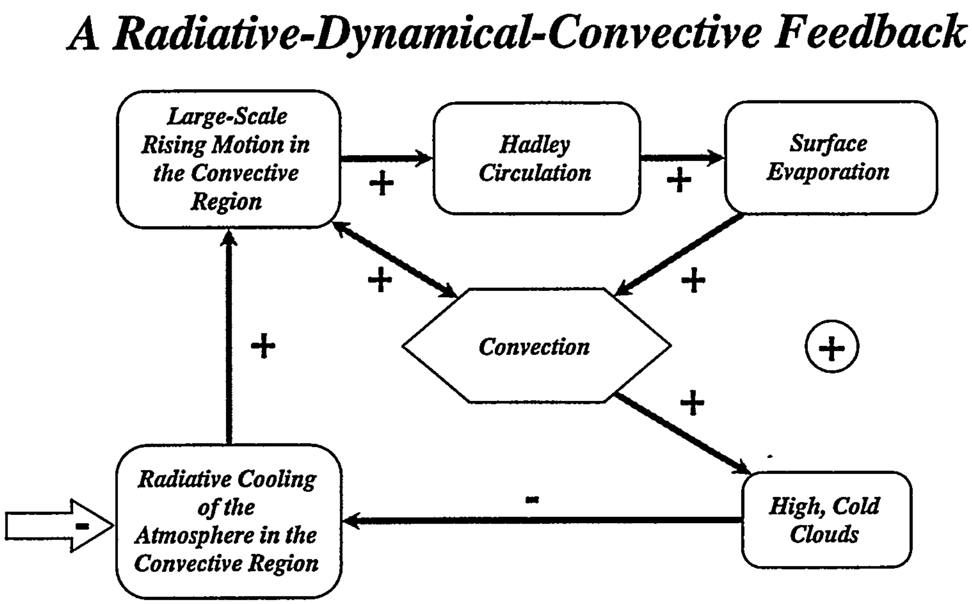


Figure 5: **Diagram illustrating the "Radiative-Dynamical-Convective Feedback" discussed in the text. A negative perturbation to the radiative cooling of the atmosphere (i.e. a perturbation corresponding to radiative warming) leads to increased large-scale rising motion, invigorating the Hadley circulation. This leads to stronger low-level winds and more surface evaporation. Convection intensifies, producing more high, cold clouds, which further reduce the atmospheric radiative cooling.**

different AGCM.

The RDC feedback is at work in both CSU91 and CSU94, but it is weaker in CSU91 because of the reduced optical thickness of the tropical anvil clouds in the newer run (see Fowler and Randall 1995). The weaker RDC feedback in CSU94 leads to weaker convection and a more realistic tropical circulation. The mean meridional circulation for July[1] differs radically between

[1] We choose to show a particular month (i.e. July) rather than the annual mean because the main Hadley circulation switches hemispheres with the seasons, so that an annual mean produces cancellations that obscure what is really going on.

the two runs, especially in the Southern Hemisphere, as shown in Fig. 7. The CSU91 results show an exaggerated Northern Hemisphere Hadley Cell in July. The CSU94 results, are considerably more realistic. Tests have confirmed that this difference is mainly due to the introduction of the cloud microphysics.

We are currently analyzing the results of numerical experiments designed to clarify the effects of the cloud microphysics on the mean meridional circulation, using a "Seaworld" model similar to that employed by Randall et al. (1989).

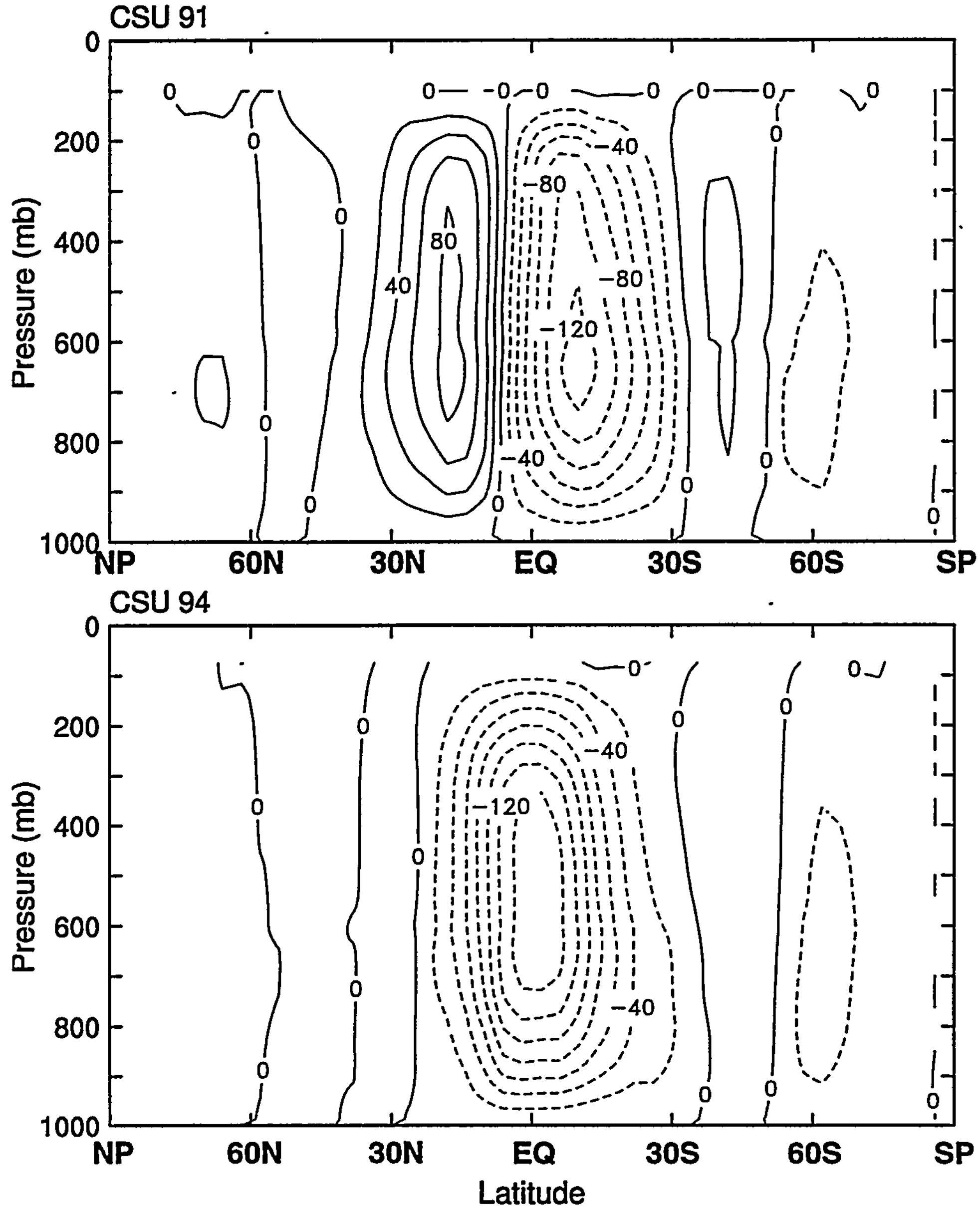
f) Development and testing of a simple global coupled ocean-atmosphere model

