# Modelling and validation of clouds and radiation in the NCAR Community Climate Model

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## 1. INTRODUCTION

Over the past two years the Climate Modeling Section (CMS) of NCAR has been developing the successor to version 1 of the Community Climate Model (CCM1, Williamson et al.,1987). This new version, CCM2, will be released for general use in the summer of 1991. CCM2 is a completely new formulation of the NCAR general circulation model. Not only have all of the physical parameterizations been vastly altered or replaced, but the model code itself has undergone a complete restructuring and rewrite. Nearly all of the changes in CCM2 have had some impact on the simulation of clouds and radiation, since these changes in physics and transport directly influenced the simulation of moisture within the model. This brief report will outline the changes that have been incorporated in CCM2, and will compare the latest results for clouds and top of atmosphere radiation budget with observations of these quantities. It is important to note that these results are preliminary; CCM2 is still undergoing refinement in some of the physical parameterizations, and these changes will no doubt alter some of the findings reported herein.

Recently, Kiehl and Ramanathan (1990) compared CCM1 top of atmosphere radiative quantities with Earth Radiation Budget Experiment (ERBE) results. They found significant differences between the model and the ERBE data. Thus, it is of special interest to see if the improvements in CCM2 have in any way addressed the problems identified in CCM1 by Kiehl and Ramanathan (1990).

An attempt is also made to compare related atmospheric quantities to various observational data sources. In particular we focus attention on the vertical distribution of tropical moisture and the total precipitable water of the model as compared to observations. There now exist a wide variety of observational data for model validation purposes. This report will indicate how the Climate Modeling Section has been using these various data sources for both model development and validation.

The final section of the report will review the problems which remain in CCM2. A brief discussion on near term development will be given along with the CMSs long term development strategy.

## 2. DESCRIPTION OF CCM2

Only those aspects of the model that strongly affect the cloud and radiation simulations will be outlined here, more detailed descriptions of the various changes in the model will appear within the next year.

### 2.1 Transport of specific humidity

CCM1 employed the spectral technique for the transport of specific humidity. It is generally recognized that serious problems arise with this technique due to Gibbs phenomena associated with the spectral representation of strong horizontal and vertical gradients of the moisture field. Numerical correctives known as 'spectral fillers' are invoked in this approach to eliminate the numerically generated negative values of specific humidity. The existence of the spectral filler can actually lead to significant spurious generation of cloud amount and precipitation (Kiehl and Williamson,1990 and Rasch and Williamson,1990). Rasch and Williamson (1990) have implemented a semi-Lagrangian transport scheme for moisture in CCM2. Although this scheme is not fully conservative, they have shown that the role of the numerical filler in this approach is negligible compared to any other term in the moisture budget equation. Furthermore, the scheme is shape preserving and hence does not distort the moisture distribution as it is being advected along a trajectory. The scheme has an important impact on not only the horizontal distribution of moisture, but also on the vertical distribution.

### 2.2 Cumulus Convection Scheme

CCM1 employed moist convective adjustment (MCA) to represent sub grid scale moist convection. Moist convective adjustment although simple in concept does not accurately describe the vertical distribution of heating due to cumulus convection. Another flaw in this approach is the lack of any strong coupling of convection to surface and boundary layer fluxes, which leads to little diurnally forced convection. In addition, the incorporation of convective transport of tracer species is not easily incorporated in such an approach. It is also clear that shallow convection plays an important role in vertical moisture transport out of the boundary layer, a feature which is not handled by moist convective adjustment. For these reasons, the moist convective scheme in CCM1 has been replace by a stability dependent convective mass flux scheme developed by J.Hack of the CSM. This scheme is designed to work on three levels at a time. The lowest layer is assumed to be a nonentraining convective element, the middle layer represents a layer where condensation and rainout occur, and the top layer allows for limited detrainment to occur. The scheme adjusts the moist static energy profile for the three layers at a given time and is then applied to the next three layers in the column until the entire atmospheric column has been treated. The scheme allows for buoyant overshoot and predicts a cloud mass flux. The scheme simulates both shallow and deep penetrative convection. Simulations from CCM2 employing this scheme compared to CCM2 with MCA indicate dramatic improvement in the temperature and moisture structure within the model.

### 2.3 Planetary Boundary Layer Scheme

CCM1 employed a crude bulk formulation for the PBL, where the drag coefficients were dependent on the Richardson number. This part of the model has been replaced by an imposed eddy mixing profile and a diagnosed PBL height. The formulation is based on the work of Holtslag and Mahrt. The implementation in CCM2 was carried out by Boville and Holtslag.

### 2.4 Solar and Longwave Radiation Scheme

The solar radiation scheme employed in CCM1 is described in Kiehl et al. (1987). The clear sky part of this scheme was based on Lacis and Hansen (1974) while the cloudy sky part employed ray tracing techniques to account for multiple scattering between clouds. This scheme suffered from a number of problems. One of the greatest being that any heating in a mult-layer cloud case was uniformly distributed below the highest cloud layer. Hence, large errors resulted in the vertical distribution of solar heating for multi-layered clouds. The cloud albedos did not explicitly depend on the cloud microphysical properties either. The ray tracing approach was also not fully consistent, in that all rays for multiply cloud overlap cases were not accounted for. The CCM1 scheme could also not easily account for the presence of aerosols. For these reasons, the solar radiation scheme has been completely replaced with an 18 spectral interval δ-Eddington model (Briegleb,1990). This scheme employs exponential sums to account for gaseous absorption and allows for the dependence of the cloud optical parameters on cloud liquid water path and effective radius as described by Slingo (1989). The scheme is found to be in excellent agreement with the detailed line-by-line results of Ramaswamy and Friedenreich (1990).

Whereas CCM1 did not include a diurnal cycle, CCM2 does. The solar and longwave heating rates are calculated every hour. For the longwave calculations, the absorptivity and emissivity arrays are only updated every 12 hours, while the temperature dependence of the Planck function is evaluated every hour. Thus, the dominant temperature dependence is included in the diurnally varying longwave cooling rates.

### 2.5 Subsurface soil model

With the addition of the diurnal variation in radiation, one must include a finite heat capacity for the land surfaces to prevent large diurnal variations in surface temperature. The model used in

CCM2 treats the land and snow covered surfaces with a heat conduction formulation. The sub-surface system is modelled by four discrete layers, which have prescribed thermal properties, to capture the daily, weekly, monthly and annual penetration of heat from the surface. The heat diffusion equation is posed as a tri-diagonal matrix system which is evaluated for the temperatures of each surface layer at each time step.

## 2.6 Cloud Amount and Cloud Water Profile

Kiehl and Ramanathan (1990) pointed out that at T42 resolution CCM1 severely underestimated cloud cover. To correct for this bias CCM2 employs a reformulation of the cloud scheme of Slingo (1987). A number of changes to the scheme of Slingo have been introduced.

First, Slingo assumes that clouds occur in only three altitude regimes (high, middle and low). The cloud amount for these three regimes is determined by choosing the model level that contains the largest predicted cloud fraction that falls within the particular height regime. The assumption of a three layer cloud structure has been lifted in CCM2. Thus, the cloud prediction formulations are allowed to fill clouds in any model layer and no search for maximum cloud fraction within a given altitude regime is carried out. This change was adopted to allow for multiple layers of high cloud, since a single high cloud in the tropics, in particular, led to large local radiative heating rates; large that is for the spatial scales that are being modeled in the general circulation model.

