CLOUD PREDICTION SCHEME IN THE ETA MODEL AT NCEP

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Abstract

An explicit cloud prediction scheme has been developed and incorporated into the Eta Model at the National Centers For Environmental Prediction (NCEP) to improve the cloud and precipitation forecasts. In this scheme, the cloud liquid water and cloud ice are explicitly predicted by adding only one prognostic equation of cloud mixing ratio to the model. Precipitation of rain and snow in this scheme is diagnostically calculated from the predicted cloud fields. The model–predicted clouds are also used in the model's radiation calculations. Results from the parallel tests performed at NCEP show significant improvements in precipitation forecasts when prognostic cloud water is included. Compared with the diagnostic clouds, the model–predicted clouds are more accurate in both amount and position. Improvements in specific humidity forecasts have also been found, especially near the surface and above the freezing level. The inclusion of cloud ice, the horizontal advection of cloud water, and the better treatment of precipitation evaporation below cloud bases are each important factors in the improvements of model forecasts.

1. INTRODUCTION

During the last three decades, significant progress has been made in the improvement of large–scale wind and mass field forecasts. However, concomitant improvements in the treatments of clouds in general circulation models (GCMs) and numerical weather prediction (NWP) models have not occurred. Diagnostic cloud schemes based on the work of Slingo (1987) are currently used by most operational models in their radiation parameterizations. While realistic cloud fractions have been produced by the diagnostic schemes, the incomplete hydrological cycle in these schemes can lead to significant errors in the moisture and precipitation forecasts.

Recently, the importance of the explicit treatments of clouds in GCMs and NWP models has been increasingly recognized by many modelers. Great efforts have been made to include cloud water and/or ice into model's prediction equations. A parameterization scheme for large–scale models was proposed by Sundqvist (1978) and Sundqvist et al (1989) in which cloud water was explicitly predicted. After this pioneering work, an increasing number of GCMs and NWP models have included a prognostic equation for the mass of cloud water and/or cloud ice to parameterize the cloud processes (Smith, 1990; Tiedtke, 1993).

An explicit cloud prediction scheme was developed and incorporated into the Eta Model at the National Centers for Environment Prediction (NCEP) about three years ago to improve the model's radiation calculations and precipitation forecasts(Zhao et al, 1991; Zhao and Black, 1994). During the last three years, a large number of experiments have been carried out to test and improve the cloud scheme. Results from these experiments show that the cloud prediction scheme improves the moisture and precipitation forecasts significantly. Compared with the diagnostic clouds, the model–predicted clouds are more accurate in both amounts and locations. Recently, a parallel test of the cloud scheme has been completed at NCEP. The current scheme has been incorporated to the standard code to be used by all versions of the Eta Model.

The purpose of this paper is to provide a full description and discussion of the cloud prediction scheme. The cloud scheme will be described in section 2. The main features of the Eta Model will also be covered in this section. In section 3, we will present some results from recent experiments and the parallel tests. Finally, conclusions will be stated in section 4.

2. DESCRIPTION OF THE CLOUD SCHEME

The primary feature of the cloud prediction scheme is the explicit calculation of cloud water and cloud ice contents in both large–scale and convective condensations as illiustrated in Fig. 1. Instead of using two separate variables, we use only one predictive variable, the cloud water/ice mixing ratio m, to represent both cloud water and cloud ice. This reduces the model computational time and storage requirements. After incorporation of the cloud scheme, the model predictive equations for temperature T, specific humidity q and cloud water/ice mixing ratio m are

$$\frac{\partial q}{\partial t} = q_{non'} + E_c + E_r - C_b - C_g \qquad (2.1)$$

$$\frac{\partial T}{\partial t} = T_{non'} - \frac{L}{C_p}(E_c + E_r - C_b - C_g) - \frac{L_f}{C_p} P_{sm} \qquad (2.2)$$

$$\frac{\partial m}{\partial t} = m_{non'} - E_c + C'_b + C_g - P \qquad (2.3)$$

where q_{non}, T_{non} and m_{non} are the non–condensation terms, C_g and C_b are the grid–scale and convective condensation rates, and E_c and E_r are the evaporation rates for clouds and precipitation, respectively. P_{sm} is the melting rate of snow below the melting level, P is the precipitation production rate from cloud water/ice mixing ratio, C'_b is the net convective condensation rate, C_p is the specific heat of air at constant pressure, L is the latent heat of condensation/deposition, and L_f is the latent heat of freezing.

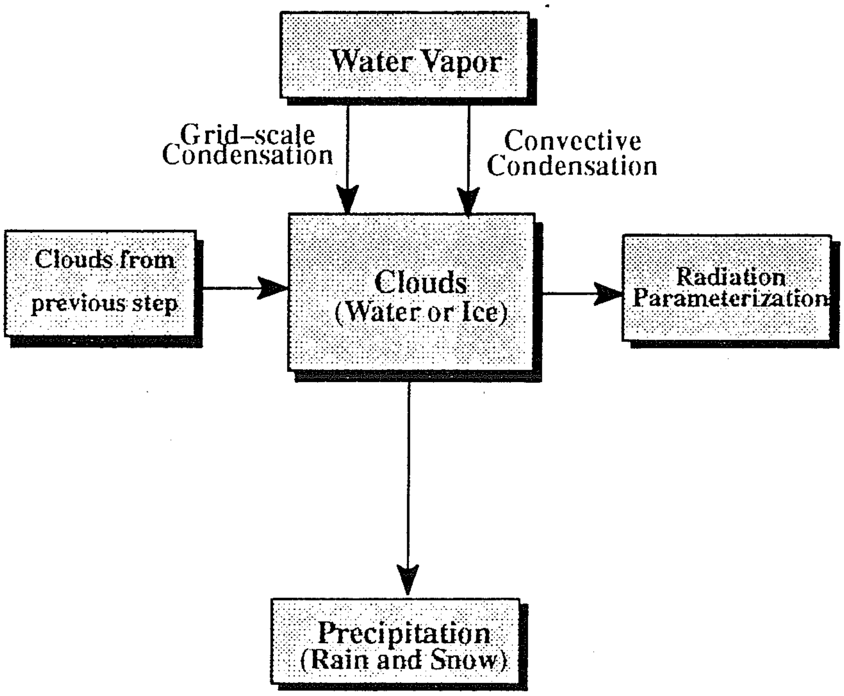


Fig.1 Schematic illustration of the cloud prediction scheme.

2.1 Grid–scale condensation

Following Sundqvist et al (1989), the grid–scale condensation for stratiform clouds is calculated by

$$C_g = \frac{M - q_s \frac{\partial U}{\partial t}}{1 + \frac{\varepsilon U L^2 q_s}{R C_p T^2}} + E_c \tag{2.4}$$

where

$$M = A_q - \frac{\varepsilon U L q_s}{R T^2} A_T + \frac{U q_s}{p} \frac{\partial p}{\partial t} \tag{2.5}$$

$$\frac{\partial U}{\partial t} = \frac{2(1-b)(U_s-U_{00})[(1-b)M + E_c]}{2q_s(1-b)(U_s-U_{00}) + \frac{m}{b}} \tag{2.6}$$

Here, U is the relative humidity, A_q and A_T are the changes in q and T caused by all the processes except grid–scale condensation and evaporation, p is the pressure, b is the cloud fraction, q_s is the saturation specific humidity, $U_s = 1.0$ is the relative humidity in a cloud region, U_{00} is the critical value of relative humidity for condensation, E_c is the evaporation rate of cloud water/ice and ε=0.622. The cloud fraction b is calculated from

$$b = 1-\left[\frac{U_s-U}{U_s-U_{00}}\right]^{\frac{1}{2}} \quad (2.7)$$

when U > U_{00} and b=0 otherwise. U_{00} is a very sensitive parameter in this cloud scheme. Currently, we use the value of 0.75 for U_{00} over land. Since condensation can more easily occur over ocean than over land because of the availability of moisture, the value of U_{00} is set to 0.85 over ocean to avoid over–condensation.