We have coupled the CSU GCM to an ocean mixed layer model and a sea ice model, as proposed.

The ocean model is similar to the "Q-flux" model developed by Hansen et al. (1984); it is purely thermodynamic, with a mixed layer of prescribed seasonally varying depth and ocean heat transports prescribed to be consistent with the climate that the model produces when run with prescribed climatological sea surface temperatures. The model ocean is thermally active above the annual mixed layer maximum. In addition to the upper mixed layer, which exchanges heat with the atmosphere through radiative, latent and sensible heat fluxes, the model includes a deeper oceanic layer, which exchanges energy with the mixed layer through entrainment and detrainment. Horizontal energy transport by advection and diffusion is calculated as the implied oceanic heat divergence/convergence resulting from net heat flux into the ocean when the GCM is forced by observed SST. The variation in mixed layer depth is prescribed from climatology, while the SST and heat storage between the mixed layer depth and its annual maximum is predicted by the model. Cooling of sea water at its freezing point results in formation of sea ice and possible accumulation of snow. Ice, snow thickness and sea ice temperature are prognostic variables in the sea ice model, which is an implicit one-layer version of the Semtner (1976) thermodynamic model. A description of the model is given in Jensen et al. (1991).

Streamfunction of the Mean Meridional Circulation: July

10^9 kg per second



Contour Interval is 20.00

Figure 6: The stream function of the mean meridional circulation, for July, in CSU91 and CSU94. The contour interval is 20×10^9 kg s^{-1}. Solid lines denote counterclockwise circulation, and dashed lines denote clockwise circulation.

The mixed-layer ocean and sea ice model have been used for coupled runs with the GCM. Great care has been taken to ensure consistency is the formulation of flux calculations to avoid climate drift. We have done two coupled runs: One for present climate conditions and one with an instantaneous doubling of CO_2. The methodology is as follows:

a) A climatology data set of monthly sea surface temperature (SST) and sea ice coverage was created from observed SST and sea ice coverage from the AMIP period 1979-1988. The average sea ice thickness was assumed to be 1 m.

b) An 8 year control integration with this climatological data set prescribed over the oceans was used to compute the net downward heat flux into the ocean.

c) From the climatological SST and sea ice data, the net downward heat flux from the control and observations of mixed layer depth (NODC data), the oceanic heat transport can be computed during the year.

d) A coupled GCM-ocean model run with present level CO_2 serves as a reference and to check that no or little climate drift occurs.

e) A second coupled run is made to investigate the response to increased CO_2 levels.

Fig. 7 shows the global mean surface temperature for the two coupled 30-year runs. The present day climate simulation has a very small tendency towards a colder climate (about 0.05 K decade^{-1}). In comparison we found a 2.3 K increase during the 30-year 2 x CO_2 run. The areas of sea ice in the Northern Hemisphere and Southern Hemisphere (Fig. 8) are smaller for the 2 x CO_2 run, in particular for the Southern Hemisphere, where the annual sea ice production has been reduced.

The Qflux model's main advantage is its simplicity and very low computational cost. Yet, our results show that it is applicable to decadal climate simulations. These results are remarkably

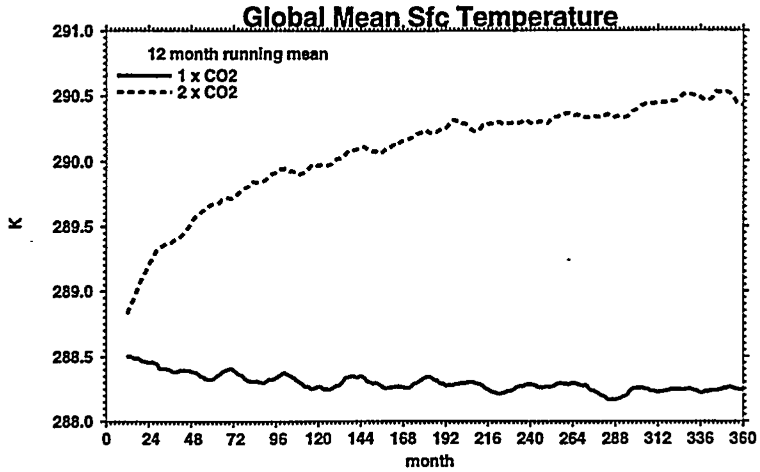


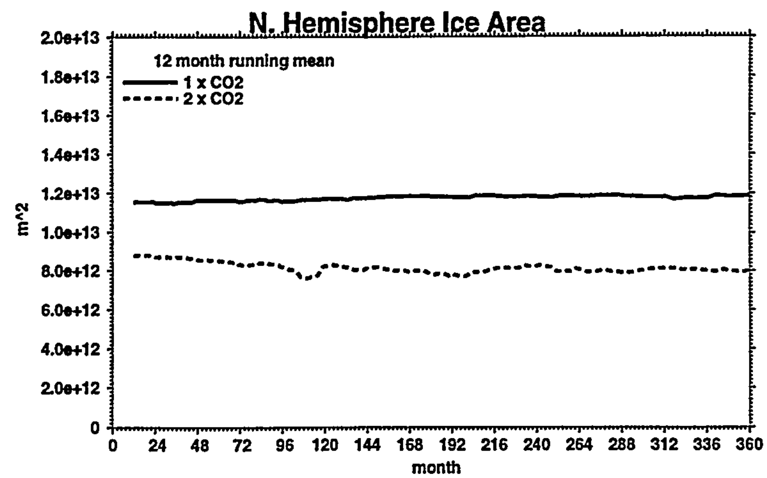
Figure 7: **Surface temperature for coupled 30 year runs. Results for the present climate are shown by the full line, and results for the 2 x CO_2 climate are denoted by the dashed line.**