Second, the high cloud amount formula associated with deep convection was eliminated. As stated by Slingo this formula was invoked in ECMWF model due to the Kuo convection schemes inability to moisten the upper troposphere. The mass flux scheme in CCM2 does not suffer from this problem, and the upper troposphere is sufficiently moist that cloud amount is well defined by the general functional dependence on the large scale relative humidity. This functional form used for all model layers is given by,

$$A_c = \mathrm{Max}\left\{0.0, \left(\frac{RH - RH_{lim}(p,\varphi)}{1 - RH_{lim}(p,\varphi)}\right)^2\right\} \qquad (1)$$

where $RH_{lim}$ is used to account for the variation in tropopause height with latitude, $\varphi$. This is especially important for models that have more than one level in the region of the tropopause. $RH_{lim}$ is defined as,

$$RH_{lim} = \begin{cases} 0.8 + 0.18\left(\dfrac{p_s - p}{p_s - p_{top}}\right) & p \geq p_{top} \\ 0.98 & p < p_{top} \end{cases} \quad (2)$$

where $p_s$ is the surface pressure and $p_{top}$ in mb is,

$$p_{top} = 250 - 150 \cos^2 \varphi \quad (3)$$

The functional form of $p_{top}$ is defined to represent the latitudinal shape of the tropopause.

Third, below 800 mb the cloud amount (1) is modified, following Slingo, to account for clouds associated with extra-tropical fronts and tropical disturbances. Slingo multiplied (1) by (-10.0 $\omega$), where $\omega$ is the vertical velocity in Pa $s^{-1}$, for ascents stronger than -0.1 Pa $s^{-1}$. For ascents between 0 and -0.1 Pa $s^{-1}$ the $\omega$ factor was linearly interpolated to zero. Figure 2 of Slingo indicates that this factor plays a large role in determining the low cloud amount in the extra-tropical storm tracks. The present study has found that the linear ramp actually suppressed too <u>much</u> low cloud in the extra-tropical storm tracks when compared with ERBE shortwave forcing data. Thus, the formulation employed in CCM2 for these clouds is,

$$A_c(\text{low}) = \begin{cases} A_c & \text{for } \omega < 0 \\ 0 & \text{for } \omega \geq 0 \end{cases} \quad (4)$$

Fourth, the low cloud associated with inversions has at present been disabled in CCM2. The reason for this is somewhat interesting. With the implementation of the semi-Lagrangian moisture transport scheme in CCM2, large increases occurred in relative humidity near the poles. This is due to the new schemes ability to realistically transport moisture into these regions. However, during polar winter there are relatively strong low level inversions also present over these regions. The combination of the strong inversions and larger relative humidities caused an almost 100 percent low cloud cover to form over much of the Canadian and Siberian land masses, along with the polar region. This cloud was associated with the inversion cloud cover predicted in Slingo's scheme. At present this cloud type has been disabled. However, the corrective action that will allow these clouds to be enabled has been found. It is noted that the desired regions for this low level inversion cloud cover is also associated with fairly large (>75 $Wm^{-2}$) surface turbulent heat fluxes (latent plus sensible). While in the cold polar regions, the surface heat fluxes are quite small (< 15 $Wm^{-2}$). Thus, one more condition will be added to the Slingo low level inversion cloud type which will check to see if total turbulent surface heat flux is greater than 75 $Wm^{-2}$.

Fifth, total column cloud cover associated with convective activity is given by,

$$\overline{A}_{conv} = 0.20 + 0.125\ln(0.4493 + P) \qquad (5)$$

where P is the convective precipitation in mm $d^{-1}$ ,and the overbar denotes a column cloud amount. Total column convective cloud cover is not allowed to exceed 0.8. This function differs from Slingo (1987) in that it allows for 10 percent cloud cover for non-precipitating cumulus, which are formed by the convective mass flux scheme. The convective cloud cover in any layer is obtained from the random overlap assumption, hence

$$A_{conv} = 1.0 - \left(1.0 - \overline{A}_{conv}\right)^{1/N} \qquad (6)$$

where N is the number of layers over which convective activity extends. It is perhaps worth mentioning that a maximum overlap assumption for this cloud type would be more realistic.

The δ-Eddington cloud optical properties require both a cloud liquid water path and an effective cloud drop radius. The cloud effective radius is assumed to be 10 μm in accordance with Slingo(1989). The cloud liquid water path is determined from,

$$LWP = \int \rho_l \, dz \qquad (7)$$

where $\rho_l$ is the cloud liquid concentration in gm $m^{-3}$. The cloud liquid concentration is assumed to decrease exponentially with height, with a scale height $h_l$,

$$\rho_l = \rho_l^0 \exp\left(-z/h_l\right) \qquad (8)$$

where $\rho_l^0$ is 0.2 gm $m^{-3}$ and,

$$h_l = 300 + 2900\cos\varphi \qquad (9)$$

in meters is a latitude dependent liquid water scale height. Thus, the total integrated liquid water for the atmosphere is given by,

$$TLW = \rho_l^0 h_l \qquad (10)$$

This quantity when weighted by the total cloud fraction can be compared with SSM/I determined total liquid cloud water. The zonal distribution of LWP (gm $m^{-2}$) is shown in figure

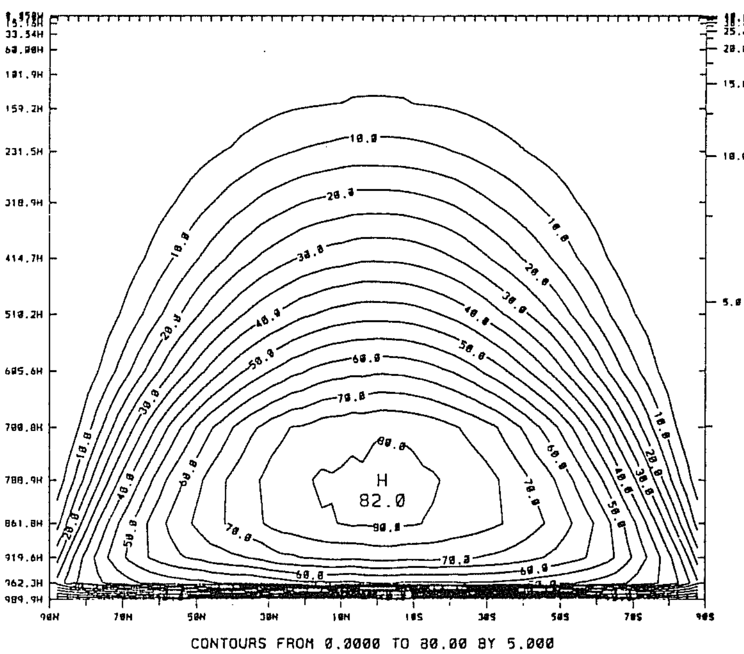



Fig. 1 Zonal cloud liquid water path in gm $m^{-2}$ employed in CCM2

1. Note that the liquid water path peaks in the tropics around 800 mb, with a value of 82 gm $m^{-2}$. Liquid water paths in the upper tropical troposphere are around 5 gm $m^{-2}$ and less. It should be made clear that the particular coefficients for $h_l$ were chosen based on comparison of longwave cloud forcing from CCM2 with ERBE data.

Finally, the cloud emissivities are determined from,

$$\varepsilon = 1 - \exp(-0.1\mathrm{LWP}) \qquad (11)$$

for all cloud types, as compared to CCM1, where (11) was used only for stratiform clouds that were detached from deep convective clouds.

## 3. <u>DATA SOURCES FOR MODEL VALIDATION</u>

Over the past two years, the Climate Modeling Section has collected a number of data sets for model development and validation. These data fall into three categories: surface, atmospheric, and satellite data. In this report only the atmospheric and satellite data will be employed for validation purposes. The satellite data are from the Earth Radiation Budget Experiment (ERBE) for months of January 1986 and July 1985. Other months in this data set have been compared with the model, but these two months are chosen to be representative of the performance of the model. The fields considered for validation are the clear and total outgoing longwave radiation, the total absorbed shortwave flux, the shortwave and longwave cloud forcing (all in $Wm^{-2}$). Certain data from the International Satellite Cloud Climatology Project (ISCCP) are also used for validation. In particular, the total, low-, mid- and high-level cloud fractions have been compared. The ISCCP data also includes the TOVS retrieved total precipitable water and this has been compared with CCM2. In the present study the total, effective high cloud and precipitable water will be used for validation purposes.

