ON THE SENSITIVITY OF PRECIPITATION FORECASTS TO THE MOIST PHYSICS AND THE HORIZONTAL RESOLUTION OF NUMERICAL MODEL*

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ABSTRACT

The impacts of the enhanced model's moist physics and horizontal resolution upon the QPFs (quantitative precipitation forecasts) are investigated by applying the HIRLAM (high resolution limited area model) to the summer heavy-rain cases in China. The performance of the control run, for which a 0.5°×0.5° grid spacing and a traditional "grid-box supersaturation removal+Kuo type convective paramerization" are used as the moist physics, is compared with that of the sensitivity runs with an enhanced model's moist physics (Sundqvist scheme) and an increased horizontal resolution (0.25°×0.25°), respectively. The results show:

(1) The enhanced moist physics scheme (Sundqvist scheme), by introducing the cloud water content as an additional prognostic variable and taking into account briefly of the microphysics involved in the cloud-rain conversion, does bring improvements in the model's QPFs. Although the deteriorated QPFs also occur occasionally, the improvements are found in the majority of the cases, indicating the great potential for the improvement of QPFs by enhancing the model's moist physics.

(2) By increasing the model's horizontal resolution from 0.5°×0.5°, which is already quite high compared with that of the conventional atmospheric soundings, to 0.25°×0.25° without the simultaneous enhancement in model physics and objective analysis, the improvements in QPFs are very limited. With higher resolution, although slight amelioration in locating the rainfall centers and in resolving some finer structures of precipitation pattern are made, the number of the mis-predicted fine structures in rainfall field increases with the enhanced model resolution as well.

Key words: quantitative precipitation forecasts (QPFs), moist physics, resolution, HIRLAM model (high resolution limited area model), heavy rain in China

I. INTRODUCTION

During the last two decades, great progresses have been made in numerical weather

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forecasting due to the rapid increases in computer power and the improvements in algorithms for the objective analysis, initialization, model integration and parameterization of the sub-grid physical processes. Now not only has the numerical forecasting of the large-scale circulation become main guidance for the routine operational weather forecasting practice, the numerical products of QPFs (quantitative precipitation forecasts) but also have important value for the weather forecasters. However, generally speaking, the accuracy and the lead time of numerical QPFs are still far from being satisfactory. On one hand, we can not expect the numerical forecasting for the precipitation to have the same quality as for the large-scale circulation. Here it concerns the predictability. The spatial distribution and the central intensity of rainfall depend not only on the large-scale environment, but also to a great extent on the immediate precipitation-producing weather systems which mostly are in mesoscale or small-scale, especially in convective precipitation cases. Therefore, the upper limit of predictability for the rainfall is much inferior to that for the large-scale circulation. That is, the numerical forecasting for precipitation has larger intrinsic uncertainty than the forecasting for the large-scale circulation. On the other hand, we believe that there is still a great gap between the current state-of-the-art and the intrinsic predictability upper limit of numerical QPFs, the room for improvements is large. One of the important aspects which need to be enhanced in order to improve QPFs is the sub-grid scale process parameterization, particularly the moist physics. It is known that, in a NWP (Numerical Weather Prediction) model, the treatment of the dynamic part is quite rigorous while the treatment of the physical part (i. e., sub-grid process parameterization) is relatively crude. The reasons for the relatively poor representation of the sub-grid processes in a NWP model are as follows: (1) The effects of the sub-grid processes upon the grid variables can not be uniquely determined by the grid variables themselves, some closure assumptions must be made in order to close the equation set. This is a major limitation of parameterization; (2) Lack of good understanding for the interactions between the sub-grid and grid-resolved processes; (3) The computer is not powerful enough to give a more accurate representation of the sub-grid processes. With the rapid increase in computer power and the progress made in understanding the interactions between the atmospheric motions of various scales, it is possible to give a more physics-based and more accurate representation of the sub-grid processes. As a consequence, the uncertainties caused by the above-mentioned second and third reasons can be reduced. In order to improve the numerical QPFs, another important aspect to be enhanced is the objective analysis which provides the initial field for model integration, especially the analysis for the initial moisture field. In this paper, we will discuss the sensitivity of the performance of numerical QPFs to the parameterization of moist physics. Besides, we will also make a brief discussion on the impacts of a further enhanced horizontal resolution upon rainfall forecasts when the original resolution is already relatively high compared with that of the conventional radiosonde network. The limited-area numerical weather forecasting system of the Nordic countries, HIRLAM (high resolution limited area model) was used in this study, with several summer heavy-rain events in China selected as rainfall cases.

II. MODEL DESCRIPTION AND EXPERIMENT DESIGN

HIRLAM (Machenhauer 1988) is a limited-area primitive equation model with u, v, T (temperature), q (specific humidity), P_s (surface pressure), and an additional scalar variable (could be the "cloud water mixing ratio" or other variable) as prognostic variables, staggered on the Arakawa C grid. A rotated latitude-longitude horizontal grid and a hybrid sigma-pressure vertical coordinate are used. A semi-implicit time stepping scheme is used for the model integration. The horizontal diffusion in the model is a linear fourth order scheme. The initialization scheme is the implicit adiabatic nonlinear normal mode technique based on Machenhauer's (1977) idea. As the lateral boundary scheme, the simplified Davies (1976) relaxation technique is used to relax the model's variables towards externally specified time dependent values (in this study these values taken from ECMWF analysis) within a narrow boundary zone. The HIRLAM system has its own data assimilation cycle of 6-h period, with the optimal interpolation (OI) technique as analysis scheme. The model contains a comprehensive physics parameterization package for vertical diffusion (turbulence), radiation, condensation and precipitation (moist physics), and surface processes (land-air or sea-air interaction).