2.2 Convective condensation

The modified Betts–Miller convective adjustment scheme (Betts, 1988; Betts and Miller, 1989; Janjic, 1990, 1994) is used to produce convective clouds. In this scheme, precipitation is produced only by deep convection. Therefore, shallow convection is not considered here. The condensation rate in the Betts–Miller scheme is

$$C_b = \frac{q-q_r}{\tau} \quad (2.8)$$

where q_r is the moisture reference profile for deep convection, and τ is the time scale of convective adjustment. Consider an atmospheric column where deep convection occurs. At some levels $q>q_r$ and $C_b>0$ (condensation), while at others, $q<q_r$ and $C_b<0$ (evaporation). Therefore, some of the condensed water must be transferred to the points where $C_b<0$ and evaporated in order to complete the convective adjustment process. It is assumed that vertical mixing inside the convective clouds is so strong that some of the cloud water/ice formed at condensation points is immediately transferred to the evaporation points for evaporation. The rest of the cloud water/ice is assumed to stay at the condensation points and therefore the final net condensation rate C_b' at each condensation level is calculated from

$$C_b' = RB \quad (2.9)$$

where

$$R = \frac{\int_{cloud\ top}^{cloud\ bottom} C_b d\eta}{\int_{cloud\ top}^{cloud\ bottom} B d\eta} \quad (2.10)$$

and $B=C_b$ if $C_b \geq 0$, B=0 if $C_b<0$. The constraint for C_b' is

$$\int_{cloud\ top}^{cloud\ bottom} C_b' d\eta = \int_{cloud\ top}^{cloud\ bottom} C_b d\eta \qquad (2.11)$$

where η is the vertical coordinate of the Eta Model. If $R < 0$, no adjustment is allowed.

2.3 Distribution of cloud water and cloud ice

Figure 2 shows the distribution of cloud water and cloud ice inside clouds in this cloud prediction scheme. In regions where T>0 °C, there is no cloud ice while in regions where T < –15 °C, no cloud water is allowed. In the regions where T is between 0 °C and –15 °C, however, the phase of hydrometers is determined by the cloud top temperature T_p. If T_p >–15 °C, then the cloud is assumed to consist of supercooled water. If T_p <–15 °C, which means there are ice particles above, the cloud should freeze very quicky because of the seeding effects of ice particles from above. The distinction between cloud water and cloud ice is made by the three–dimensional cloud identification number IW which is zero for cloud water and unity for cloud ice.

2.4 Evaporation of clouds

Cloud evaporation is allowed to take place only when the relative humidity $U<U_{00}$, i.e., when there is no condensation occurring. All water vapor from evaporation is used to increase the relative humidity at this point. Evaporation will stop when U_{00} is reached. The evaporation rate is

$$E_c = \frac{q}{\Delta t}(U_{00}-U) \qquad (2.12)$$

where Δt is the time step for precipitation calculation in the Eta Model.

2.5 Precipitation

Once it is produced from the cloud water/ice, precipitation is assumed to fall to the ground in one precipitation time step. The microphysical processes used for producing precipitation from clouds are given in Fig. 3. All the equations used to calculate the microphysical processes are given by Zhao (1993). Two important features in this scheme should be discussed here, namely, the melting of snow below the melting level and the evaporation of precipitation below cloud bases. Snow melting is calculated as a function of temperature, i.e., snow melts gradually, not immediately, when it falls into the warm cloud regions. This treatment allows the co–existence of snow and rain in some regions just below the melting level. That means that in some areas, snow and rain can reach the ground at the same time (see Fig.2). Another important process that may significantly affect the model's thermodynamical and hydrological fields is the evaporation of precipitation below cloud base. In this scheme, precipitation can fall through the entire unsaturated layer and reach the ground while it is evaporating.

2.6 Clouds in radiation parameterization

Cloud fractions calculated from Eq. (2.7) are indirectly used in the radiation parameterization. Currently, three layers of clouds (high, middle and low) are computed from the cloud fractions in each model layer as input to the radiation calculations. Future improvements may allow the direct use of cloud fractions in all model layers.

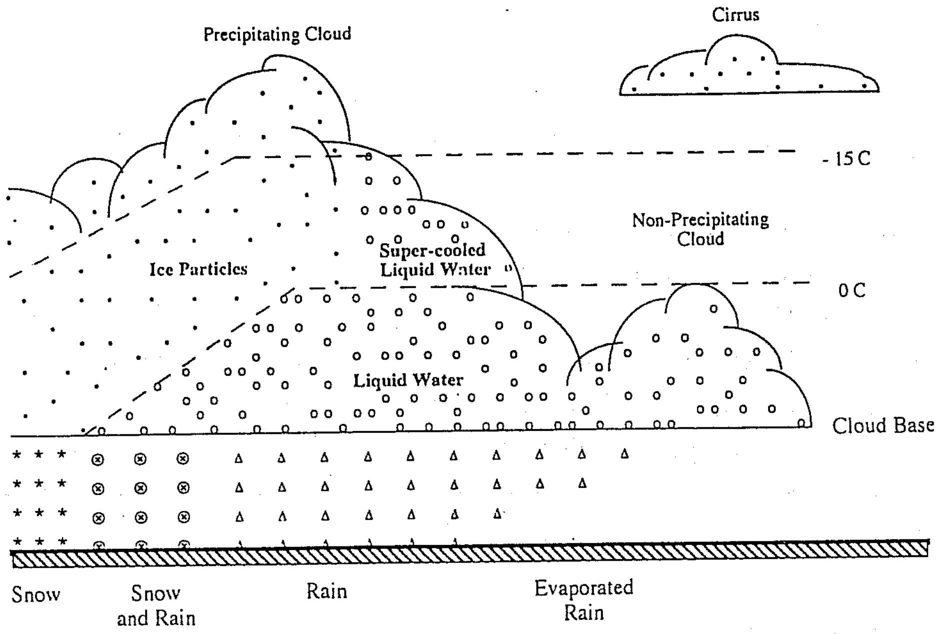


Fig.2 Distribution of cloud water and cloud ice inside clouds.

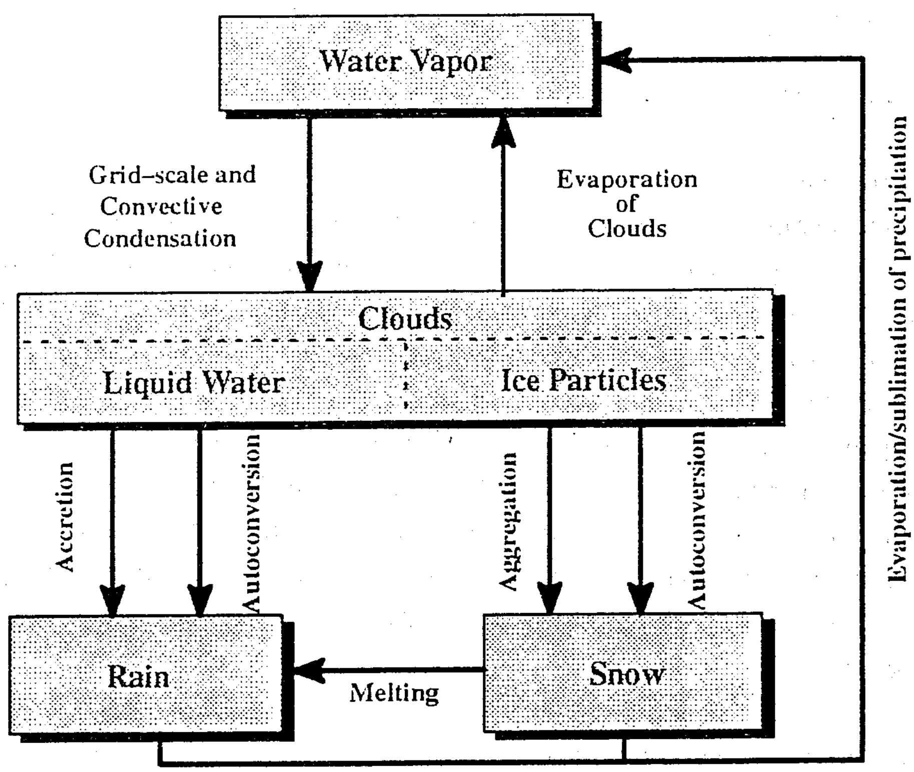


Fig.3 Microphysical processes simulated in the cloud prediction scheme.