The atmospheric data sets are based on station rawinsondes. An analysis program has been constructed to find all station data for a user specified region. The mean temperature and specific humidity profiles are determined along with the spatial and temporal standard deviation of the data for this region. The analysis program also obtains similar data from a model run and plots modeled and observed profiles for the region on one graph. This data is invaluable for looking at the thermodynamic structure of the atmosphere. The Section also uses the ECMWF analyses as gridded and formatted by Trenberth and Olson (1988). This data can be analyzed with the same techniques as the model, and hence facilitates comparison of the thermal and dynamic structure of the model.

## 4. <u>COMPARISON OF SATELLITE DATA WITH CCM2</u>

## 4.1 Global Averages

The globally averaged satellite observations and CCM2 are compared in tables 1 and 2 for January and July monthly means, respectively. Inspection of the absorbed solar fluxes in January indicate that the model absorbs 10 $Wm^{-2}$ more than the ERBE data indicate. Comparison of the total cloud fraction shows that the model cloud cover is 13% smaller than the ISCCP inferred cloud cover. A change in absorbed solar flux due to a bias in cloud cover is related by,

$$\Delta S_{abs} = -Q(\alpha_{cld} - \alpha_{clr})\Delta A_c$$

where Q is the solar insolation, $\alpha_{cld}$ is the cloud albedo, $\alpha_{clr}$ the clear sky albedo and $A_c$ is the total cloud amount. Using the ERBE values of $\alpha_{clr}$=0.18, Q=363.5 $Wm^{-2}$ and assuming a cloud albedo of 0.6, the expected solar flux deficit due to a 0.07 difference in cloud cover (ISCCP-model) is -10.7 $Wm^{-2}$. Thus, if the model cloud cover were 13% higher (to agree with ISCCP), the model absorbed solar flux would agree quite well with ERBE. As pointed out in section 2.6, the present version of CCM2 does not include the low cloud associated with inversions. The model also assumes that the cloud fraction for non-precipitating cumulus is 10%. The data of Warren et al.(1988) suggest that the coverage from these types of clouds may be more like 20%. The addition of these two changes to the model may bring the total cloud cover up by approximately 10%.

Table 1. January mean globally averaged satellite fields. First five fields are obtained from the January 1986 ERBE data and are in $Wm^{-2}$. Fields 6,7 and 8 are obtained from the ISCCP January 1984 data, precipitable water is in kg $m^{-2}$.

| Field | CCM2 | Observations |
|---|---|---|
| OLR | 238.3 | 231.9 |
| Absorbed Solar | 256.7 | 245.5 |
| Clearsky Longwave | 270.9 | 262.5 |
| LWCF | 32.6 | 29.9 |
| SWCF | -49.8 | -53.2 |
| Total Cloud Fraction | 0.483 | 0.552 |
| Effective High Cloud | 0.135 | 0.129 |
| Precipitable Water | 22.3 | 21.6 |

The model over estimates the clear sky outgoing longwave flux by 8 $Wm^{-2}$ in January and 10 $Wm^{-2}$ in July. These are fairly large differences given that the atmospheric vertical thermal and moisture structure are now in good agreement (Tables 1 and 2 and section 5). CCM2 does not incorporate the effects of trace gases such as $CH_4$, $N_2O$ and CFCs. These gases could lower the clear OLR by approximately 4 $Wm^{-2}$. Thus, the model still would over estimate the clear sky flux by 5 $Wm^{-2}$, with a larger bias in summertime. The fact that the bias is larger in summer suggests that the models surface temperatures may be too high. However, another explanation may lie in the method in which the clear sky fluxes are defined in both model and observational data. As pointed out by Cess and Potter (1987), there are essentially two ways of obtaining this flux and the differences in these methods may be a source of the bias shown in tables 1 and 2. An analysis is presently being performed with the model to see if this can explain some source of the bias.

Table 2. July mean globally averaged satellite fields. First five fields are obtained from the July 1985 ERBE data and are in $Wm^{-2}$. Fields 6,7 and 8 are obtained from the ISCCP July 1983 data, precipitable water is in kg $m^{-2}$.

| Field | CCM2 | Observations |
|---|---|---|
| OLR | 247.1 | 237.5 |
| Absorbed Solar | 246.7 | 237.5 |
| Clearsky Longwave | 277.7 | 267.6 |
| LWCF | 30.6 | 29.7 |
| SWCF | -40.5 | -47.3 |
| Total Cloud Fraction | 0.459 | 0.556 |
| Effective High Cloud | 0.126 | 0.132 |
| Precipitable Water | 26.0 | 25.4 |

The CCM2 longwave and shortwave cloud forcing are in much better agreement with the ERBE data than CCM1 (Kiehl and Ramanathan,1990). It is of interest to consider the net radiative balance (longwave+shortwave) from the model and the observational data. In January, the observed imbalance between absorbed solar and emitted longwave is 13.6 $Wm^{-2}$ whereas the model yields 18.4 $Wm^{-2}$. In July, the observed imbalance is 0 $Wm^{-2}$, while the model gives -0.4 $Wm^{-2}$. Thus, the seasonal imbalances are actually captured rather well in the model. Of course it must be kept in mind that the model employs fixed observed sea surface temperatures, which constrains the radiative budget of climate system to a considerable extent.

4.2 <u>Zonal Averages</u>

The monthly means of zonally averaged outgoing longwave radiation for January and July are shown in figures 2a and b. Results from two months each are presented for the model, however, these results indicate little inter-annual variability in the zonal means. For both months the model OLR is larger than the ERBE results. The largest over estimation occurs over the equator and in the summer hemisphere. Differences are larger in the July summer hemisphere and thus may be linked to problems with predicted land surface temperatures. The model does quite well in the winter hemisphere for the two seasons. The problem over the equator is no doubt linked to an under estimation of effective high cloud cover, which is substantiated by comparing the models effective high cloud fraction with that obtained from the ISCCP data (figure 3a-b). Note that the ERBE and ISCCP data sets are not for the same years, but inter-annual variability in the zonal means is expected to be small. For January, the extra-tropical effective high cloud is in good agreement with the ISCCP results, however, agreement