The scheme for the condensation and precipitation parameterization varies from model to model, and in general the convective and stratiform precipitations are treated separately. There are two options for the precipitation parameterization in the HIRLAM model. One is the traditional "grid-box supersaturation removal + Kuo type convective parameterization (Kuo 1974)". The other is the Sundqvist scheme (Sundqvist et al. 1989; Sundqvist 1993). In the latter one, the liquid water content of both convective and stratiform clouds is included into the model as a prognostic variable. In regard to the treatment of convective precipitation, the Sundqvist scheme retains the basic features of the Kuo scheme (e. g. the closure assumption and trigger mechanisms) except the inclusion of the cloud water as a prognostic variable and the modification of the vertical moistening and heating functions by considering the evaporation of cloud water entrained into the environment. The key part of Sundqvist scheme is a cloud-precipitation conversion formulation in which the main microphysical processes concerning the condensation and the precipitation, such as the auto-conversion, coalescence and Bergeron-Findesen mechanism are parameterized in a highly simplified way. Besides the cloud water content, the Sundqvist scheme can also give the fractional cloud cover within a grid area by diagnostic relations.

The experiment design is shown in Table 1. CONL, SUND and ENHR represent the control experiment (with the "grid-box supersaturation removal + Kuo type convective parameterization" as moist physics scheme), the experiment with Sundqvist scheme and the experiment with enhanced horizontal resolution, respectively. To evaluate the rainfall forecasts, the predicted 0—24 h or 24—48 h accumulated precipitation is compared with the corresponding observed 24 h rainfall. Two points are emphasized in the comparisons: one is the consistency between the predicted and observed precipitating areas enclosed by the 10 mm 24 h rainfall isogram, concerning its orientation, shape, position and extent; the other is the consistency between the predicted and observed positions of the heavy-rain (heavy-rain defined as 24 h rainfall exceeding 50 mm) centers.

Table 1. Experimental Design

Experiment	CONL	SUND	ENHR
Forecast domain and grid resolution	65—145.5°E, 12.5—62°N; 0.5°×0.5°	65—145.5°E, 12.5—62°N; 0.5°×0.5°,	80—120.5°E, 12.5—56°N ; 0.25°×0.25°
N. of vertical levels	31	31	31
Time step	150 s	150 s	120 s
Lateral boundary condition	ECMWF analysis (1.5°×1.5°)	ECMWF analysis (1.5°×1.5°)	HIRLAM analysis (0.5°×0.5°)
Moist physics parameterization	gridscale diagnostic +Kuo scheme	Sundqvist scheme	gridscale diagnostic +Kuo scheme
Initial field	HIRLAM analysis (0.5°×0.5°)	HIRLAM analysis (0.5°×0.5°)	HIRLAM analysis (0.25°×0.25°)

III. RESULTS AND DISCUSSION

1. *Impacts of the Enhanced Moist Physics*

Compared with the traditional "grid-box supersaturation removal + Kuo-type convective parameterization", a further step is made with the Sundqvist scheme towards the physical reality by including the cloud water content as an additional prognostic variable. Besides providing the condensation heating, moistening and precipitation, Sundqvist scheme also gives the cloud water content and cloud amount in the sky. Otherwise, the last two variables, which are needed in the calculation of the cloud-involved radiation heating, can only be estimated separately by a very crude empirical formula. Hence, with Sundqvist scheme, the better internal consistency of model is obtained. However, the gain in model's internal consistency does not guarantee that the numerical QPFs will be equally improved, and the conclusion can only be drawn after careful cases study.

The first selected case is a series of heavy rain events during the 1991 summer's severe flooding period in the middle and lower reaches of Changjiang River. A well developed southwestern vortex (SW-vortex) moved northeastward along the southwest-northeast oriented Meiyu front and caused heavy rains along its track. Figure 1a shows the observed 24 h accumulated precipitation during the period from 0000 GMT 05 July to 0000 GMT 06 July 1991, and the corresponding 0—24 h accumulated rainfall predictions made in CONL and SUND runs are shown in Figs. 1b and 1c, respectively. In CONL, although the distribution pattern and the amount of the 24 h rainfall were generally well predicted, several faults can still be noticed. The most marked fault is that the predicted rainfall area between 113°E and 120°E extends too northwards. This problem was completely cured in SUND run in which the Sundqvist scheme was used. Another fault in CONL run is the mis-prediction of a rainfall zone over the southeastern flank of the Qinghai-Xizang Plateau, which was also alleviated to a great extent in the corresponding SUND run.

The observed and predicted accumulated precipitations for the following 24 h (0000 GMT 06 July—0000 GMT 07 July 1991) are shown in Fig. 2. First, we examine the 0—24