good, given the well-known tendency of one-dimensional thermodynamic sea ice models to be noisy and to induce climate drift when coupled to GCM with a daily cycle. The main reason for this is that the albedo for sea ice is often modeled like a simple step function dependent on temperature, i.e. high albedo below and low albedo above freezing.

We found a high sensitivity to snow and sea ice albedo in semi-coupled runs, where the air-sea interaction and ocean was forced by history tapes of GCM output. As discussed by Meehl and Washington (1990), this is also found to be these case in other studies using one-dimensional thermodynamic ice models. In particular we discovered that the effective albedo was lower for the same model run with a daily cycle than the same without it.

In order to get a more realistic sea ice albedo for this simple model, which does not take leads in account, we adopted an albedo formulation in which the albedo varies bi-linearly with temperature and sea ice thickness, as shown in Fig. 9.

When snow with a constant albedo of 0.8 was allowed to accumulate snow on top of the sea ice we found that the coupled model again became noisy. The main reason is that large



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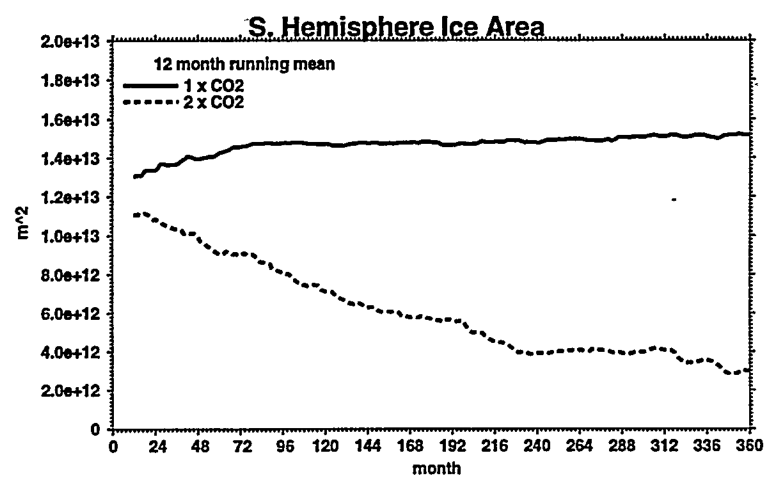

b

Figure 8: **a) Northern hemisphere sea ice area for coupled 30-year runs. Results for the present climate are shown by the full line, and results for the 2 x CO_2 climate are denoted by the dashed line. b) Same for Southern Hemisphere.**

fluctuations in albedo and heat flux may occur instantaneously when a single grid cell is covered with a thin, but highly insulating snow cover. In order to obtain a more realistic simulation, effects as snow to ice conversion, snow aging and possibly fractional coverage must be included.

Our first control and 2xCO_2 runs were done with the “old” version of our cloud parameterization. We have also performed 30-year coupled simulations, very similar to those described above, but using our new cloud microphysics parameterization, in order to investigate the sensitivity of our results to the parameterized clouds. The results, which are still being analyzed as this is written, show that in terms of globally averaged surface temperature the model's sensitivity to a CO_2 increase is very nearly the same with both cloud parameterizations.

An account of this work is in preparation for publication. The two main conclusions to date are:

1) The simulated climate is incredibly sensitive to the details of the sea ice parameterization. For example, a small (~5%) change in the albedo of the snow on the ice can lead to a large change in the global sea ice cover and thereby to a substantial change in the global climate.

2) The two cloud parameterizations tested give very similar climate sensitivities in the $2xCO_2$ experiments. This is interesting because both parameterizations give small cloud feedbacks in the FANGIO experiments, and both perform relatively well in the FANGIO seasonal cloud radiative forcing tests.

g) Development of a dynamically active upper ocean model

As the next step toward coupling with more realistic ocean models, a new thermodynamic ocean modelling system (TOMS) for the upper ocean has been developed as part of CHAMMP and as part of this project.

The model can be setup for a number of different applications, from a simple 2-D hydrodynamic calculation in a box to a full GCM on a sphere. The model has full prognostic equations for momentum, temperature, salinity and tracers. Bottom topography can be included or the model can be used in a reduced gravity upper ocean mode. As an option, the model can be run without prognostic thermodynamics. An arbitrary Lagrangian-Eulerian (ALE) coordinate is used in the vertical, making the model a hybrid between a traditional z-coordinate model and an isopycnal model. In the horizontal, spherical coordinates or rectangular coordinates may be used.