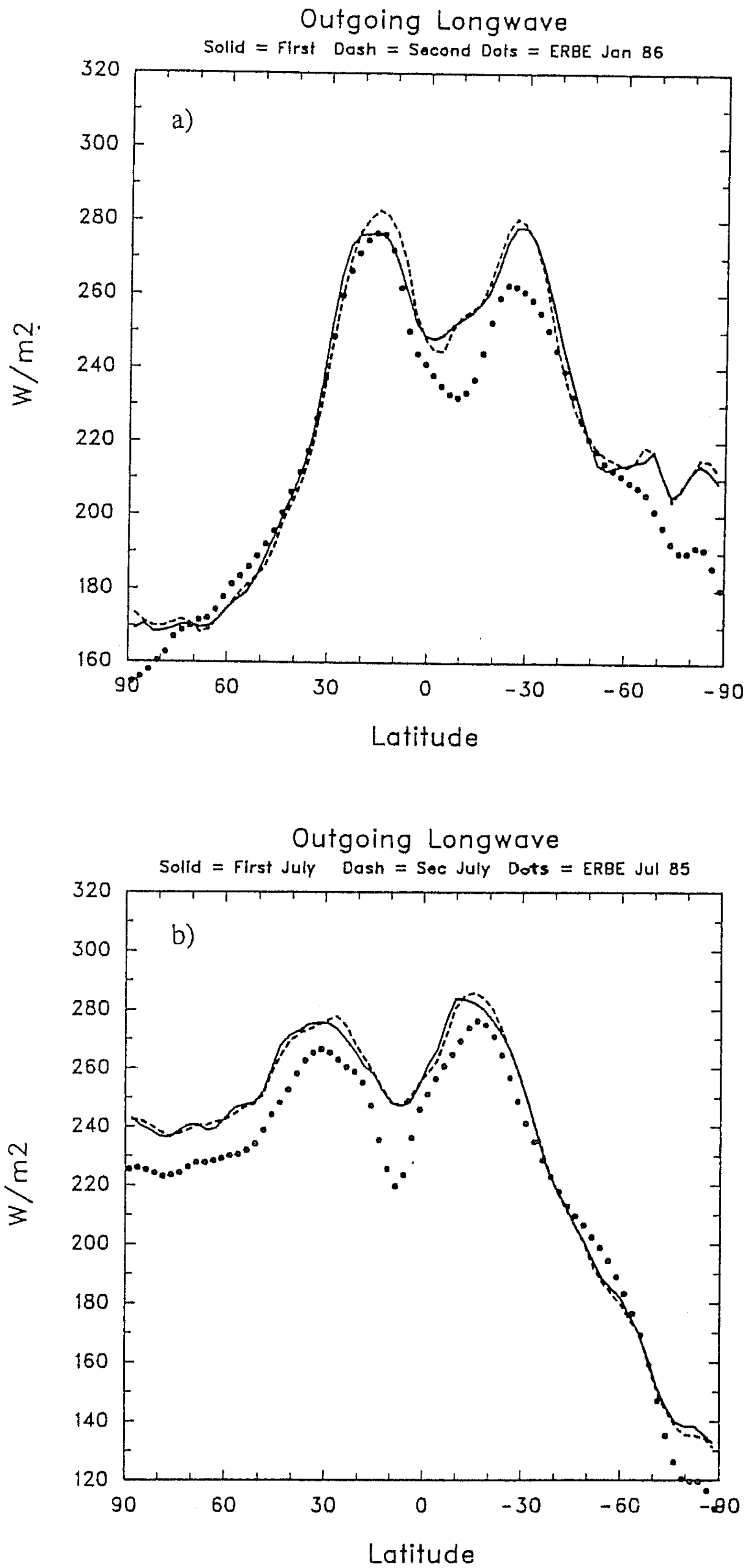


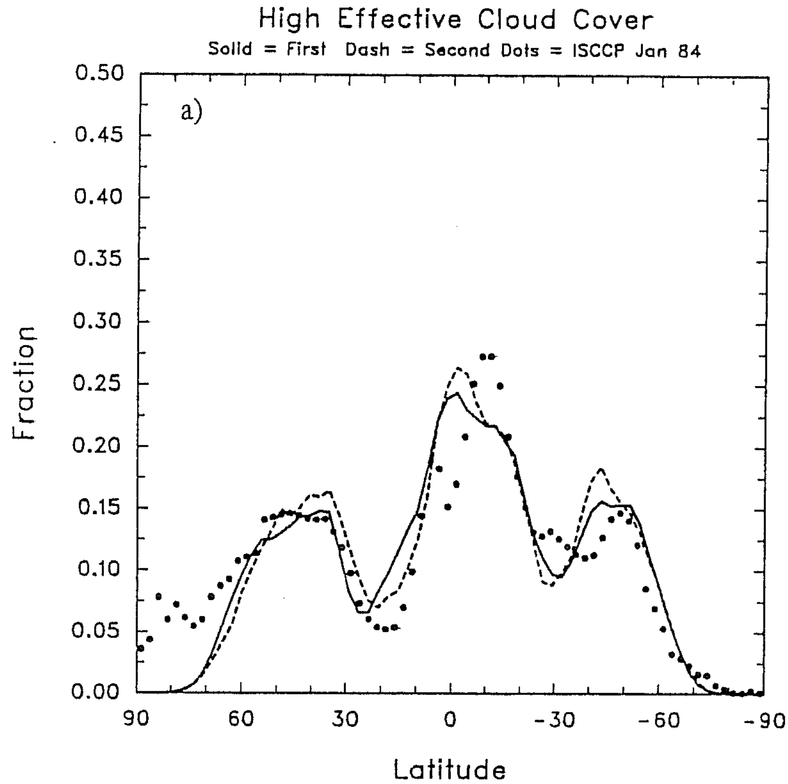

Fig. 2 Monthly mean of zonally averaged outgoing longwave flux ($Wm^{-2}$) for a) January and b) July, solid and dashed lines CCM2, dots from ERBE data

in the July summer extra-tropics is not as good. There is also a significant disagreement between model and observations in July over Antarctica. ISCCP suggests a 25% effective high cloud amount for this region. The model predicts little high cloud in this region due to the functional form of the cloud liquid water path (see figure 1). Since retrieval of cloud amount is somewhat difficult at high latitudes, it is important to verify that the ISCCP results for this region are truly representative.

The monthly means of zonally averaged clear sky outgoing longwave radiation for January and July are shown in figures 4a and b. These figures indicate substantial over prediction of outgoing radiation from the model compared to the ERBE data. As discussed in the previous section, some of this results from the models lack of trace gases, but the majority of this remains unexplained. For this reason, an analysis of the effects of calculating the clear sky flux from two methods (Cess and Potter,1987) is presently being carried out in CCM2 to see if this explains the differences between model and observations.

A comparison of the shortwave cloud forcing from the model and the ERBE data is shown in figures 5a and 5b. CCM2 shortwave cloud forcing in January is in very good agreement with the observational data. The only exception to this is poleward of 70S where the ERBE data are not reliable. The large cloud forcing (-160 $Wm^{-2}$) in the southern hemisphere associated with storm track regions is well represented in the model. As discussed in section 2.6, this agreement was obtained by lifting the linear $\omega$ ramp in the original Slingo cloud formulation. For July, there is an underestimation in shortwave cloud forcing in the model near 60 degrees. This is no doubt due to an under prediction of low cloud cover at these latitudes, which in turn could be due to reduced transient activity in the model.

A comparison of longwave cloud forcing between model and CCM2 data is shown in figure 6a and 6b. For January, the peak LWCF in the tropics is close to the ERBE maximum of 50 $Wm^{-2}$, however the peak seems centered over the equator in the model, while the data have a double peak structure with the larger peak being centered near 10S, which is in climatological agreement with the position of the convergence zone in the central to western Pacific. In the extra-tropics, the model over estimates the LWCF. This is due to the large over estimation of the clear sky flux (as can be seen from inspection of figures 2 and 4). Thus, it is even more imperative that the source of the clear sky flux bias be identified. It is difficult to believe that the model's clear sky fluxes are off by approximately 15 $Wm^{-2}$, especially when one considers the good agreement between the total moisture and temperature at these latitudes (see next section). In July, the comparison once again emphasizes the need to pin point the source of the clear sky bias.



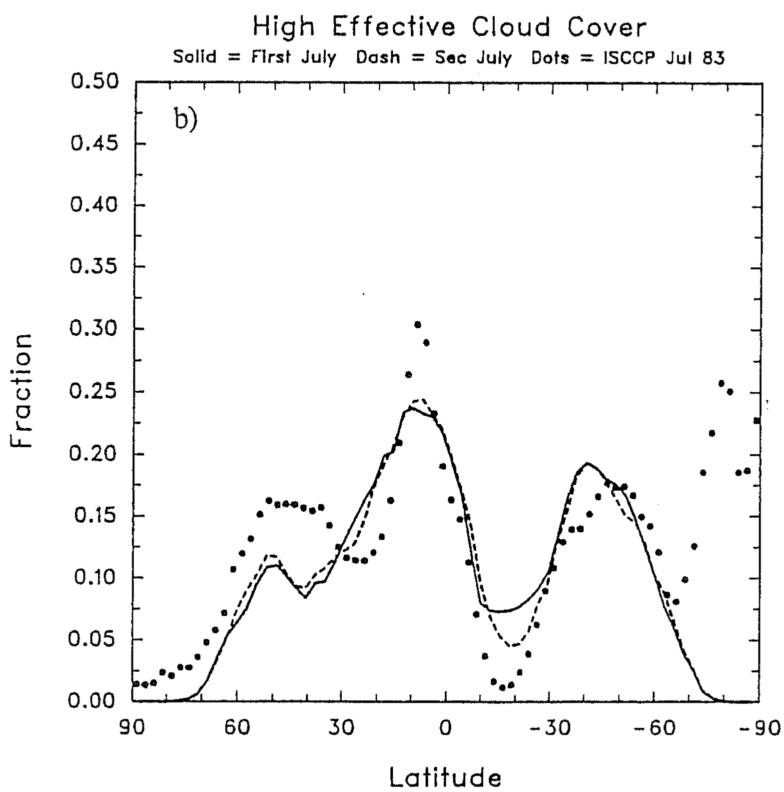




Fig. 3 Monthly mean of zonally averaged effective high cloud for a) January and b) July, solid and dashed lines CCM2, dots ISCCP data