Characteristics\ Model	Control	With cloud scheme
Grid type	Semi–staggered Arakawa E	Same
Fundamental prognostic variables	Temperature, u,v, surface pressure specific humidity, turbulent kinetic energy	Temperature, u,v, surface pressure, specific humidity, turbulent kinetic energy, cloud water/ice mixing ratio
Horizontal resolution	80km and 29km	Same
Vertical resolution	38 layers for 80km 50 layers for 29km	Same
Time differencing	Split–explicit: Adjustment uses forward–backward scheme, Horizontal advection uses a modified Euler–backward, Vertical advection uses Euler–backward	Same Horizontal advection of cloud water/ice mixing ratio uses the same scheme for q, Vertical advection of the cloud water/ice mixing ratio is neglected.
Physics	Betts (1986)/Betts–Miller (1986) convection Mellor–Yamada (1982) level 2.5 Mellor–Yamada (1982) level 2.0 Fels–Schwarztkopf (1975) radiation scheme Phillips (1981) and Hoke (1982) grid–scale rain	Betts (1986)/Betts–Miller (1986) convection Mellor–Yamada (1982) level 2.5 Mellor–Yamada (1982) level 2.0 Fels–Schwarztkopf (1975) radiation scheme Explicit prediction of grid–scale
Initial balancing	None	None
Boundary conditions	One–way interaction from AVN forecast of preceding cycle	Same

Tab. 1 Basic characteristics of the Eta model in control and experimental runs

2.7 Model description

The cloud prediction scheme was incorporated into and tested with the step–mountain, eta–coordinate regional weather prediction model (Eta Model) at NCEP. The Eta Model was first developed by Mesinger et al (1988). A comprehensive physical package has been incorporated into the model by Janjic(1990, 1994). Examples of the Eta Model performance are contained in Black et al (1993).

Currently, the Eta Model is running at three model resolutions: 80 km, 40 km and 29 km. There are 38 vertical levels for the 80 km and 40 km models and 50 levels for the 29 km model. Figure 4 gives the horizontal domain for the 40 km Eta Model and Tab.1 lists the main features of the model for both control and experimental runs.

3. RESULTS

3.1 Verification procedures

During the last three years, many interesting cases have been selected for experiments aimed at testing and

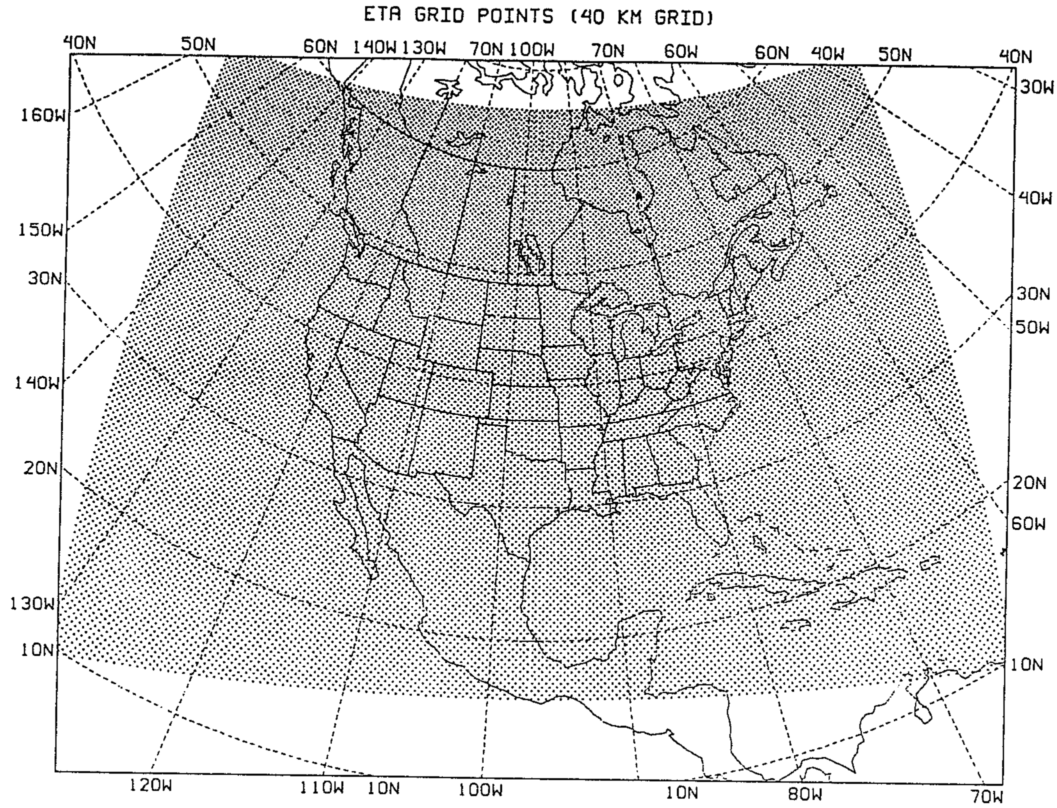


Fig.4 The horizontal domain of the 40 km Eta Model.

improving the cloud prediction scheme. Since September 1994, a parallel test has been established at NCEP for the cloud scheme. The Eta Model with the cloud scheme has been running twice daily, starting 0000 UTC and 1200 UTC, with a model resolution of 40 km in the horizontal and 38 layers in the vertical. Automatic verification of the model forecasts of precipitation and other large–scale variables are carried out daily. Validation of cloud forecasts is also performed for some interesting cases using the Real–Time Nephanalysis (RT–Neph) data from the Air Force Global Weather Center (AFGWC). The verification results are then compared with those from the control runs at the same time and with the same model resolution.

3.2 Cloud forecasts

The cloud forecasts from the cloud scheme include the three–dimensional cloud fraction b, cloud water/ice mixing ratio m and the identification number of cloud water and cloud ice IW. The total cloud coverage can be computed from the cloud fraction at each model level using the equation

$$\bar{b} = 1 - \prod_{j=2}^{LM} \frac{1-max(b_{j-1},b_j)}{b_{j-1}} \qquad (4.1)$$

where LM is the number of the vertical levels of the Eta Model.

Figure 5a gives an example of the model forecast of total cloud coverage by the cloud scheme while Fig.5b shows the cloud picture from satellite about one hour later. This is the case of a major winter storm on the east coast of the US on 13 March 1993. It can be seen that a big cloud system associated with the storm centered in Georgia was satisfactorily predicted in both structures and locations. To see the three–dimensional structures of the clouds, a vertical cross–section of clouds through the center of the storm is given in Fig. 6. The highest clouds associated with the upper–level front were located in the central area of the storm, and the cirrus clouds reach as far as several hundred kilometers away from the storm center in the down–wind direction. While the clouds shown in Fig.6 look realistic, currently there is no data available for directly verifying the three–dimensional structures of the cloud water/ice mixing ratio.