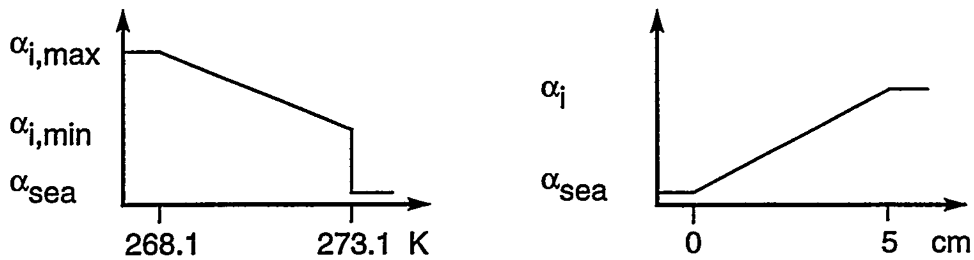

Figure 9: **Sea ice albedo as function of temperature (left). The minimum sea ice albedo at the freezing point is 70% of the maximum sea ice albedo given the same thickness. Sea ice albedo as function of thickness (right). The maximum albedo for sea ice colder than 268.1 K and thicker than 5 cm is 0.7.**

For tracers and layers thickness, the positive definite scheme of Hsu and Arakawa (1990) has been implemented. Thermodynamics and mixed layer physics has been fully incorporated in the model. The prognostic equations for temperature and salinity can be limited to the upper ocean in order to save CPU time. The deeper layers are in that case true isopycnal layers without mass exchanges. The two uppermost layers have implemented Kraus-Turner mixed layer physics, extended to include exponential damping of TKE. Inclusion of shear-induced mixing at the base of all dynamic layers is represented by a Richardson number dependent mixing (Pollard et al., 1973). Either an entrainment/detrainment formulation similar to that of McCreary and Kundu (1988; 1989) or a diffusion coefficient formulation based on Pacanowski and Philander (1981) can be chosen for any layer. The mixed layer scheme is different from those of Bleck et al, (1989) and Oberhuber (1993), which were designed to restore isopycnals. However, the same basic principle of local balance for TKE is used. The model has been tested for equatorial upwelling and downwelling, coastal upwelling and detrainment/entrainment due to heating/cooling and found to be working satisfactory. Horizontal diffusion can be a combination of Rayleigh friction, harmonic friction and biharmonic friction. Coastlines can be irregular, and a number of open boundary conditions (OBCs) are available. A Flux Relaxation Scheme for OBCs and data assimilation have been implemented to link a regional model to observations outside the computational domain.

The code consists of 1 main program, 103 subroutines and 33 include files. However, a new model setup is done by changes in the main program and two include files only. The coding is Fortran with C-directives to block out unneeded parts. This gives a rather efficient executable, with speeds up to 500 Mflops on a single processor on a Cray C-90. The modular form of the code and time integration scheme is explicit which makes implementation of new physical parameterizations easy. The layer structure is based on an Arbitrary Lagrangian Eulerian coordinate (ALE-method), which makes the model different from the Miami isopycnal model (MICOM) of Bleck and Boudra (1986) and Bleck and Smith (1990), and the Hamburg isopycnal model of Oberhuber (1993). For calculations with bottom topography a method of retarding external gravity waves to significantly speed up computations can be used (Jensen, 1995).

To allow coupling with the atmospheric GCM, a multi-layer reduced-gravity model is run in spherical coordinates with prognostic temperature and salinity. For transient phenomena, such as internal waves, the layers remain material layers. However, in situations where upwelling or downwelling takes place over a long period, an exchange of fluids takes place between the layers. For this reason, the uppermost layers are allowed to have variable densities. This in particular allows a realistic ocean mixed layer. Fig. 10 shows the vertical structure of the model: In the upper ocean there are a number of variable density layers to simulate air-sea interactions. Below these are a number of intermediate-depth layers which may be kept isopycnal. The lowest domain of the model is an infinitely deep abyss. This approximation is made to eliminates the fast barotropic mode.

Three different geometries has been used for that model. The simplest is a spherical surface segment used for testing the model for a number of physical oceanographic flows, for instance, equatorial jets, coastal upwelling, and mixed layer entrainment/detrainment. The model has been run with horizontal resolutions from 5 km to 100 km and 1 to 10 layers. The ability of the model to reproduce a coastal equatorial jet, which turns offshore at the correct latitude for various horizontal resolutions has been giving by Jensen (1994).

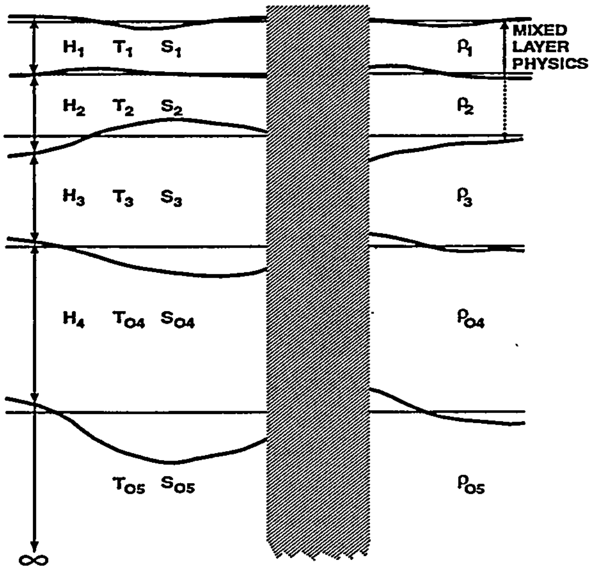

Figure 10: Vertical structure of the TOMS upper ocean model configuration. shown with two thermodynamic/hydrodynamic active layers, two hydrodynamic active layers and an infinitely deep lower layer. Subscript zero indicates that the values are constants.

Using a basin-scale model with realistic coastlines, Indian Ocean calculations were made at 0.3° by 0.3° resolution. Simulations with realistic geometry and annual and semi-annual winds demonstrated the existence of equatorial resonant modes with semi-annual periods and was published in the *Journal of Geophysical Research-Oceans* (Jensen, 1993).

The first test runs towards a global model has been made with a 1° by 1°, 2.5 layer model (2 active layers over an infinitely deep third layer). Utility programs have been written to interpolate (using cubic splines) and read in boundaries, forcing and initial conditions from data (e.g. Levitus 1982) and from GCM output. Diagnostic runs have been made for 50 days, but full prognostic runs suffer from noise when the model is initialized with the annual mean temperature and salinity from the Levitus data set. Higher horizontal resolution should solve this problem.

A description of this work is in preparation for publication.

h) Summary of accomplishments

Although the various tasks outlined above are quite diverse, they have three underlying themes. First, we are strongly committed to the FANGIO and AMIP intercomparison activities, in more than just a "participation" mode. Second, we have a particular interest in global air-sea interaction. Third, all of our research is aimed at better understanding and/or predictive capability with respect to the sensitivity of our climate to increased carbon dioxide concentrations, with special emphasis on the role of clouds.