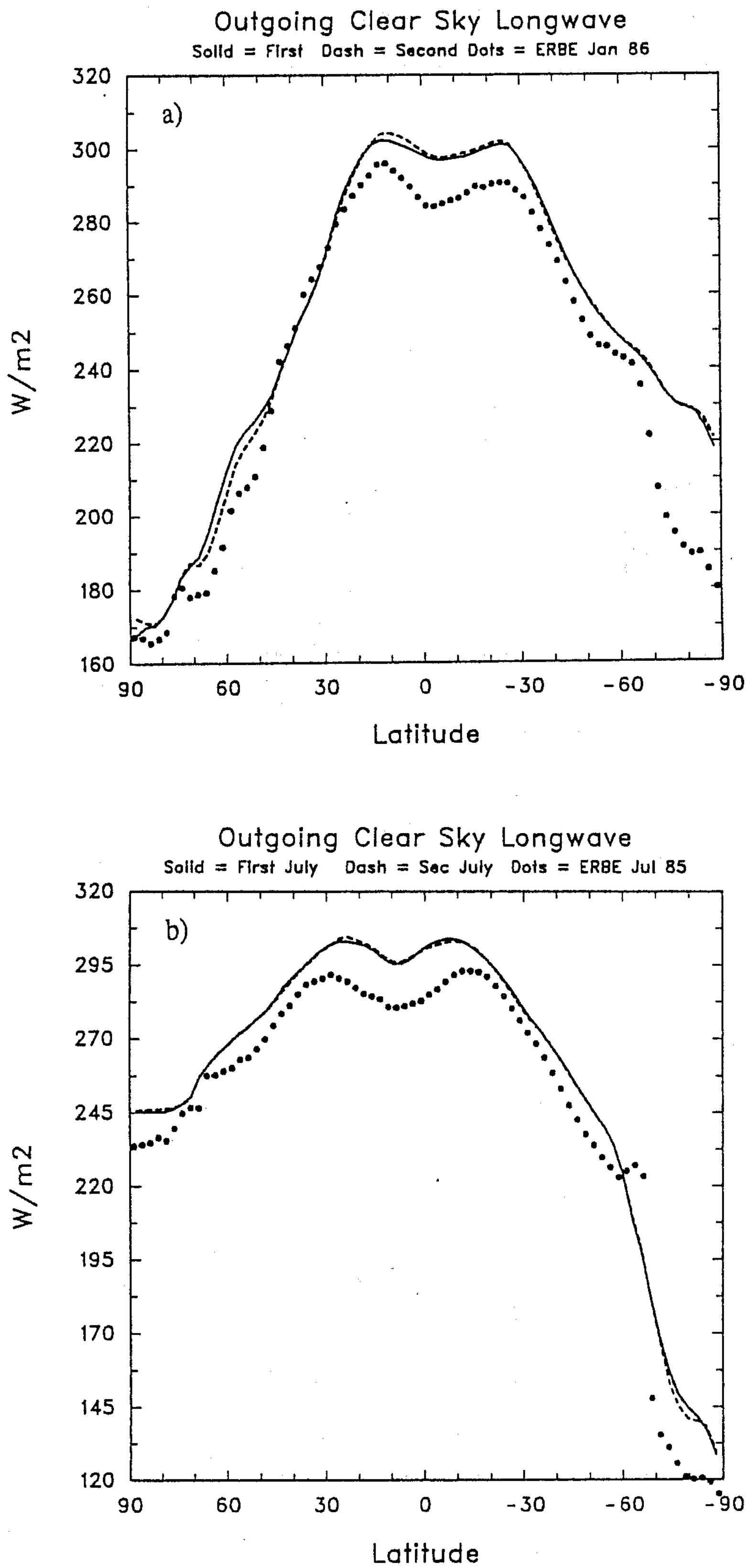
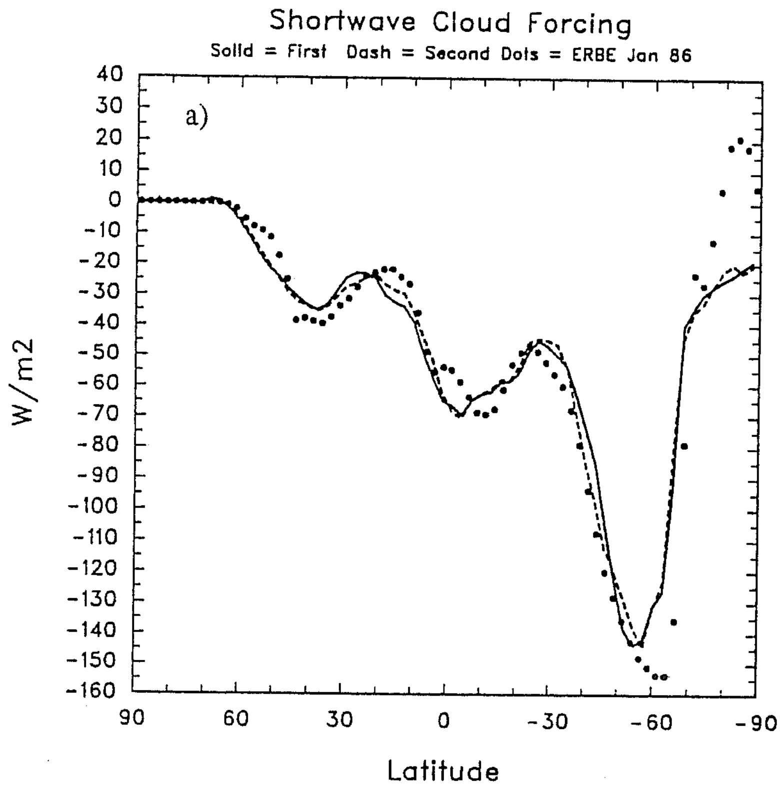



Fig. 4 Monthly mean of zonally averaged clear sky outgoing longwave flux ($Wm^{-2}$) for a) January and b) July, solid and dashed lines CCM2, dots from ERBE data