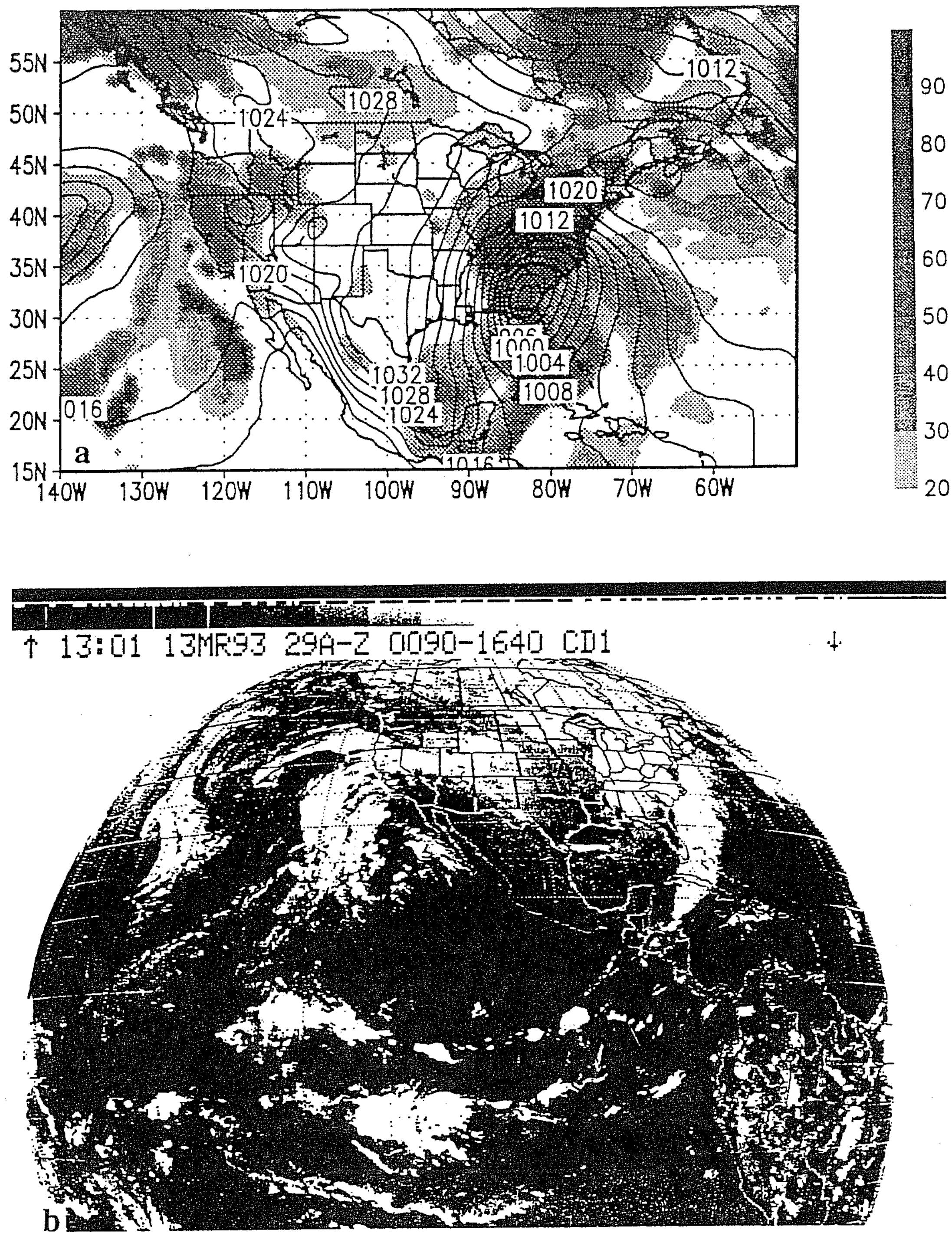


Fig.5 a) Total cloud fraction (percent, shaded areas) and mean–sea–level pressure (hPa, contours) at 1200 UTC 13 March 1993 from the 24–hour forecasts of the Eta Model with explicit cloud scheme. b) Satellite cloud picture at 1301 UTC 13 March 1993.

Quantitative verification of total cloud coverage has been done using the RT–Neph data. The RT–Neph data

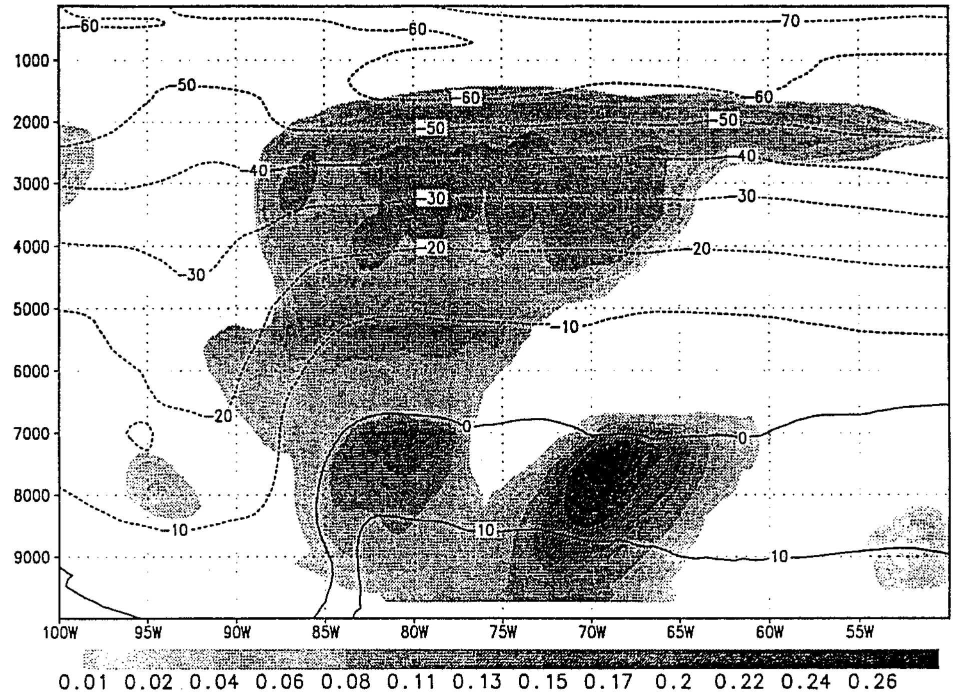


Fig.6 Cross–section of cloud water/ice mixing ratio (g/kg) and temperature (oC) at 1200 UTC 13 March 1993 at latitude of 33 oN.

is produced by AFGWC (Hamill et al, 1992) every three hours and is available daily at NCEP every six hours. The Barnes analysis scheme (Barnes, 1973) is used to interpolate the data from the Neph grids to the Eta grids. Figure 7a shows an example of the total cloud coverage analyses on the 80km Eta grids at 0600 UTC 7 July 1994. Comparison of the analysis with a satellite picture at the same time shows very good agreement between them, especially over the US. Figures 7b and 7c give the prognostic clouds from the cloud scheme and the diagnostic clouds from the control run without explicit cloud water valid at the same time, respectively. Obviously, the cloud coverage is under–estimated by the diagnostic clouds everywhere. Improvements can be seen in the prognostic clouds in Fig. 7b although underestimation of total clouds is still apparent. To see the improvements more quantitatively, four statistical scores are calculated: S_{20} score (the percent of points where the cloud amounts in the two fields differ by less than 20%), correlation, RMS error and bias difference (Hou et al , 1993). The results at every 6 hours are given in Fig. 8. In the first 6 hours of the model forecasts, little improvement can be found in the prognostic clouds. After that time, however, the prognostic clouds show significant improvement over the dignostic clouds through the increased S_{20} score and correlations and decreased bias and RMS errors. The "spinup" in the prognostic clouds is very obvious in Fig.8d. This should be largely eliminated by initializing the cloud fields in the cloud scheme in the future.

3.3 Precipitation forecasts

Another way to validate the cloud scheme is through verification of the precipitation forecasts since clouds and precipitation are two directly–linked components in the model's hydrological cycle. Furthermore, precipitation is a very important variable in NWP forecasts in and of itself.