Publications Resulting From This Project Since 1992

Cess, R. D., G. L. Potter, J. P. Blanchet, G. J. Boer, S. J. Ghan, J. T. Kiehl, H. Le Treut, Z.-X. Li, X.-Z. Liang, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, M. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald, and I. Yagai, 1990: Interpretation of cloud-climate feedback as produced by 14 atmospheric general circulation models. *Science*, **245**, 513-516.

Cess, R. D., G. L. Potter, J. P. Blanchet, G. J. Boer, A. D. Del Genio, M. Deque, V. Dymnikov, V. Galin, W. L. Gates, S. J. Ghan, J. T. Kiehl, A. Lacis, H. Le Treut, Z.-X. Li, X.-Z. Liang, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, A. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai, and M.-H. Zhang, 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, **95**, 16601-16615.

Cess, R. D., M. H. Zhang, G. L. Potter, H. Barker, R. A. Colman, D. A. Dazlich, A. D. Del Genio, M. Esch, J. R. Fraser, V. Galin, W. L. Gates, J. J. Hack, J. T. Kiehl, A. Lacis, X - Z. Liang, J. F. Mahfouf, B. J. McAvaney, V. P. Meleshko, J. - J. Morcrette, D. A. Randall, E. Roeckner, J. - F. Royer, D. A. Sheinin, A. P. Sokolov, K. E. Taylor, W. - C. Wang, and R. T. Wetherald, 1993: Intercomparison of CO_2 Radiative Forcing in General Circulation Models. *Science*, **262**, 1252 - 1255.

Cess, R. D., M. H. Zhang, G. L. Potter, V. Alekseev, H. W. Barker, E. Cohen-Solal, R. A. Colman, D. A. Dazlich, A. D. Del Genio, M. R. Dix, V. Dymnikov, M. Esch, L. D. Fowler, J. R. Fraser, V. Galin, W. L. Gates, J. J. Hack, W. J. Ingram, J. T. Kiehl, H. Le Treut, K. K.-W. Lo, B. J. McAvaney, V. P. Meleshko, J.-J. Morcrette, D. A. Randall, E. Roeckner, J.-F. Royer, M. E. Schlesinger, P. V. Sporyshev, B. Timbal, E. M. Volodin, K. E. Taylor, W. Wang, and R. T. Wetherald, 1995: Cloud Feedback in Atmospheric General Circulation Models: An Update. In preparation for *Science*.

Gleckler, P. J., and D. A. Randall, 1994: The validation of ocean surface heat fluxes in AMIP. Paper presented at the of the *Sixth Conference on Climate Variations of the American Meteorological Society*, Nashville, Tennessee.

Gleckler, P. J., D. A. Randall, G. Boer, R. Colman, M. Dix, V. Galin, M. Helfand, J. Kiehl, A. Kitoh, W. Lau, X.-Z. Liang, V. Lykossov, McAvaney, K. Miyakoda, S. Planton, and W. Stern, 1995: Interpretation of ocean energy transports implied by atmospheric general circulation models. *Geophysical Research Letters*, **22**, 791-794.

Hu, Q., 1992: Low frequency oscillations in radiative-convective models. Ph.D. thesis, Colorado State University.

Hu, Q., and D. A. Randall, 1994: Low-Frequency Oscillations in Radiative-Convective Systems. *Journal of the Atmospheric Sciences*, **51**, 1089-1099.

Hu, Q., and D. A. Randall, 1995: Low-Frequency Oscillations in Radiative-Convective Systems. Part II: An idealized model. Accepted for publication in the *Journal of the Atmospheric Sciences*.

Jensen, T. G., D. A. Randall, and D. A. Dazlich, 1991: Coupling of a Simple Thermodynamic Ocean Mixed Layer and Sea Ice Model to the CSU General Circulation Model. Paper presented at the *5th Conference on Climate Variations of the American Meteorological Society*, Denver, Colorado.

Jensen, T. G., D. A. Randall, and D. A. Dazlich, 1992: Coupling of a Simple Thermodynamic Ocean Mixed Layer and Sea Ice Model to the CSU General Circulation Climate Model. Paper presented at the *Second Scientific Meeting of the Oceanography Society*, St. Petersburg.

Jensen, T. G., 1993: Equatorial variability and resonance in a wind-driven Indian Ocean model. *J. Geophys. Res.*, **98**, 22533-22552.

Jensen, T. G., 1994: A Quasi-Isopycnal Upper Ocean Model for Climate Modelling. *Fifth Symposium on Climate Change Studies*, American Meteorological Society, Nashville, 77-80.

Jensen, T. G., 1995: A note on artificial retardation of barotropic waves in layered ocean models. Manuscript in preparation.

Kelly, Michael A., and D. A. Randall, 1994: Investigation of the Earth's Entropy Budget:

Comparison of Observations with a General Circulation Model. Paper presented at the of the *Conference on Atmospheric Radiation of the American Meteorological Society*, Nashville, Tennessee.

Kelly, M., 1994: *Investigations of the Earth's Entropy Budget: Comparison with a General Circulation Model*, M.S. Thesis, Colorado State University.

Intergovernmental Panel on Climate Change (D. A. Randall, Lead Author), 1995: *Scientific Assessment of Climate Change.* WMO/UNEP, Cambridge University Press, In preparation.

Randall, D. A., 1992: Radiation-Dynamics Interactions in the Tropics. Paper presented at the *International Radiation Symposium*, Tallinn, Estonia, August 1992 (Invited Paper).

Randall, D. A., R. D. Cess, J. P. Blanchet, G. Boer, A. DelGenio, M. Deque, V. Dymnikov, V. Galin, W. L. Gates, S. J. Ghan, J. T. Kiehl, A. Lacis, H. Le Treut, Z.-X. Li, X.-S. Liang, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J. J. Morcrette, G. L. Potter, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, A. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai, and M.H. Zhang, 1992: Intercomparison and Interpretation of Surface Energy Fluxes in Atmospheric General Circulation Models. *Journal of Geophysical Research*, **97**, 3711 - 3724.