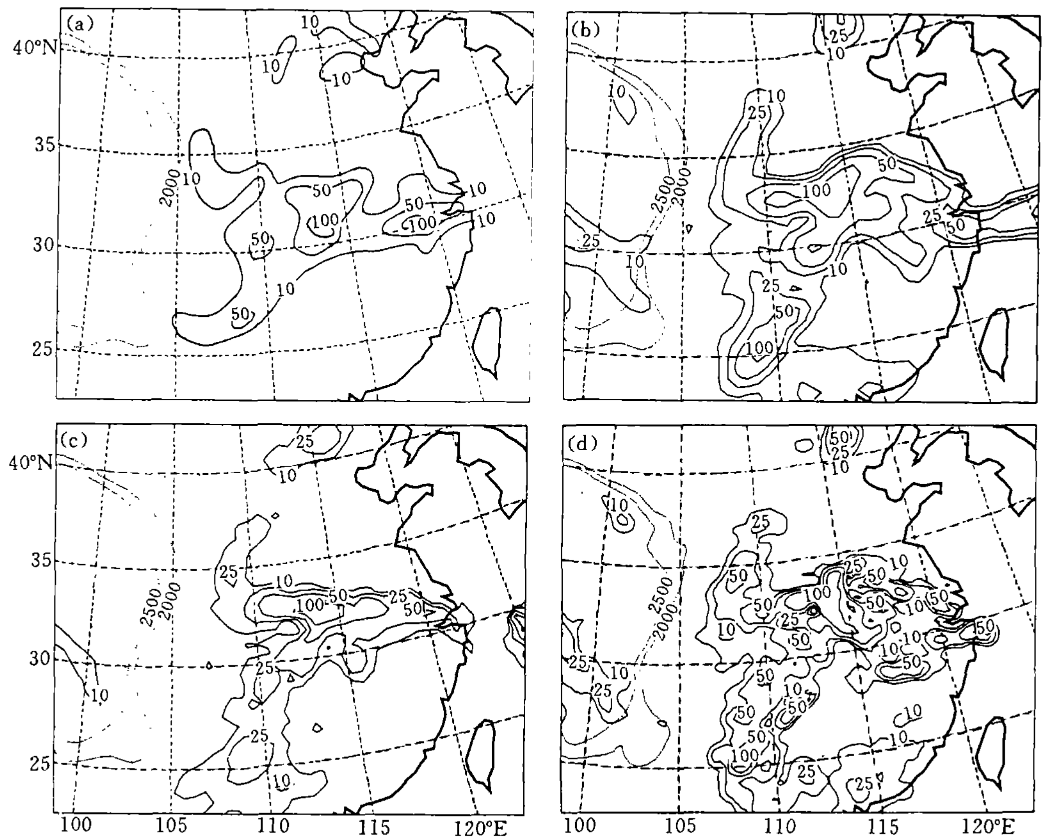

Fig. 1. The 24 h accumulated rainfall (mm) (0000 GMT 05 — 0000 GMT 06 July 1991). (a) Observed; (b) 0—24 h forecast for CONL run; (c) 0—24 h forecast for SUND run; (d) 0 —24 h forecast for ENHR run. The 2000 m and 2500 m terrain contours are drawn with dotted line.

h accumulated rainfall forecasts. The observed northeast-southwest oriented main rainfall zone (Fig. 2a), which extends more than 2000 km from northern part of Jiangsu Province to Guangxi Province, was well reproduced with CONL (Fig. 2b) with regard to its orientation, position, shape and extent. However, there is a failure with CONL in reproducing the right position of the observed strongest rainfall centre (33. 5°N, 120°E, Fig. 2a) within the main rainfall zone. It is encouraging to note that the relative large errors in locating the strongest rainfall center in CONL run was greatly reduced in SUND run (Fig. 2d). The large improvement was also made with SUND in locating the second maximum rainfall center (30. 5°N, 118°E, Fig. 2a) over the corresponding CONL run. Furthermore, the observed narrow rainfall zone over the eastern edge of the Qinghai-Xizang Plateau, with its southern part connecting with the main rainfall zone, was also better predicted in SUND than in CONL. Although this narrow rainfall zone was predicted by CONL, it is completely separated with the main rainfall zone. The observed attachment between two rainfall zones, which is missing in CONL, is recovered in SUND. Evidently, this 0—24 h accumulated rainfall forecast (Fig. 2d) made in SUND run is very successful.