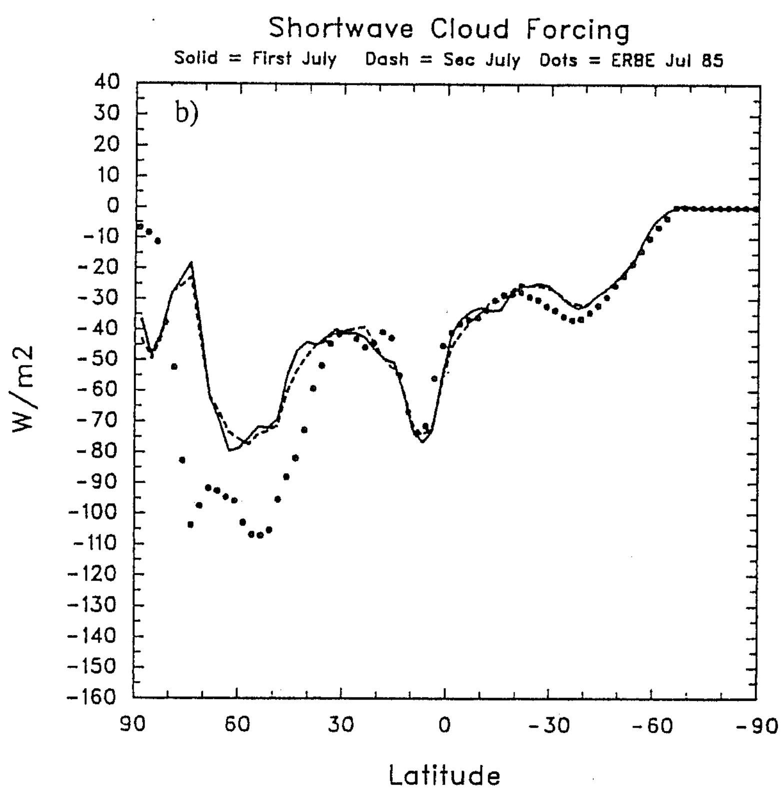
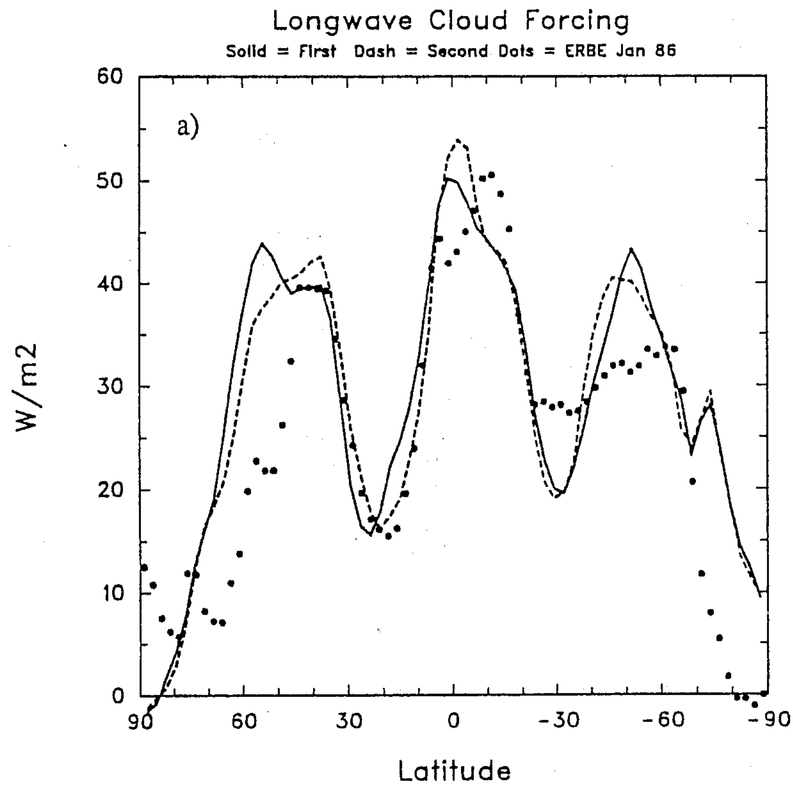




Fig. 5 Monthly mean of zonally averaged shortwave cloud forcing ($Wm^{-2}$) for a) January and b) July, solid and dashed lines CCM2, dots from ERBE data



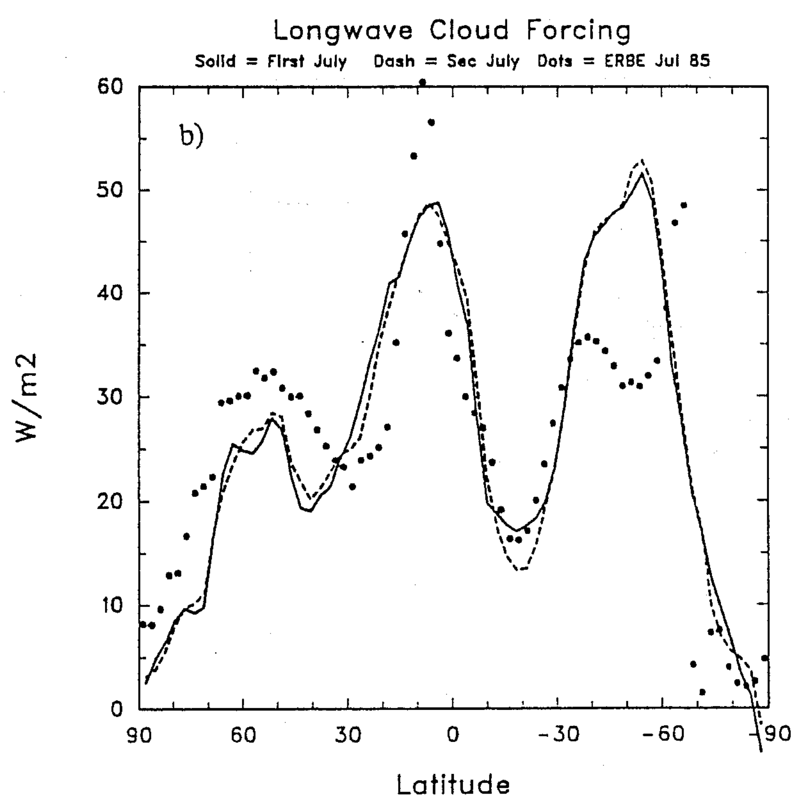



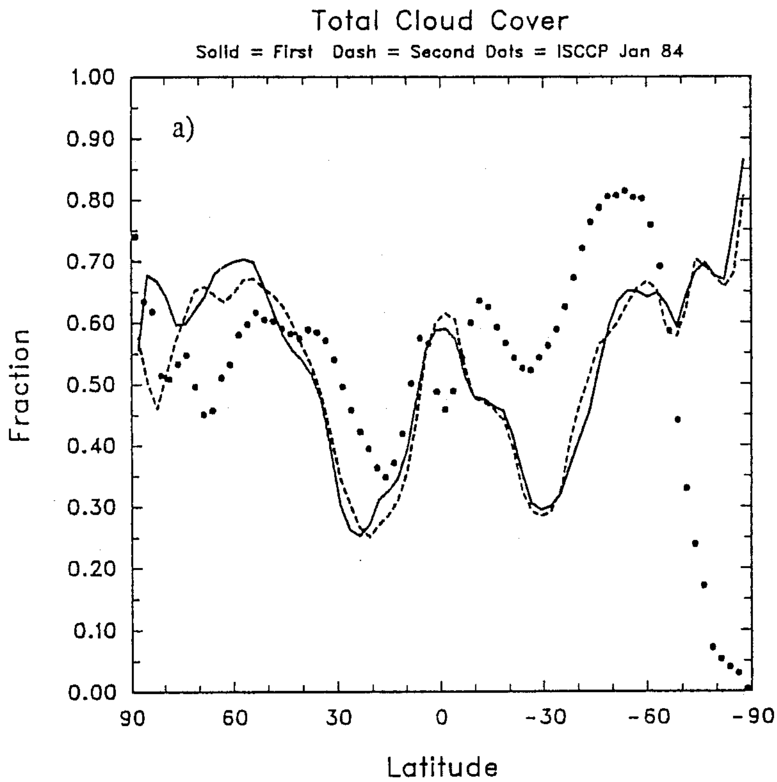

Fig. 6 Monthly mean of zonally averaged longwave cloud forcing ($Wm^{-2}$) for a) January and b) July, solid and dashed lines CCM2, dots from ERBE data

Finally, a comparison between the ISCCP retrieved total cloud fraction and the model cloud fraction (assuming random overlap) is shown in figures 7a-b for January and July, respectively. Note that ISCCP cloud cover over Antarctica for both seasons is quite low compared to the model results. The ground based observations of Warren et al.(1988) suggest a much greater cloud cover for this region, around 0.6. Elsewhere, the model in general underestimates the total cloud cover. In particular, the under estimation is largest near 30S and 30N, this is no doubt due to the lack of marine stratus and low trade cumulus cloud amount in the model. Implementation of the marine stratus cloud formulation outlined in section 3 should help alleviate this bias.