Randall, D. A., 1992: Global Climate Models: What and How. *In Global Warming: Physics and Facts*. B. G. Levi, D. Hafemeister, and R. Scribner, Eds. American Physical Society. pp. 24 - 35.

Randall, D. A., R. D. Cess, J. P. Blanchet, S. Chalita, R. Colman, D. A. Dazlich, A. D. Del Genio, V. Dymnikov, V. Galin, D. Jarrett, E. Keup, A. Lacis, H. Le Treut, X.-Z. Liang, B. J. McAvaney, J. F. Mahfouf, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, P. M. Norris, G. L. Potter, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, J. M. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai, and M.-H. Zhang, 1994: Analysis of Snow Feedbacks In Fourteen General Circulation Models. *Journal of Geophysical Research,* **99**, 20,757-20,771.

Randall, D. A., and P. J. Gleckler, 1994: Interpreting the implied meridional oceanic heat transport in AMIP. Paper presented at the of the *Sixth Conference on Climate Variations of* *the American Meteorological Society*, Nashville, Tennessee.

Randall, D. A., Q. Hu, K.-M. Xu, and S. K. Krueger, 1994: Radiative-Convective Disequilibrium. *Atmospheric Research*, **31**, 315-327.

Randall, D. A., 1994: The role of clouds in the general circulation of the atmosphere. Paper presented at the *Seminar on Physical Parameterizations*, European Centre for Medium Range Weather Forecasts, Reading, England.

Randall, D. A., and P. J. Gleckler, 1994: Cloud-Radiative Effects on Implied Oceanic Energy Transports As Simulated by Atmospheric General Circulation Models. Paper presented at the *UCLA/U. Tokyo Joint Workshop on Climate Phenomena in the Pacific Basin and Rim.*

Stephens, G. L., D. A. Randall, S. J. Tjemkes, I. M. Wittmeyer, and D. A. Dazlich 1993: The Earth's Radiation Budget in Relation to Atmospheric Hydrology Cycle. Part III. Comparison of observations with a GCM. *Journal of Geophysical Research*, **98**, 4931 - 4950.

References

Barnett, T. P., L. Dümenil, V. Schlese, E. Roeckner, and M. Latif, The effect of Eurasian snow cover on regional and global climate variations, *J. Atmos. Sci.*, *46*, 661-685, 1989.

Bleck, R. and D. B. Boudra, 1986: Wind-driven spin-up in eddy-resolving ocean models formulated in isopycnic and isobaric coordinates, *J. Geophys. Res.*, **91**, 7611-7622.

Bleck, R., H. P. Hanson, D. Hu and E. B. Kraus, 1989: Mixed layer-thermocline interaction in a three-dimensional isopycnic coordinate model. *J. Phys. Oceanogr.*, **19**, 1417-1439.

Bleck, R. and L. T. Smith, 1990: A wind-driven isopycnic coordinate model of the North and Equatorial Atlantic Ocean. 1. Model development and supporting experiments. *J. Geophys. Res.*, **95**, 3273--3285.

Cess, R. D., G. L. Potter, J. P. Blanchet, G. Boer, S. J. Ghan, J. T. Kiehl, X.-Z. Liang, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, M. R. Riches, E. Roeckner, U. Schlese, A. Slingo, K. E. Taylor, W. M. Washington, R. T. Wetherald, and I. Yagai, 1989: Intercomparison and Interpretation of Cloud-Climate Feedback as Produced by Fourteen Atmospheric General Circulation Models, *Science*, **245**, 513-516.

Cess, R. D., G. L. Potter, J. P. Blanchet, G. J. Boer, A. D. Del Genio, M. Deque, V. Dymnikov, V. Galin, W. L. Gates, S. J. Ghan, J. T. Kiehl, A. Lacis, H. Le Treut, Z.-X. Li, X.-Z. Liang, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, D. A. Randall, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, A. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai, and M.-H. Zhang, 1990: Intercomparison and interpretation of climate feedback processes in 19 atmospheric general circulation models. *J. Geophys. Res.*, **95**, 16601-16615.

Cess, R. D., G. L. Potter, M.-H. Zhang, J.-P. Blanchet, S. Chalita, R. Colman, D. Dazlich, A. D. Del Genio, V. Dymnikov, V. Galin, D. Jerrett, E. Keup, A. Lacis, H. Le Treut, X.-Z. Liang, J.-F. Mahfouf, B. J. McAvaney, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, P. M. Norris, D. A. Randall, L. Rikus, E. Roeckner, J.-F. Royer, U. Schlese, D. A. Sheinin, J. M. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, and I. Yagai, 1991: Interpretation of Snow-Climate Feedback as Produced by 17 General Circulation Models, *Science*, **253**, 888-892.

Cess, R. D., M. H. Zhang, G. L. Potter, H. Barker, R. A. Colman, D. A. Dazlich, A. D. Del Genio, M. Esch, J. R. Fraser, V. Galin, W. L. Gates, J. J. Hack, J. T. Kiehl, A. Lacis, X - Z. Liang, J. F. Mahfouf, B. J. McAvaney, V. P. Meleshko, J. - J. Morcrette, D. A. Randall, E. Roeckner, J. - F. Royer, D. A. Sheinin, A. P. Sokolov, K. E. Taylor, W. - C. Wang, and R. T. Wetherald, 1993: Intercomparison of CO_2 Radiative Forcing in General Circulation Models. *Science*, **262**, 1252 - 1255.

Cess, R. D., M. H. Zhang, G. L. Potter, V. Alekseev, H. W. Barker, E. Cohen-Solal, R. A. Colman, D. A. Dazlich, A. D. Del Genio, M. R. Dix, V. Dymnikov, M. Esch, L. D. Fowler, J. R. Fraser, V. Galin, W. L. Gates, J. J. Hack, W. J. Ingram, J. T. Kiehl, H. Le Treut, K. K.-W. Lo, B. J. McAvaney, V. P. Meleshko, J.-J. Morcrette, D. A. Randall, E. Roeckner, J.-F. Royer, M. E. Schlesinger, P. V. Sporyshev, B. Timbal, E. M. Volodin, K. E. Taylor, W. Wang, and R. T. Wetherald, 1995: Cloud Feedback in Atmospheric General Circulation Models: An Update. In preparation for *Science*.