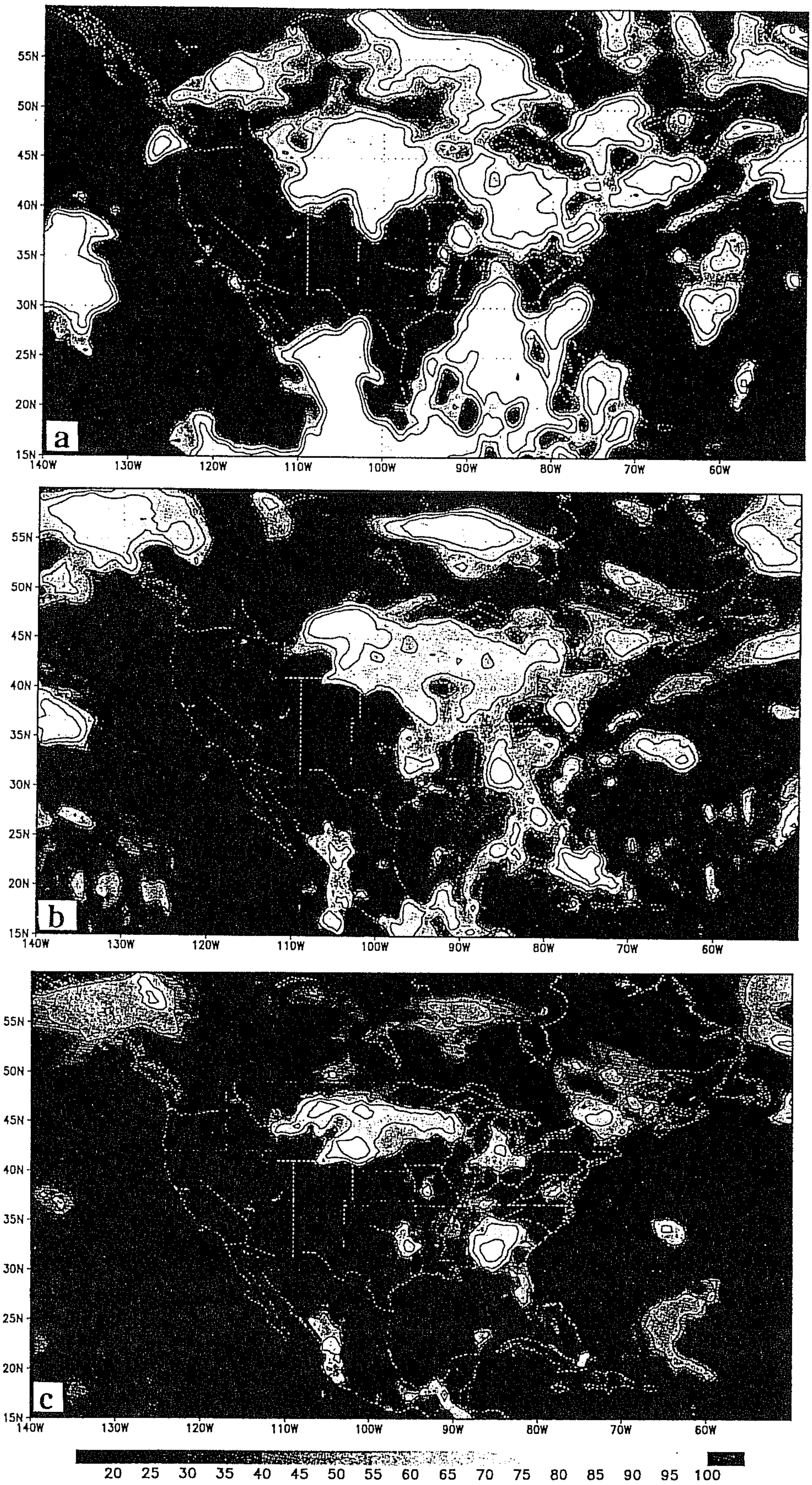


Fig.7 Total cloud fraction (percent, white areas) at 0600 UTC 7 July 1994 from (a) RT–Nephanalysis, (b) 18–hour forecasts of the Eta Model with explicit cloud scheme, and (c) diagnostic clouds of the Eta Model without explicit cloud scheme. Contours from outside are: 40%, 60%, and 80%.

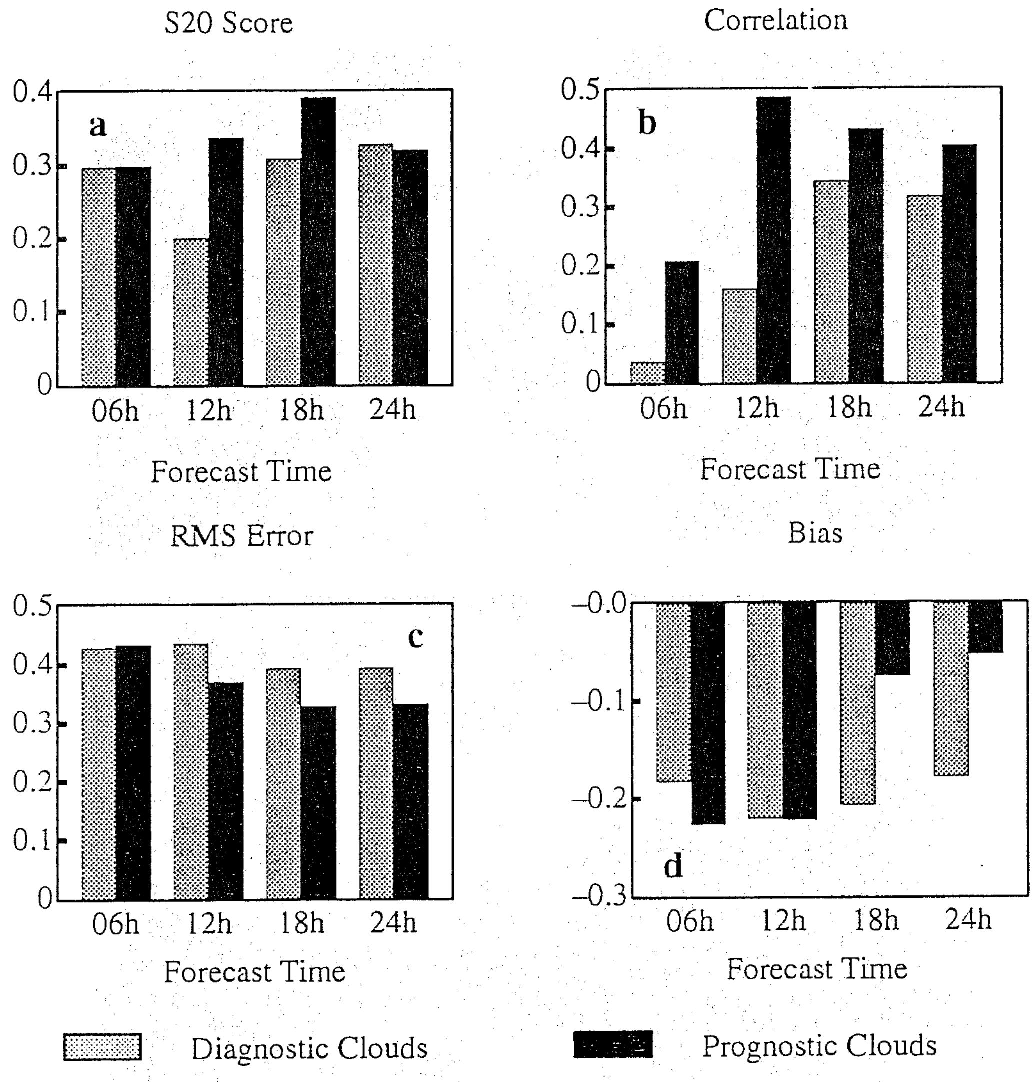


Fig.8 Statistical scores of the total cloud fraction for both the predicted and diagnostic clouds from the 40 km Eta Models with and without explicit cloud scheme, respectively, at different forecast times starting at 1200 UTC 6 July 1994.