## 5. ASSOCIATED ATMOSPHERIC FIELDS

Although it is important to employ top of atmosphere radiative quantities for model validation. There are a number of associated quantities that strongly influence and are influenced by clouds. In particular, the atmospheric moisture profile, total atmospheric water vapor amount and the thermal structure are key variables in determining the cloud distribution in a general circulation model. This section calls attention to the data that can be employed for validating these fields, and indicates how this information can be used in conjunction with the previous satellite data for model validation.

As discussed in Kiehl and Ramanathan (1990), CCM1 possessed both a cold temperature bias and an extremely dry atmosphere (see their figure 2). Considerable work in the development of CCM2 has been devoted to address these two deficiencies in the model. The adoption of a new convection scheme has done much to alleviate these two biases. To study this bias a procedure was developed to access all available rawinsonde data for a chosen region. The mean temperature and moisture profile are determined along with spatial and temporal standard deviation of the observations within the region. The procedure also obtains similar data from the model simulations. Results from this analysis tool are described for two regions: a region where deep tropical convection is occurring and a region where shallow convection is taking place. Figure 8a-b shows the temperature and moisture profiles for a region centered over Truk island in the western Pacific for the month of July. The horizontal bars denote the observations while solid lines indicate the model results. The center line is the models mean value, while lines on either side indicate standard deviation. Note that the observational data are based on more than ten years of data, while the model results represent the second July from the annual cycle simulation from CCM2. The model thermal structure is in good agreement with the observations, there is even a slight warm bias at this location. The moisture structure has vastly improved over that in CCM1. The threefold dryness factor found in CCM1 has been eliminated. Figure 9a-b show similar profiles for a region centered over Ascension island in the eastern equatorial Atlantic; this region is representative of a shallow convective regime. The



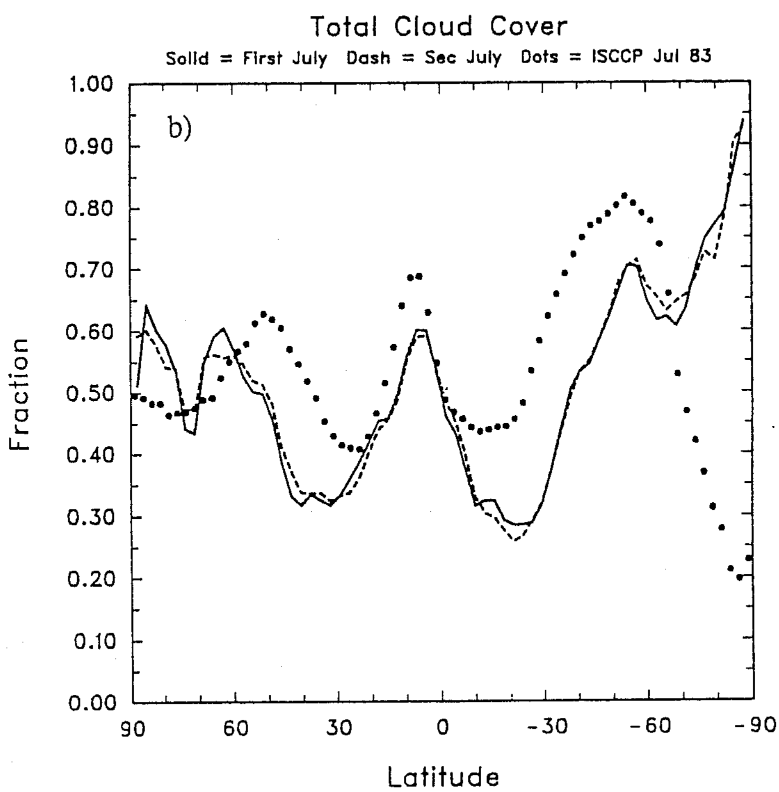




Fig. 7 Monthly mean of zonally averaged total cloud cover for a) January and b) July, solid and dashed lines CCM2, dots from ISCCP data

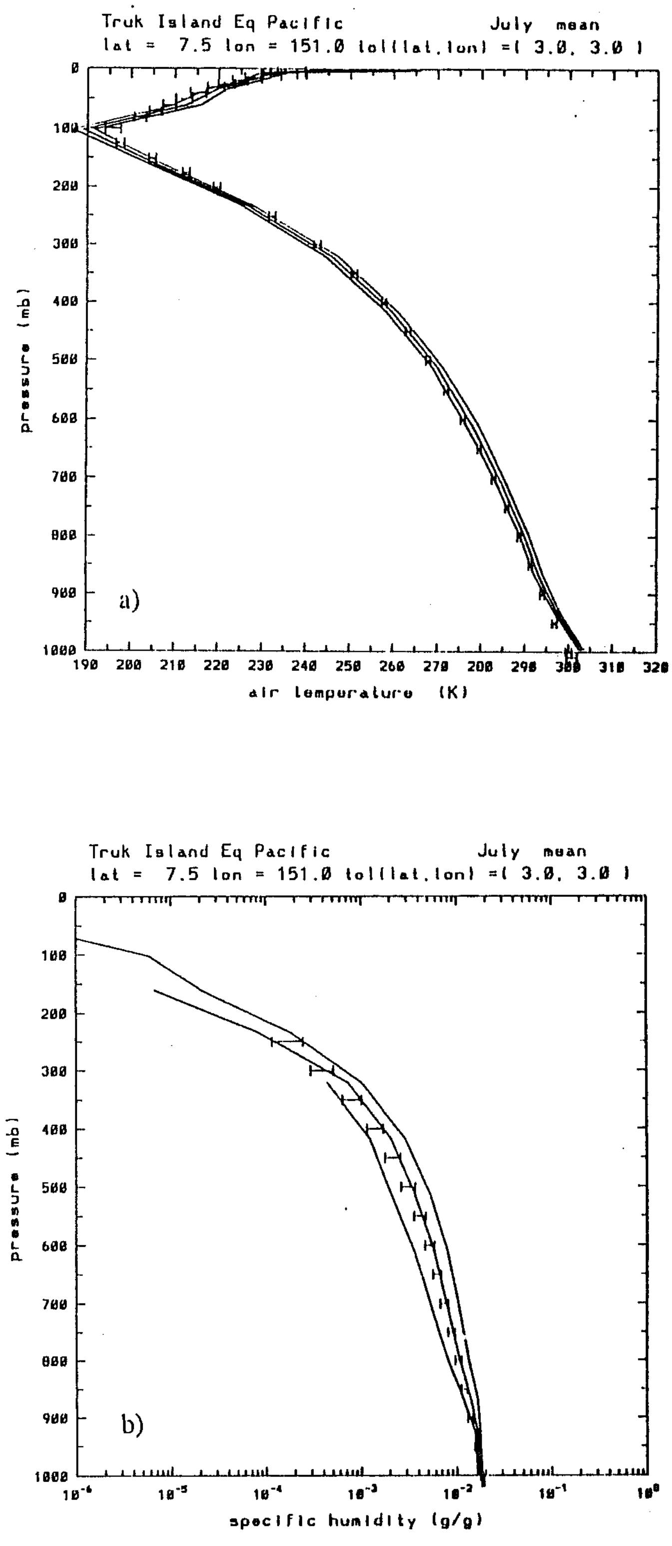
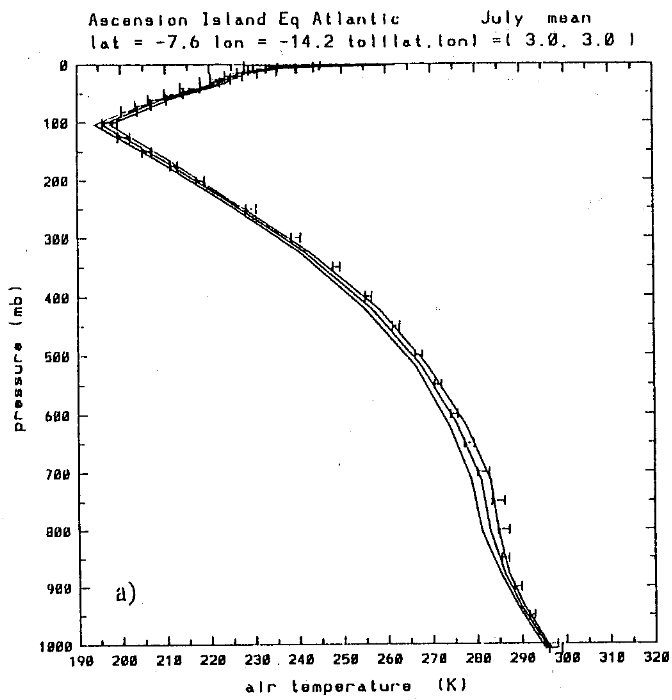