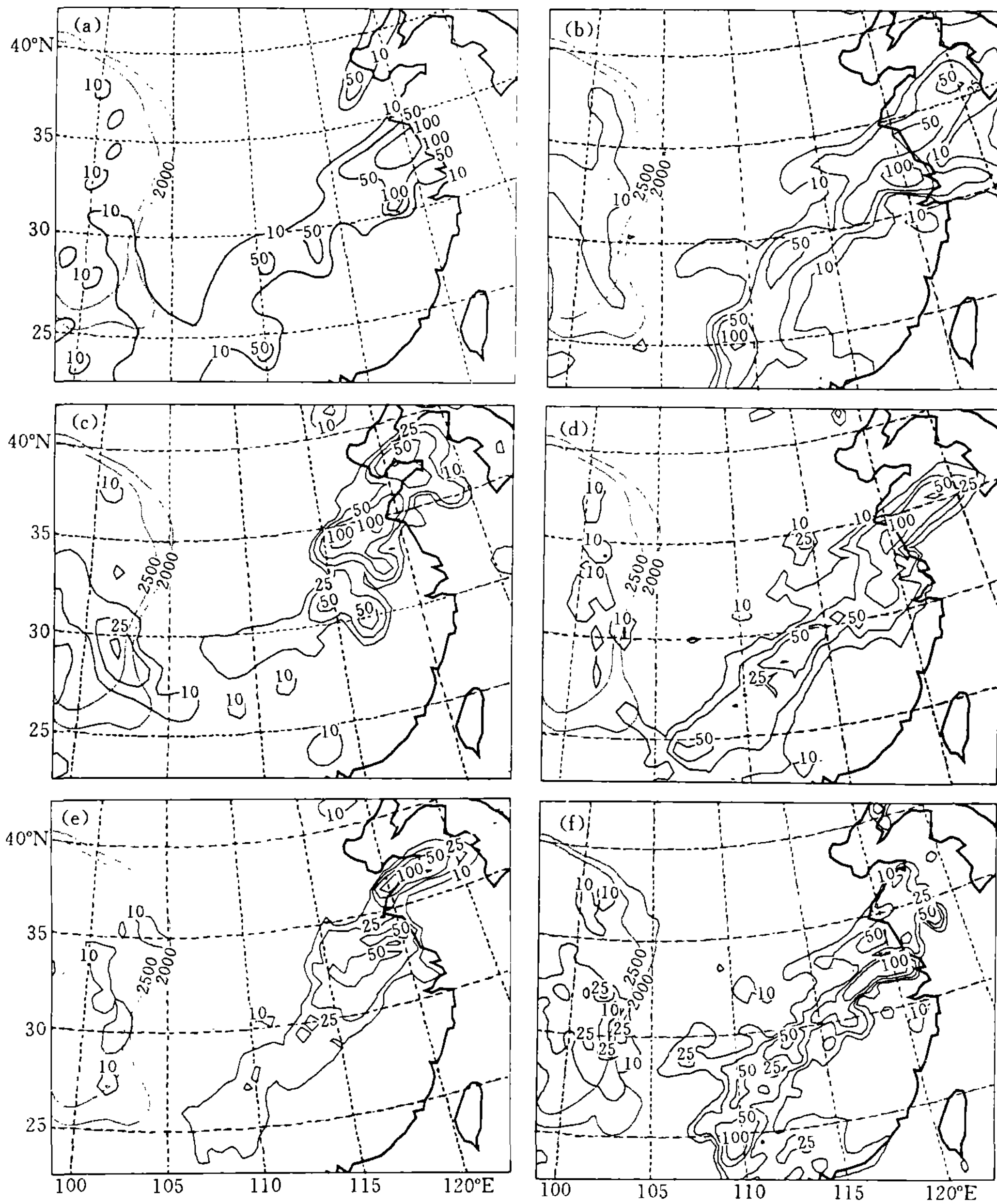

Fig. 2. The 24 h accumulated rainfall (mm) from 0000 GMT 06 July to 0000 GMT 07 July 1991. (a) Observed; (b) 0—24 h forecast for CONL run; (c) 24—48 h forecast for CONL run; (d) 0—24 h forecast for SUND run; (e) 24—48 h forecast for SUND run; (f) 0—24 h forecast for ENHR run.

Figures 2c and 2e show the 24—48 h accumulated precipitation forecasts made with CONL and SUND, respectively. Compared with their 0 — 24 h counterparts, a much deteriorated quality is observed in both runs, though some important features of the observed rainfall are still captured by them. We can note that in SUND marked improvements were made over the corresponding CONL run, in regard to the orientation,

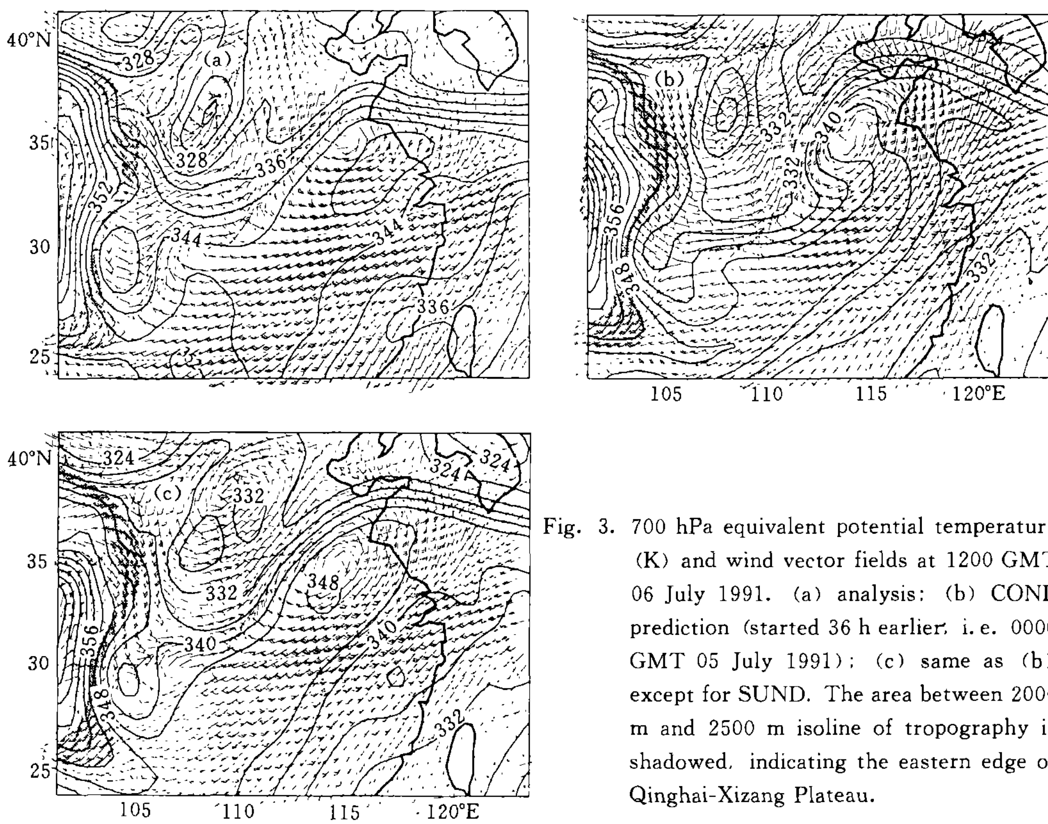

Fig. 3. 700 hPa equivalent potential temperature (K) and wind vector fields at 1200 GMT 06 July 1991. (a) analysis; (b) CONL prediction (started 36 h earlier, i. e. 0000 GMT 05 July 1991); (c) same as (b) except for SUND. The area between 2000 m and 2500 m isoline of tropography is shadowed, indicating the eastern edge of Qinghai-Xizang Plateau.

the position and the shape of the observed main rainfall zone as well as the position of the strongest rainfall center. These improvements in precipitation forecast are partly the result of the amelioration in the forecast of the Meiyu front structure by using the Sundqvist scheme (Fig. 3). A mis-prediction was made with CONL of a dry-and-cold tongue extending through the middle of the Meiyu front towards warm zone (Fig. 3b) and the position of Meiyu front in the eastern edge of the continent was also predicted too northwards. The problem of mis-prediction of a dry-and-cold tongue in CONL was completely removed in SUND (Fig. 3c), and the too northwards position of Meiyu front at the eastern edge of the continent in CONL was also largely alleviated in SUND. Consequently, as mentioned above, the corresponding 24—48 h accumulated precipitation forecast was largely improved in SUND compared with that in CONL.