Objective verification of precipitation amounts has been done during the parallel tests of the cloud scheme with the use of the Office of Hydrology's River Forecast Centers database (Black et al, 1993). The 24–hour accumulated precipitation amounts from the model forecasts is verified against the analysis of 24–hour amounts covering the contiguous United States. For quantitative verification, an Equitable Threat Score (ETS) (Schaefer, 1990) and bias are computed using the equations

$$ETS = \frac{H - CH}{F + O - H - CH} \tag{4.2}$$

$$BIAS = \frac{F}{O} \tag{4.3}$$

where F is the number of forecast points above a threshold, O is the number of observed points above a threshold, H is the number of hits above a threshold, and CH is the expected number of hits in a random forecast of F points for O observed points, which is equal to:

$$CH = \frac{F \times O}{M} \tag{4.4}$$

where M is the number of points to be verified.

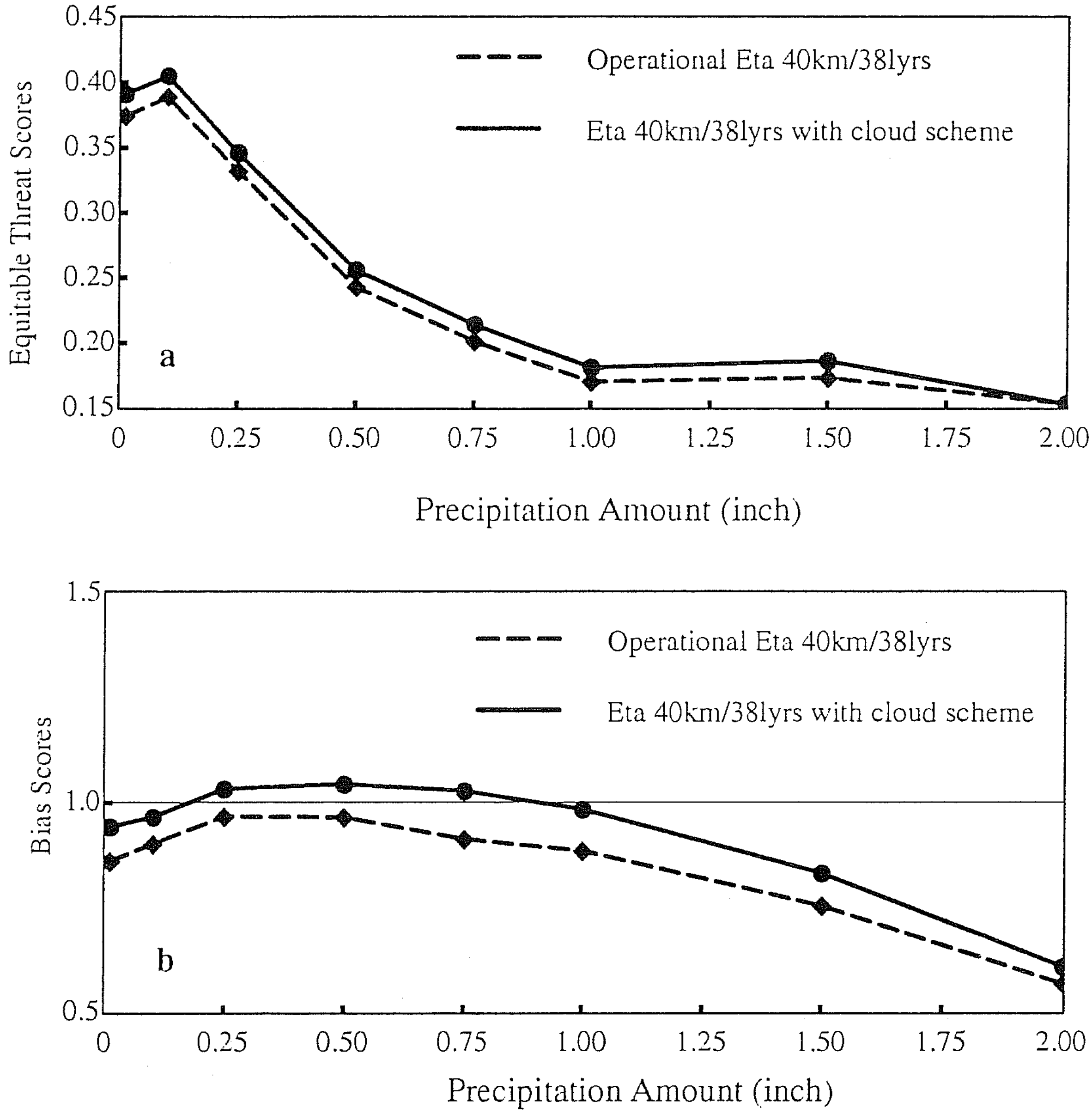


Fig.9 Equitable threat scores (a) and biases (b) of the combined 0–24 and 12–36 hour precipitation forecasts of the 40 km Eta Models with and without explicit cloud scheme for the parallel tests from 4 September to 18 October 1994.

The ETS and bias calculations from the parallel tests during the period from 4 September to 18 October 1994 are given in Fig.9. The cloud scheme has improved the precipitation forecast skill at all thresholds. As a typi-