Fig. 8 Truk island region July monthly mean vertical profiles of a) temperature and **b) specific humidity, solid lines for CCM2 and horizontal bars from rawinsonde data. Central line is mean.**



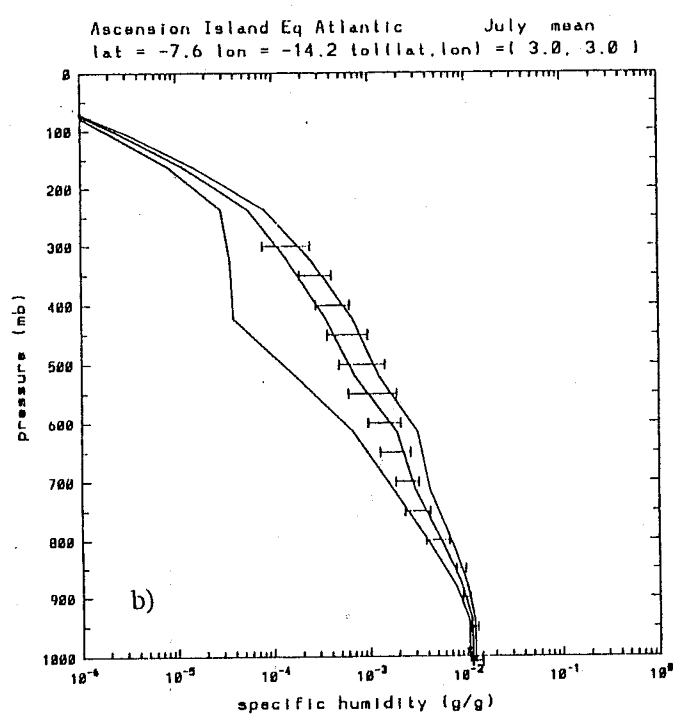




Fig. 9 Ascension island region July monthly mean vertical profiles of a) temperature and b) specific humidity, solid lines for CCM2 and horizontal bars from rawinsonde data. Central line is mean.

additional levels in CCM2 now allow for the existence of a trade inversion in the model. The model is slightly too cold around 300 to 400 mb and may be an indication that the subsidence is too weak at the T42 resolution (see Kiehl and Williamson,1990). The moisture profile is in very good agreement with the observations, both the new convection scheme and the new PBL scheme have helped resolved this problem in the model.

Finally, a comparison of the total moisture content in the atmosphere, the precipitable water, can be made with either the data from SSM/I or with that obtained from the TOVS instrument. Comparisons are made with TOVS data since these results were available for the month of July from the ISCCP data compilation. Comparison of the July monthly mean precipitable water (kg $m^{-2}$) between TOVS and CCM2 is shown in figure 10. Comparing these results to those in figure 3 of Kiehl and Ramanathan (1990) indicate that CCM2 now captures this feature of the atmosphere quite well, certainly within the uncertainty of the data.

## 6. FUTURE IMPROVEMENTS OF CCM2

This brief survey has presented preliminary results from the new version of the NCAR CCM. A number of the deficiencies in clouds and the earth radiation budget identified by Kiehl and Ramanathan (1990) have been addressed with CCM2. The cloud radiative forcing in CCM2 is now is good agreement with the ERBE data. The moisture profile and column amount agree quite well with available observational data. Despite these improvements in the CCM, a number of problems need to be resolved before the completion of CCM2.

First, the formulation for stratus clouds associated with low level inversions should be implemented with the additional condition of large (>75 $Wm^{-2}$) total turbulent surface heat flux. In addition, the cloud amount for non-precipitating shallow cumulus should be increased to 20%. Both of these changes will enhance the total cloud cover and thus, should bring the model in closer agreement with the ERBE and ISCCP data.

Second, the cause for the bias in the clear sky fluxes must be identified. Given the improved thermal and moisture structure of CCM2 and given the accuracy of the clear sky fluxes modeled by the CCM radiation code (see appendix of Kiehl and Ramanathan,1990), the predicted clear sky fluxes should be much closer to the ERBE results than are found by direct comparison. Indeed, Ramanathan and Downey (1986) have shown that one can obtain very good agreement (within 2-3 $Wm^{-2}$) between modeled clear sky fluxes and ERBE data. It is suggested herein that the source of the problem may lie in how the clear sky fluxes are determined in the model compared to how they are determined by the ERBE retrieval algorithm. Studies are underway to determine if this is the source of discrepancy, if so more

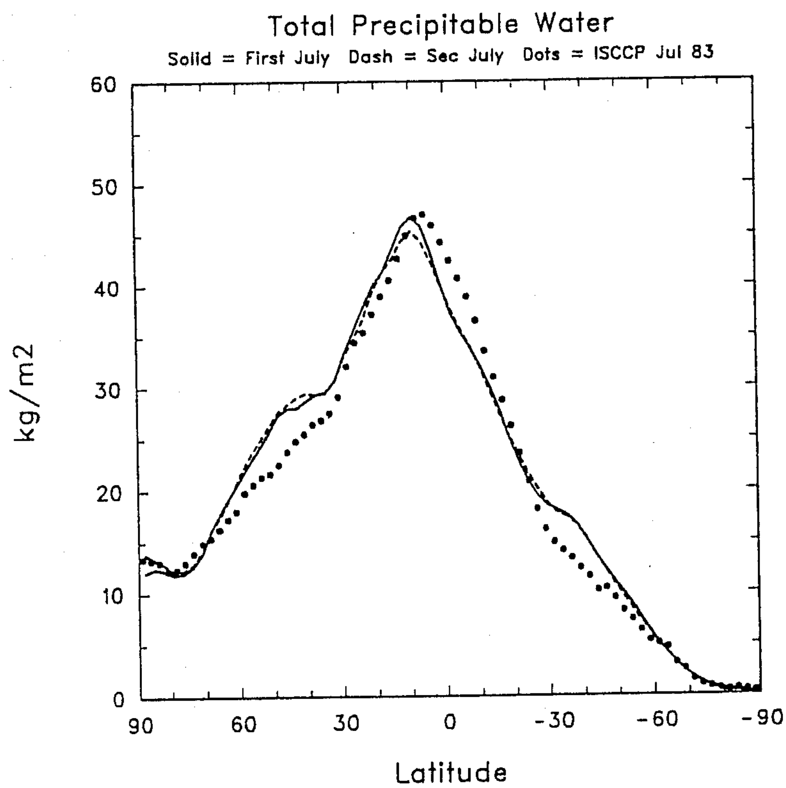



Fig. 10 July monthly mean of zonally averaged precipitable water (kg m$^{-2}$): solid and dashed lines CCM2, dots from TOVS data

care must be used when comparing models with the clear sky fluxes and the cloud forcing data.

Obviously, a key parameter in determining the models earth radiation budget at present is the cloud liquid water path. This is being prescribed in CCM2 from the mathematically concise, but no doubt physically unrealistic profile given in section 2.6. Thus, to a great extent the cloud radiative properties are left to the whim of the modeler; and hence the temptation to 'tune' the radiation budget to agree with the observations. A longer term goal of the Climate Modeling Section is to lift the prescription of cloud liquid water and allow for a prognostic formulation of cloud liquid water. Although this approach will not be implemented in CCM2, it is felt that the model now contains the basic features that allow for the realistic development of such a scheme.

## 7. ACKNOWLEDGEMENTS

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