Chen, Ching-Hsuan, and D. A. Randall, 1995: Modeling the Effects of Convective Downdrafts on the General Circulation of the Atmosphere. In preparation for the *Journal of Geophysical Research.*

Dey, B., and O. S. R. U. Bhanu Kumar, 1982: An apparent relationship between Eurasian snow cover and the advanced period of the Indian summer monsoon, *J. Appl. Meteor.*, *21*, 1929 - 1932.

Fowler, L. D., and D. A. Randall, 1994: A Global Radiative-Convective Feedback. *Geophysical Research Letters,* **21**, 2035 - 2038.

Fowler, L. D., D. A. Randall, and S. A. Rutledge, 1995: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 1: Model Description and Simulated Microphysical Processes. Accepted for publication in the *Journal of Climate*.

Fowler, L. D., and D. A. Randall, 1995: Liquid and Ice Cloud Microphysics in the CSU General Circulation Model. Part 2: Simulation of the Earth's Radiation Budget. Accepted for publication in the *Journal of Climate*.

Fu, R., A. D. Del Genio, W. B. Rossow, and W. T. Liu, 1992: Cirrus-cloud thermostat for tropical sea surface temperatures tested using satellite data. *Nature*, **358**, 394-397.

Gates, W. L., 1992: AMIP: The Atmospheric Model Intercomparison Project. *Bull. Amer. Meteor. Soc.*, **73**, 1962 - 1970.

Gleckler, P. J., D. A. Randall, G. Boer, R. Colman, M. Dix, V. Galin, M. Helfand, J. Kiehl, A. Kitoh, W. Lau, X.-Z. Liang, V. Lykossov, McAvaney, K. Miyakoda, S. Planton, and W. Stern, 1995: Interpretation of ocean energy transports implied by atmospheric general circulation models. *Geophysical Research Letters*, **22**, 791-794.

Groisman, P. Ya., T. R. Karl, and R. W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures, *Science*, **263**, 198-200.

Hansen, J., A. Lacis, D. Rind, G. Russell, P Stone, I. Fung, R. Ruedy, and J. Lerner, 1984: Climate sensitivity: Analysis of feedback mechanisms. Climate process and climate sensitivity, Maurice Ewing Series (5), J. E. Hansen and T. Takahashi, Eds., Amer. Geophys. Union, 130-163.

Hanson, H. P., 1991: Marine stratocumulus climatologies. *Internat. J. of Climatol.*, **11**, 147-164.

Harshvardhan, D. A. Randall, T. G. Corsetti, and D. A. Dazlich, 1989: Earth radiation budget and cloudiness simulations with a general circulation model. *J. Atmos. Sci.*, **46**, 1922-1942.

Hsu, Y.-J. and A. Arakawa, 1990: Numerical modeling of the atmosphere with an isentropic vertical coordinate. *Mon. Wea. Rev.*, **118**, 1933-1959.

Ingram, W. J., C. A. Wilson, and J. F. B. Mitchell, 1989: Modeling climate change: An assessment of sea ice and surface albedo feedbacks, *J. Geophys. Res.*, **94**, 8609 - 8622.

Jensen, T. G., D. A. Randall, and D. A. Dazlich, 1991: Coupling of a Simple Thermodynamic Ocean Mixed Layer and Sea Ice Model to the CSU General Circulation Model. Paper presented at the *5th Conference on Climate Variations of the American Meteorological Society*, Denver, Colorado.

Jensen, T. G., 1993: Equatorial variability and resonance in a wind-driven Indian Ocean model, *J. Geophys. Res.*, **98**, 22,533-552.

Jensen, T. G., 1994: A Quasi-Isopycnal Upper Ocean Model for Climate Modelling. *Fifth Symposium on Climate Change Studies*, American Meteorological Society, Nashville, 77-80.

Jensen, T. G., 1995: A note on artificial retardation of barotropic waves in layered ocean models. Manuscript in preparation.

Kim, Y.-J., and A. Arakawa, 1995: Improvement of orographic gravity wave parameterization using a mesoscale gravity-wave model. Submitted to *J. Atmos. Sci.*

Klein, S. A., and D. L. Hartmann, 1993: The seasonal cycle of low stratiform clouds. *J. Climate*, **6**, 1587-1606.

Lau, K. M., C.-H. Sui, M.-D. Chou, and W. K. Tao, 1994: An inquiry into the cirrus-cloud thermostat effect for tropical sea surface temperature. *Geophys. Res. Lett.*, **21**, 1157-1160.

Levitus, S., 1982: Climatological atlas of the world oceans. *NOAA Prof. Paper 13*, U. S. Govt. Printing Office, Washington, D.C.

Lilly, D. K., 1968: Models of cloud-topped mixed layers under a strong inversion. *Quart. J. Roy. Meteor. Soc.*, **94**, 292-309.

Lin, Y.-L., R.D. Farley, and H.D. Orville, 1983: Bulk parameterization of the snow field in a cloud model. *J. Clim. Appl. Meteor.*, **22,** 1065-1092.

Lindzen, R. S., and S. Nigam, 1987: On the role of sea surface temperature gradients in forcing low-level winds and convergence in the tropics. *J. Atmos. Sci.*, **44**, 2418 - 2436.

Loth, B., H.-F. Graf, and J. M. Oberhuber, 1993: Snow cover model for global climate simulations,. *J. Geophys. Res.*, **98**, 10451-10464.

McCreary, J. P. and P. K. Kundu, 1988: A numerical investigation of the Somali Current during the Southwest Monsoon, *J. Mar. Res.*,**46**, 25-58.

McCreary, J. P. and P. K. Kundu, 1989: A numerical investigation of sea surface temperature variability in the Arabian Sea, *J. Geophys. Res.*, **94**, 16097-16114.