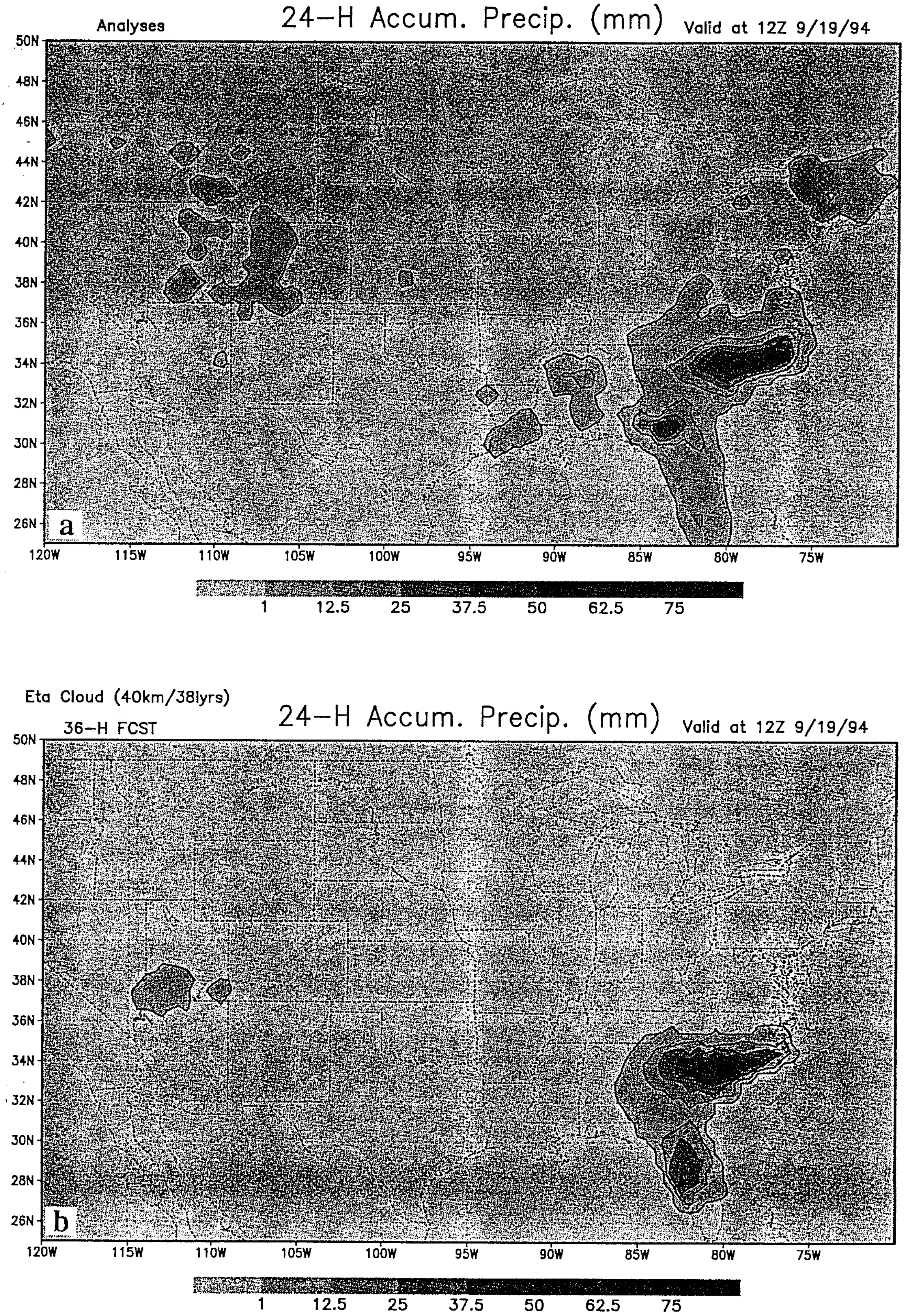


Fig.10 (a) Observed 24–hour accumulated precipitation for the period ending at 1200 UTC 19 September 1994. (b) 36–hour forecasts of the 24–hour accumulated precipitation from the 40 km Eta Model with explicit cloud scheme for the same period. (c) The same as (b) except from the 40 km Eta Model without explicit cloud scheme. Contour interval is 12.5 mm.

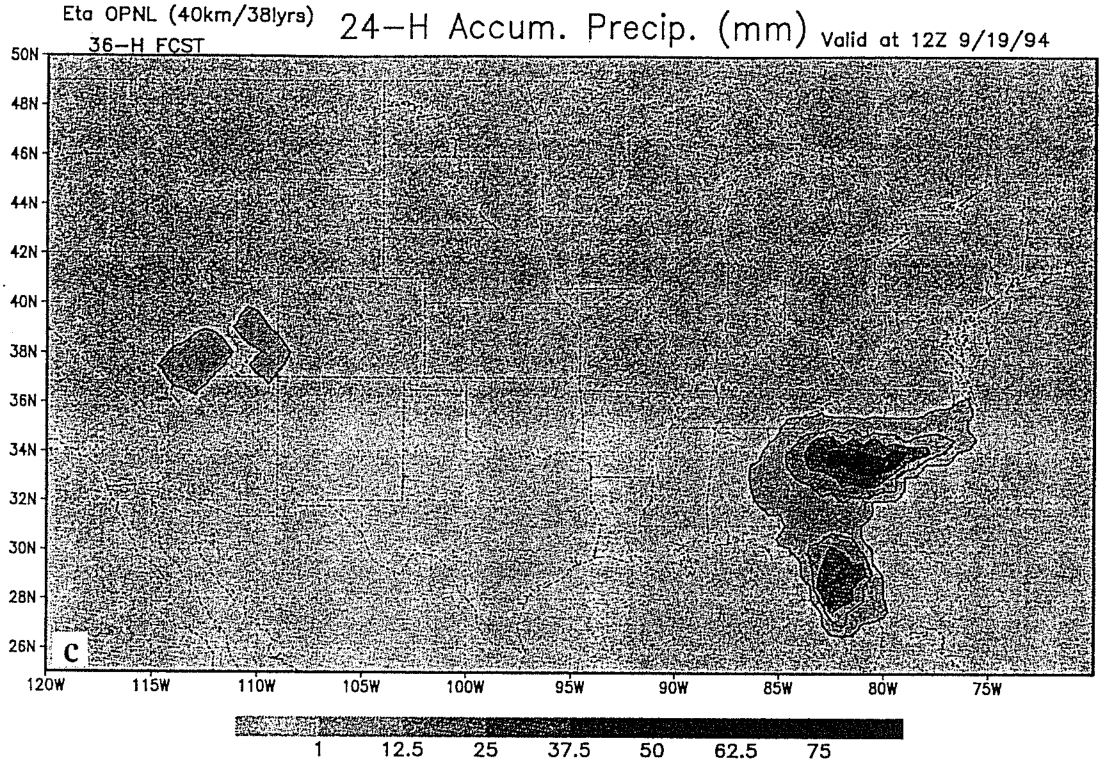


Fig 10 (Continued)

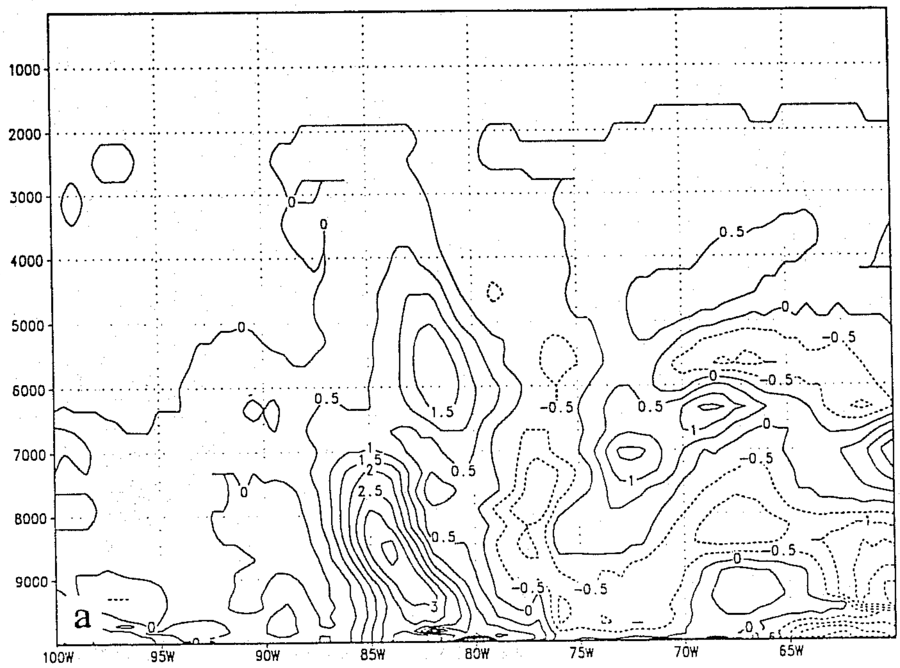
cal example of the improvements in precipitation forecasts by the cloud scheme, Fig.10 presents the 24–hour accumulated precipitation amounts from both the analyses and model forecasts of the both cloud scheme and the control runs on 19 September 1994. There was a large area of heavy precipitation in the southeastern U.S. with a maximum of more than 65 mm in South Carolina. Both the control and the cloud runs predicted the correct area of precipitation but the maximum in South Carolina was significantly underpredicted in the former. The cloud scheme, however, produced a maximum of about 55mm which is much closer to the observed. The increases in the forecasts of both precipitation amounts and areas by the cloud scheme over those in the control can also be seen in Fig.9b. The total biases from the control runs are less than 1.0 at all precipitation thresholds while the biases from the cloud scheme are larger everywhere. Previous studies (Zhao, 1993) show that the inclusion of cloud ice above the freezing level and the better treatment of precipitation evaporation below cloud bases may be the most important factors in the increases in precipitation amounts.