As shown above, three forecasts of 24 h accumulated rainfall (two 0—24 h and one 24—48 h) have been compared between CONL and SUND for the 1991 summer heavy rain case, the results indicate the significant positive impacts upon the rainfall forecasting by introducing a prognostic cloud scheme (Sundqvist scheme).

The second selected heavy rain case occurred during the period from July 14 to July 15, 1993. The main rainfall area was a narrow zone, extending from the western Sichuan Basin towards northeast (Fig. 4a). The main rainfall center was located at the western part of the Sichuan Basin with an extreme value of 153 mm (for 24 h). From northeast end of the main rainfall zone towards the southeast, several small rainfall cores, which

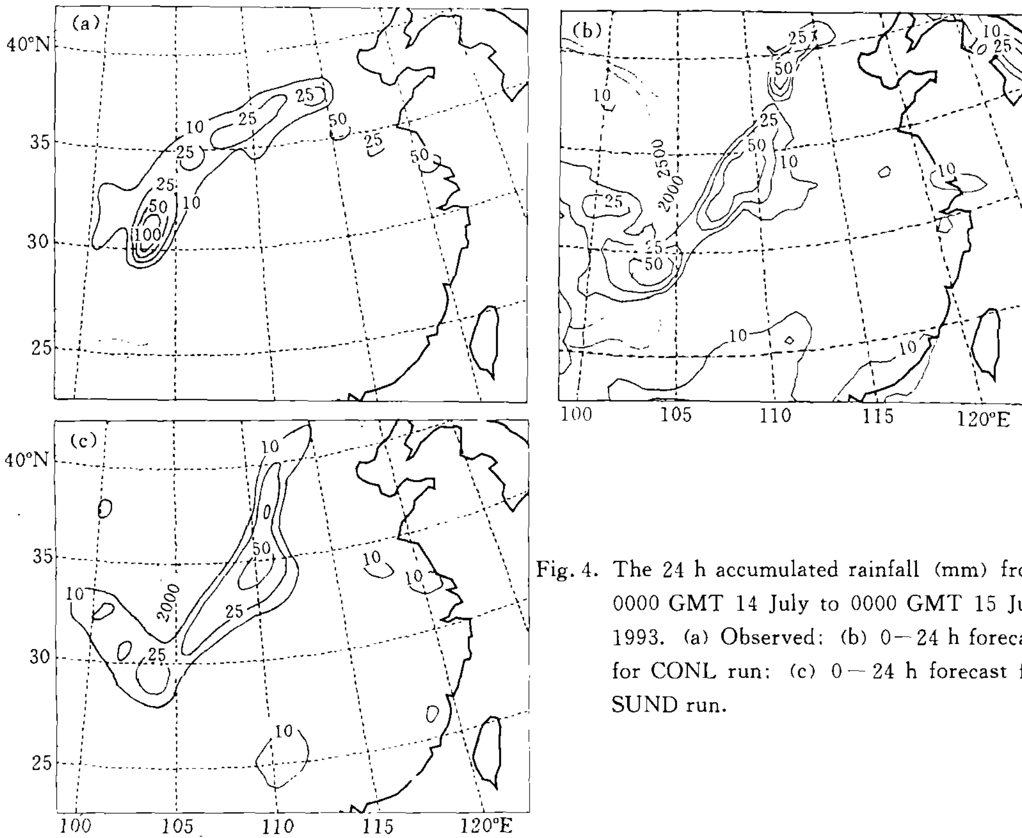

Fig. 4. The 24 h accumulated rainfall (mm) from 0000 GMT 14 July to 0000 GMT 15 July 1993. (a) Observed; (b) 0—24 h forecast for CONL run; (c) 0—24 h forecast for SUND run.

evidently were produced by strong convective cells, ranked in a line. This heavy rain event occurred when an eastward-moving upper-level trough was blocked over the eastern edge of the Qinghai-Xizang Plateau by the intruding subtropical high, causing the rainfall-producing wind shearline (which was associated with Meiyu front) confined to a southwest-northeast oriented narrow zone in front of the upper-level trough. The heaviest rainfall over the western Sichuan Basin was mainly produced during a 6 h short period from 1800 GMT 14 July to 0000 GMT 15 July, localized within a small area. Both CONL and SUND (Figs. 4b and 4c) were able to predict a main rainfall zone extending from the Sichuan Basin toward northeast, which is partly consistent with the observation. To the east of the main rainfall zone, the observed isolated rainfall cores were also marginally predicted by CONL and SUND. However, in both CONL and SUND failure was made in reproducing the shape of the observed main rainfall zone which bends to northwest while the predicted rainfall zone in both CONL and SUND bends to southeast, with an over-estimation of rainfall amount in the central part of rainfall zone. As to the northern part of the observed main rainfall zone where the maximum rainfall center (with a 24 h rainfall more than 100 mm) was located, although both CONL and SUND were able to predict a rainfall core there, its intensity is largely under-estimated, especially in SUND run, and its location is more than 150 km north-shifted. For the forecasting of this rainfall case, it is seen that SUND shows no improvement over CONL, and even has a degraded quality with regard to reproducing the intensity of the observed maximum rainfall center.