Meehl, G. A. and W. M. Washington, 1990: CO_2 climate sensitivity and snow-sea-ice albedo parameterization in an Atmospheric GCM coupled to a mixed-layer ocean model. *Climate Change*, **16**, 283-306.

Miller, R. L., and A. D. Del Genio, 1994: Tropical cloud feedbacks and natural variability of climate. *J. Climate*, **7**, 1388 - 1402.

Oberhuber, J. M., 1993: Simulation of the Atlantic Circulation with a coupled sea ice-mixed layer-isopycnal general circulation model. Part I: Model description., *J. Phys. Oceanogr.*, **23**, 808-829.

Pacanowski, R. C. and G. Philander, 1981: Parameterization of vertical mixing in numerical models of the tropical oceans. *J. Phys. Oceanogr.*, **11**, 1443-1451.

Pierrehumbert, R. T., 1995: Thermostats, radiator fins, and the local runaway greenhouse. *J. Atmos. Sci.*, in press.

Pollard, R. T., P. Rhines and R. O. R. Y. Thompson, 1973: The deepening of the wind-mixed layer. *Geophys. Fluid Dyn.*, **3**, 381-404.

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

Ramanathan, V., and W. Collins, 1991: Thermodynamic regulation of ocean warming by cirrus clouds deduced from observations of the 1987 El Nino. *Nature*, **351**, 27-32.

Randall, D. A., 1980: Conditional instability of the first kind, upside-down. *J. Atmos. Sci.*, **37**, 125-130.

Randall, D. A., J. Coakley, C. Fairall, R. Kropfli, and D. Lenschow, 1984: Outlook for research on marine subtropical stratocumulus clouds. *Bull. Amer. Meteor. Soc.*, **65**, 1290-1301.

Randall, D. A., Harshvardhan, D. A. Dazlich and T. G. Corsetti, 1989: Interactions among radiation, convection, and large-scale dynamics in a general circulation model. *J. Atmos.*

Sci., **46**, 1943-1970.

Randall, D. A., and S. Tjemkes, 1991: Clouds, the Earth's Radiation Budget, and the Hydrologic Cycle. *Paleoecology (Global and Planetary Change Section)*, **90**, 3-9.

Randall, D. A., and D. - M. Pan, 1993: Implementation of the Arakawa-Schubert cumulus parameterization with a prognostic closure. In *Cumulus Parameterization*, a Meteorological Monograph published by the American Meteorological Society, K. Emanuel and D. Raymond, Eds., pp. 137 - 144.

Randall, D. A., R. D. Cess, J. P. Blanchet, S. Chalita, R. Colman, D. A. Dazlich, A. D. Del Genio, V. Dymnikov, V. Galin, D. Jarrett, E. Keup, A. Lacis, H. Le Treut, X.-Z. Liang, B. J. McAvaney, J. F. Mahfouf, V. P. Meleshko, J. F. B. Mitchell, J.-J. Morcrette, P. M. Norris, G. L. Potter, L. Rikus, E. Roeckner, J. F. Royer, U. Schlese, D. A. Sheinin, J. M. Slingo, A. P. Sokolov, K. E. Taylor, W. M. Washington, R. T. Wetherald, I. Yagai, and M.-H. Zhang, 1994: Analysis of Snow Feedbacks In Fourteen General Circulation Models. *Journal of Geophysical Research,* **99**, 20,757-20,771.

Randall, D. A., P. J. Sellers, J. A. Berry, D. A. Dazlich, C. Zhang, J. A. Collatz, A. S. Denning, S. O. Los, C. B. Field, I. Fung, C. O. Justice, and C. J. Tucker, 1995: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 3: The Greening of the CSU General Circulation Model. Submitted to the *Journal of Climate*.

Robock, A., 1980: The seasonal cycle of snow cover, sea ice, and surface albedo. *Mon Wea. Rev.*, **108**, 267 - 285.

Robock, A., 1983: Ice and snow feedbacks and the latitudinal and seasonal distribution of climate sensitivity. *J. Atmos. Sci.*, **40**, 986 - 997.

Rutledge, S.A., and P.V. Hobbs. 1983: The mesoscale and microscale structure and organization of cloud bands and precipitation in midlatitude cyclone. VIII: A model for the "Seeder Feeder" process in warm-frontal bands. *J. Atmos. Sci.,* **40,** 1185-1206.

Sellers, P. J., D. A. Randall, G. J. Collatz, J. Berry, C. Field, D. A. Dazlich, C. Zhang, 1995: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 1: Model formulation. Submitted to the *Journal of Climate*.

Sellers, P. J., S. O. Los, C. J. Tucker, C. O. Justice, D. A. Dazlich, G. J. Collatz, and D. A. Randall, 1995: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 2: The generation of global fields of terrestrial biophysical parameters from satellite data. Submitted to the *Journal of Climate*.

Semtner, A. J., Jr., 1976: A model for the thermodynamic growth of sea ice in numerical investigations of climate. *J. Phys. Oceanogr.*, **6**, 379-389.

Semtner, A. J., Jr., and R. M. Chervin, 1992: Ocean general circulation from a global eddy-resolving model. *J. Geophys. Res.*, **97C**, 5493-5551.

Slingo, A., and J. M. Slingo, 1988: The response of a general circulation model to cloud longwave radiative forcing. I: Introduction and initial experiments. *Quart. J. Roy. Meteor. Soc.*, **114**, 1027 - 1062.

Slingo, A., 1990: Sensitivity of the Earth's radiation budget to changes in low clouds. *Nature*, **343**, 49-51.

Stephens, G. L., and P. J. Webster, 1979: Sensitivity of radiative forcing to variable cloud and moisture. *J. Atmos. Sci.*, **36**, 1542-1556.

Wallace, J. M., 1992: Effect of deep convection on the regulation of tropical sea surface temperature. *Nature*, **357**, 230-231.

Yasunari, T., A. Kitoh, and T. Tokioka, 1991: Local and remote responses to excessive snow mass over Eurasia appearing in the northern spring and summer climate. A study with the MRI GCM. *J. Meteor. Soc. Japan*, *69*, 473-487.

ATTACHMENTS:

PUBLICATIONS RESULTING FROM THIS PROJECT.