3.4 Large–scale variable forecasts

It has been found that the changes in the forecasts of temperature, sea–level pressure and wind fields by the inclusion of cloud water/ice are relatively small. However, the improvements in the forecasts of the moisture field, another important component connected to clouds, are significant. A typical example is from the storm case on 13 March 1993 (see Fig.5 and Fig. 6). Figure 11 shows the cross–sections of moisture forecast errors through the center of the storm from the control run and the cloud scheme experiment. The control run underpredicted the moisture field in regions in front of the storm, and overpredicted the moisture field in the central part of the storm above 600 kPa and in the area below 700 kPa just behind the storm center. Those errors, however, have been significantly reduced by the cloud scheme. The most significant improvements in moisture forecast, however, are in the areas downstream from the storm. It was found that cloud particles from

Q(24h–fcst, cloud+new rad.) – Q(anly)

Valid Time=12Z 3/13/93, Lat.=33 ^{o}N, Contour Int.=0.5 g/kg



Q(24h–fcst, opnl) – Q(anly)

Valid Time=12Z 3/13/93, Lat.=33 ^{o}N, Contour Int.=0.5 g/kg

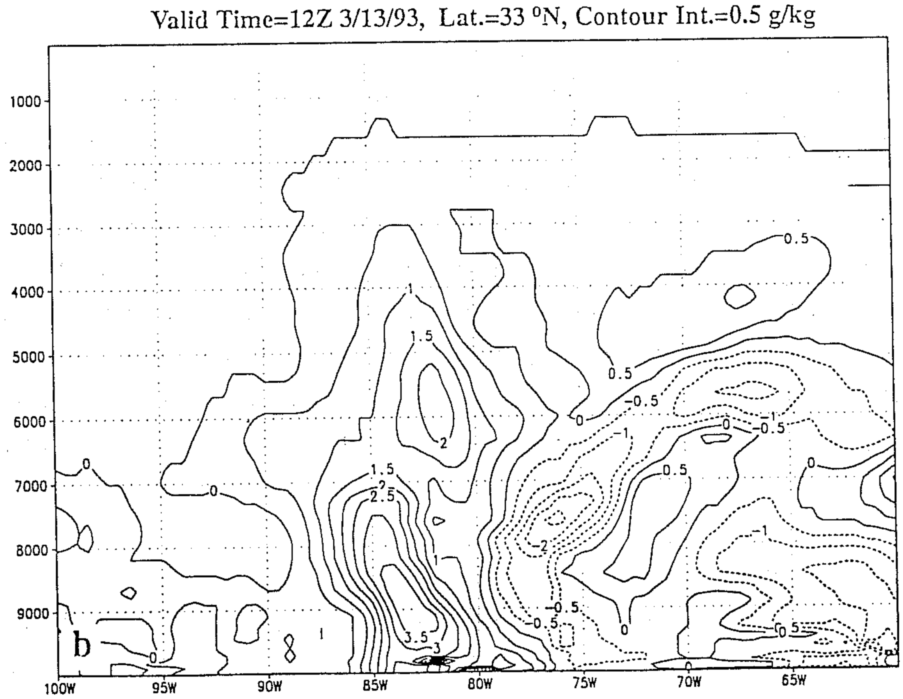


Fig.11 Cross–section of 24–hour specific humidity forecast errors (forecasts minus analyses) from the 40 km Eta Models (a) with explicit cloud scheme and (b) without explicit cloud scheme valid at 1200 UTC 13 March 1993 at latitude of 33 oN. Contour interval is 0.5 (g/kg).

the storm were advected into these areas by the strong winds and then evaporated there resulting in increased moisture in these areas.

Daily verification of moisture profiles from the forecasts has been done by comparing them with the radiosonde data over the continental U.S. during September 1994. RMS errors were computed at pressure levels and are given in Fig.12. Although the vertical distributions of the RMS errors from both model runs are basically the same, improvements in moisture forecasts by the cloud scheme can be found at levels below 800 kPa and above 550 kPa. As mentioned before, the scheme's describing the more rapid moisture deposition onto ice particles rather than only condensation onto liquid water droplets could be an important factor in the moisture forecast improvements at upper levels. The improvements near the surface reflect the effects of the improved parameterization of large–scale condensation of clouds and the better treatments of precipitation evaporation below cloud bases.

4 CONCLUSIONS

A description of the cloud prediction scheme in the Eta Model has been provided along with results from recent experiments and parallel tests. As a new predictive variable, cloud water/ice introduced in the model greatly improves the hydrological cycle and hence improves moisture and precipitation forecasts. More realistic cloud predictions are important not only because of their effects on the radiation calculations, but also because of the consequences of transport and storage of the condensed water substances. The primary microphysical processes associated with precipitation production are also important in transferring water mass from one phase to another. The inclusion of cloud ice, the horizontal advection of clouds and the better description of precipitation evaporation are shown to play an important role in the improved cloud, precipitation and moisture forecasts.

It has been found that the lack of initialization of cloud fields in the current cloud scheme causes "spinup" of clouds in the first 12 hours of the model integration, and as a result, affects the model forecasts of other variables during this period. More efforts are needed to incorporate cloud information into the Eta Data Assimilation System at NCEP. Further improvements in model forecasts can be expected from the improved cloud initial conditions.

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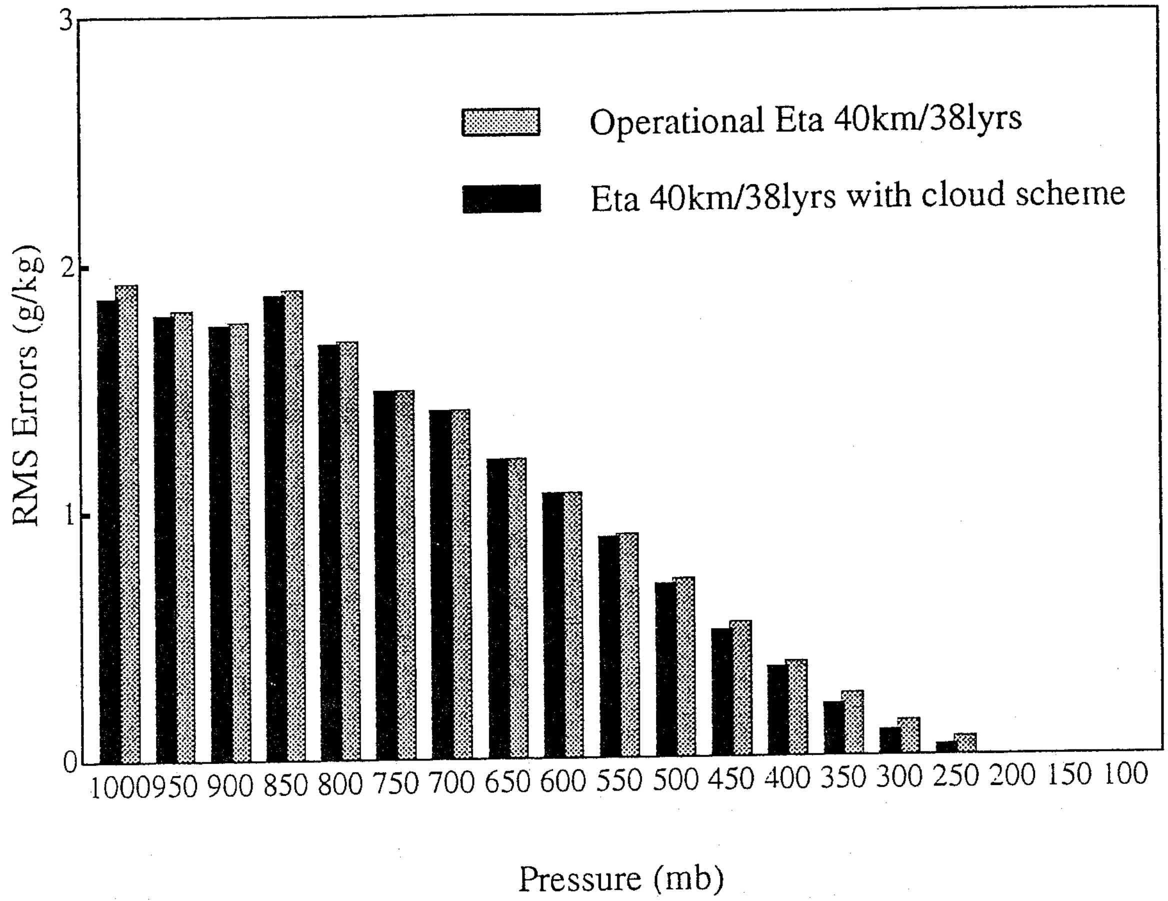

Fig.12 RMS errors of the 24–hour specific humidity forecasts at pressure levels from the 40 km Eta Model with and without explicit cloud scheme for September 1994.

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