Our last heavy rain case occurred during the period of July 18 — 19, 1993. The observed 24 h rainfall pattern is shown in Fig. 5a. The east-west oriented main rainfall zone which consists of four separated rainfall areas is along the middle and lower reaches of Changjiang River Valley. To the west of this main rainfall zone, there are three isolated rainfall cores ranking in an arc shape, extending from the Yunnan-Guizhou Plateau to the east edge of the Qinghai-Xizang Plateau. The corresponding atmospheric circulation background is that two upper-level short troughs passed over the Meiyu front along the Changjiang River Valley successively, and to the southwest of the Meiyu front a Southwest vortex maintained with its center located at the northeastern part of the Sichuan Basin. The 24 — 48 h prediction of the 24 h accumulated rainfall by CONL (Fig. 5b) is disappointing. Although a rainfall zone is predicted along the Changjiang River Valley, which is partly in agreement with the observation, the observed maximum rainfall center located at 30°N, 110°E and two other heavy rain centers in the lower reach of the Changjiang River were totally missed in the CONL's 24—48 h rainfall forecast, and there is a large exaggeration, both in amount and in extent, of the observed rainfall over the Yunnan-Guizhou Plateau and the eastern Qinghai-Xizang Plateau. The corresponding 24 — 48 h rainfall prediction made with SUND shows marked improvement compared with CONL, the facts are that the observed heavy rainfall cores (near 30°N, 120°E) reproduced in SUND are missed in CONL in the lower reach of the Changjiang River, and though the

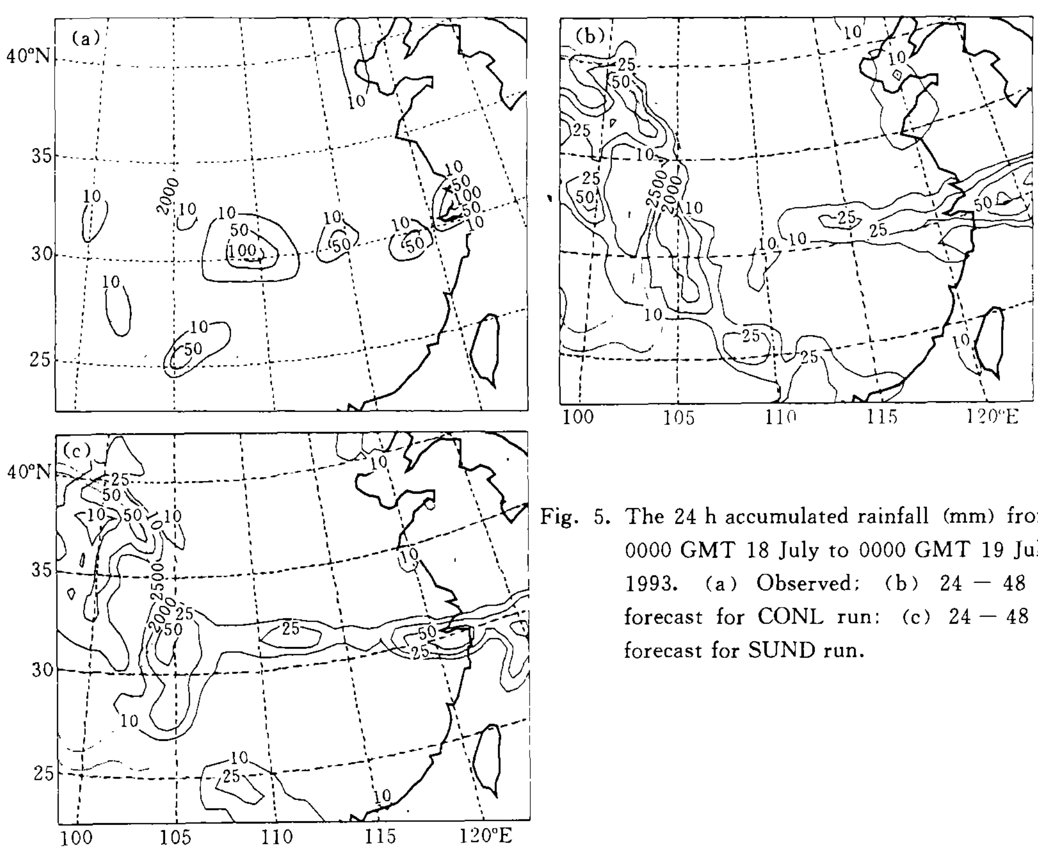

Fig. 5. The 24 h accumulated rainfall (mm) from 0000 GMT 18 July to 0000 GMT 19 July 1993. (a) Observed; (b) 24 — 48 h forecast for CONL run; (c) 24 — 48 h forecast for SUND run.

observed maximum rainfall center around 30°N, 110°E is also missed in SUND, but some amelioration can be found compared with CONL. With regard to the rainfall areas over the Yunnan-Guizhou and the eastern Qinghai-Xizang Plateaus, no improvements are made in SUND over CONL, the rainfall amount and extent are still largely over-estimated.

It is seen from the above comparisons between CONL and SUND runs that the Sundqvist scheme, in which the cloud water content is included as a prognostic variable and the microphysics involved in the condensation-cloud-precipitation processes is taken into account briefly, can indeed bring improvements to model's performance in rainfall forecast. Sometimes the improvement is marked, sometimes it is less marked, and even we can find the case where a slightly deteriorated forecast is made by using the Sundqvist scheme. On the whole, however, the improvements are found in the majority of cases, indicating the great potential for the improvement of numerical QPFs by enhancing the model's moist physics parameterization. This conclusion has already been reached by HIRLAM research groups of Nordic countries after comparisons being made between the run with traditional moist physics and the run with Sundqvist scheme over the Europe region. We just further confirmed this conclusion for the summer heavy-rain cases in China. The strikingly good agreement between the observed 24 h rainfall and the corresponding 0—24 h accumulated precipitation predicted in SUND for the period from 0000 GMT 06 July to 0000 GMT 07 July 1991 is very impressive (see Figs. 2a and 2d) and encouraging. It is worthy to point out that if the Sundqvist scheme is used in the prediction, it should also be used in the data assimilation cycle where a 6 h forecast is done to provide the first guess for the analysis of initial field. Otherwise, the cloud water content at initial time will be zero, leading to possible delayed precipitation caused by spin-up problem.

The Sundqvist's original motive, when he proposed his scheme, was to provide a parameterization for condensation-cloud-precipitation processes in a more physics-based and internally-consistent way in which the heating and moistening profile of condensation, precipitation amount, cloud water content and the cloud cover are all given by a single scheme, rather than determining the last two parameters, needed in the radiation calculation, by a separate empirical formula. Although the enhanced internal consistency does not guarantee the improvement of model's performance in rainfall forecast, the rainfall forecasts have been actually ameliorated in most cases when the traditional moist physics scheme is replaced by the Sundqvist scheme, as mentioned above. This fact can be partly attributed to the enhanced model's running ability on moist physics parameterization when the cloud water content is included as a prognostic variable. In the traditional parameterization scheme of moist physics, the liquid water falls out immediately as precipitation when condensation occurs, while in the Sundqvist scheme, water vapor first condenses into cloud, and cloud is then converted to precipitation, nearer to the real processes in nature. By changing the characteristic time scale and the threshold value of cloud-precipitation conversion in the Sundqvist scheme, the timing and intensity of precipitation can be adjusted within certain range. As a consequence, the rainfall forecasts can be improved to a certain extent in this way. It is evidently impossible to adjust the timing and intensity of precipitation in this way with a traditional moist physics parameterization.

Besides including the cloud water content as a prognostic variable, Sundqvist scheme retained the basic assumptions of Kuo scheme (Kuo 1974) of convection parameterization, the only modification introduced is concerning the convective heating and moistening vertical profile by taking into account of the evaporation of cloud droplets entrained into the environment. The Kuo scheme has been frequently found to remove too much moisture in the lower troposphere, causing the excessive drying in the lower layers of the model (Belair and Zhang 1994), while the Sundqvist scheme, by including an additional cloud entraining term in the convective heating and moistening formulation besides retaining the original Kuo's term, tends to alleviate the over-drying problem. The added entrainment term is proportional to the cloud water content, so including the cloud water content as a prognostic variable preconditions the above mentioned modification of Kuo scheme.

Before becoming a formal option of moist physics scheme in HIRLAM model, the Sundqvist scheme had experienced extensive and delicate tunings. Once the appropriate values for all parameters in Sundqvist scheme are found by tuning, they are quite universal. No further tuning efforts were attempted when the HIRLAM model was applied to the heavy rain cases in our current study. It is of interest to point out that the parameters in the Sundqvist scheme can be only adjusted to their optimal values in statistic sense. That means, they will be appropriate in most cases, but can be inappropriate in some cases. This explains, at least partly, why the model run with the Sundqvist scheme sometimes even results in deteriorated rainfall forecast compared with the run with traditional moist physics scheme. Anyway, the fact is that, by using the Sundqvist scheme, not only is the model's internal consistency enhanced, but also the rainfall forecasts are improved in most cases as well. It is a success indeed. Besides, the Sundqvist scheme is robust with regard to the numerical stability and is also relative simple without requiring too much increase in computer time (only 20% of increase). In recent years, it has been received extensive attention in European meteorological circle.

As mentioned above, the Sundqvist scheme retains the basic assumptions of Kuo scheme in regard to the convection parameterization. However, it is equally possible to include the other type of convection parameterization within the main frame of Sundqvist scheme. Tiedtke (1993) included cloud water content as a prognostic variable into the moist physics scheme of the operational ECMWF global model whose convection scheme was a mass-flux type developed by himself (Tiedtke 1989). For the microphysical processes involved in the cloud-precipitation conversion, he adopted the Sundqvist's formulation, and we can say that this scheme is a combination of Sundqvist type condensation-cloud-precipitation scheme with the Tiedtke's convection parameterization of mass-flux type. The comparison experiments have shown that the enhanced moist physics with this prognostic cloud scheme does bring an increase in model's forecasting skills (Tiedtke 1993). This new version of the ECMWF model's moist physics scheme has been the operational scheme since 1995.

2. *Impacts of a Higher Horizontal Resolution*

The great progress made in NWP (numerical weather prediction) during the last two decades owes a great deal to the enhancement of horizontal resolution , which has been made possible by the rapid increase in computer power. The practice of NWP has shown that large improvements can be made in rainfall forecasts with a fine mesh model over that with a coarse mesh model. However, we will discuss a quite different situation here, that is, when the model's resolution is already relatively high (e. g., $0.5° \times 0.5°$ in CONL) with regard to the conventional observation network, what will be the impacts on model's performance in rainfall forecasts by further enhancing model's resolution (e.g., $0.25° \times 0.25°$ in ENHR).

First, we examine the 0—24 h accumulated rainfall predictions for the period from 0000 GMT 05 July to 0000 GMT 06 July 1991. The position, orientation, shape and extent of the main rainfall zone predicted by ENHR (Fig. 1d) are in good agreement with those predicted by CONL (Fig. 1b). The heavy rain centers in CONL also correspond well to those in ENHR. It is worthy to note that, compared with CONL, the ENHR's prediction for rainfall pattern shows finer structures, and some of these finer structures have no correspondences in the observation (Fig. 1a). For this 0—24 h accumulated rainfall prediction, ENHR made no improvement at all over CONL. Now we look into the 0—24 h predictions of the 24 h accumulated precipitation during the following 24 h (i.e., from 0000 GMT 06 July to 0000 GMT 07 July 1991). Although no marked improvements have been made, some subtle amelioration can be found in ENHR (Fig. 2f) compared with CONL (Fig. 2b). Within the observed main rainfall zone (Fig. 2a), two separated heavy-rain areas (24 h rainfall exceeding 50 mm) lie between 27—30°N and 110—115°E. CONL only forecasts an elongated zone of heavy-rain instead of two heavy rain cores in observation, while in ENHR both two heavy-rain cores are reproduced. Furthermore, the location of another observed heavy rain center at 24°N, 110°E is slightly better predicted in ENHR than in CONL. We also notice an increase in the number of fine structures in rainfall field predicted by ENHR compared with CONL, and some of these fine structures are not found in the corresponding observation. Hence, when the relative high resolution (with regard to conventional observation network) of a NWP model (e.g., $0.5° \times 0.5°$) is further enhanced (e.g., to $0.25° \times 0.25°$), the improvement in rainfall forecasts is very limited. The enhanced model resolution leads to an increase in fine structures of predicted rainfall pattern. Some of these increased fine structures are in agreement with observation, indicating the slight improvements brought by the enhanced resolution, while others have no correspondences in the observation, that means, an increase in false fine structures is also produced as a high model resolution is further enhanced.

The enhanced resolution will reduce the truncation errors of a NWP model and weather systems of smaller scale can be resolved as well, this is the benefits of using a higher resolution in model. For QPFs, a higher resolution can lead to the improvements in locating rainfall centers and in reproducing finer structures of observed rainfall pattern, etc. In these aspects, our case study shows that ENHR does have a slightly better performance than CONL, but on the whole, the improvement of ENHR over CONL is not large. It is noted in our case that the number of the mis-predicted fine structures of rainfall pattern increases with the higher horizontal resolution in the model, this may be partly attributed to the little improvement in the initial field of ENHR over that of CONL. To obtain the initial field for model integration, the same observed data from conventional observation network have been used in the analysis procedure for both CONL and ENHR. As mentioned above, the CONL's horizontal resolution $0.5°\times0.5°$ is already quite high compared with the density of the conventional observation network, and when it is further enhanced to $0.25°\times0.25°$ in ENHR, it is difficult for the analysis procedure to extract more information from the observed data (by contrast, more information can be easily extracted from the observed data when the resolution raises, say, from $2.5°\times2.5°$ to $1.0°\times1.0°$). Moreover, the further enhanced resolution can also lead to an increase in analysis errors for the smaller scale systems newly resolved by the higher resolution run, due to the relative coarse network of the conventional observation, generating more irregular small scale noises in the forecast fields. The above mentioned increase in the number of mis-predicted fine structures of rainfall pattern with enhanced resolution is evidently related to these increased irregular small scale noises. Hence, in order to reduce the analysis errors for the newly resolved smaller scale systems when a higher resolution is used, a denser observation network should be set up. The most practical way to do it lies in making use of the non-conventional observations such as satellite and radar data. The current widely-used OI technique for objective analysis has serious limitations for the assimilation of non-conventional data. The most promising substitution for OI is the four dimensional variational data assimilation technique (4DVAR), which will become operational at ECMWF in near future. The main advantage of 4DVAR analysis procedure consists in its ability to tackle the problem of nonlinearity between the some observation (such as radiance measured by satellite and the observed precipitation) and model state variables (such as T, q, p, u, v), and the problem of flow-dependent prediction error structure (Thepaut et al. 1993). Kuo et al. (1996) and Zou and Kuo (1996) 's results show that with the satellite estimated precipitable water and the rainfall observations being included in the 4DVAR analysis procedure, the QPFs can be largely improved. Another important point to emphasize is that when the relative high resolution of a NWP model is enhanced further as in our case, the moist physics scheme will better be enhanced accordingly in order to make non-trivial improvements. According to Belair and Zhang (1994), the Kuo type scheme of convective parameterization is not suitable for the simulation of meso-β scale weather systems, and it is better to use the convective parameterization based on CAPE (convective available potential energy) when the model's horizontal resolution lies between 10—30 km. The Fritsch-Chappell (Fritsch and Chappell 1980) scheme and its modified version—the Kain-Fritsch (Kain and Fritsch 1990) scheme are the examples of such kind scheme.

It is possible that the above mentioned increase in the number of the false fine structures of the predicted rainfall field with higher resolution may also be related to the fact that the predictability of atmospheric systems is reduced with the decrease of their scales. The higher a model's resolution is, the smaller the scale of smallest systems resolved by the model will be. As a consequence, the predictability limit corresponding to these smallest scale systems will be shorter. To what extent this mechanism can affect model's prediction of the fine structures in rainfall field is worth further researching.

IV. CONCLUSIONS

The results of the above sensitivity study show:

(1) The enhanced moist physics scheme (Sundqvist scheme), by introducing the cloud water content as an additional prognostic variable and taking into account briefly of the microphysics involved in the cloud-rain conversion, does bring improvements in the model's QPFs. Although the deteriorated QPFs also occur occasionally, the improvements are found in majority of cases, indicating the great potential for the improvement of QPFs by enhancing the model's moist physics.

(2) By increasing the model's horizontal resolution from $0.5^{\circ}\times 0.5^{\circ}$, which is already quite high compared with that of the conventional atmospheric soundings, to $0.25^{\circ}\times 0.25^{\circ}$ without the simultaneous enhancement in model physics and objective analysis, the improvements in QPFs are very limited. With higher resolution, although slight amelioration in locating the rainfall centers and in resolving some finer structures of precipitation pattern is made, the number of the mis-predicted fine structures in rainfall field increases with the enhanced model resolution as well.

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