Mausam, (1986), **37**, 1, 17-26

551.509.313 : 551.553.21 : 551.515.1

Prediction of a monsoon depression with a regional primitive equation model

S. S. SINGH

Indian Institute of Tropical Meteorology, Pune

and

MASATO SUGI

Electronic Computation Centre, JMA, Tokyo, Japan

(*Received 7 March 1984*)

सार — उष्ण कटिबंधीय क्षेत्र पर प्रागुक्ति परीक्षण के लिए एक जे एम ए प्रचालीय सीमित क्षेत्र निदर्श अनुप्रयुक्त किया गया। इस परीक्षण में भूमण्डलीय निदर्श पूर्वानुमान द्वारा समय परिवर्ती पार्श्विक परीसीमा उपलब्ध कराई गई। सामान्य बहुलक प्रारंभिकरण द्वारा संतुलित प्रारंभिक अवदाब क्षेत्र प्राप्त किए गए। इसके द्वारा, मानसून अवदाब के बना रहना एवं उसकी गति तथा संबंधित वर्षा क्षेत्रों की प्रागुक्ति ठीक प्रकार से की गई। आरम्भिक स्थिति में अवदाब के विकास की प्रागुक्ति भी की गई।

ABSTRACT. JMA operational limited area model is applied to a prediction experiment over the tropical belt. In the experiment, time varying lateral boundary is provided by a global model forecast. The balanced initial field is obtained by normal mode initialization. The maintenance and movement of a monsoon depression and associated rainfall area are predicted well. The development of the depression in the early stage is also predicted.

1. Introduction

Synoptic, climatological and statistical methods are generally used for the prediction of meteorological phenomena over the tropical belt. A few research and experimental numerical models have been developed (Krishnamurti *et al.* 1976; Das and Bedi 1978) and applied for the case studies of Indian summer monsoon.

Ideally speaking, a global model with high resolution in horizontal and vertical is very much desirable for the tropical prediction. However, due to computational and physical constraints, a higher resolution limited area model is considered quite adequate for the prediction of synoptic scale disturbances. The application of limited area model poses a serious problem in specification of lateral boundary conditions. An artificial imposition of boundary conditions excites the external gravity waves and reflects backward in the domain of integration. It has been recognised by many workers (*viz.*, Price and MacPherson 1973; Williamson and Browning 1974; Chen and Miyakoda 1974; Davies 1976) that the time varying boundary conditions circumvent to a large extent the problem posed by a limited area prediction model in the specification of lateral boundary conditions. Basically, there are two approaches. In one approach, the forecast with large domain is made and the boundary data to the limited area model is provided. This is known as one way interaction. In the second approach, both models are dynamically coupled and form a single dynamical system. This is known as two way interactions.

Another problem of tropical modelling which requires special treatment is the initialization. A great deal of research over past few years in the field of initialization has shown that the normal mode initialization technique is quite effective in lower latitudes. The normal mode initialization is based on the idea of expanding initial data into normal modes or free oscillations of linear versions of the model. The model amplitude thought to be unrealistically large is set to zero or considerably reduced.

In the present experiment with regional primitive equation model, we have applied the time varying boundary conditions with one way interaction to specify the lateral boundary conditions. For obtaining the initial balance of meteorological helds, the normal mode initialization is adopted. With these two sophistications, the regional model is applied to two synoptic situations for 48-hour forecast. The paper presents briefly the descriptions of the model, computational scheme and the physical processes incorporated in the model. Furthermore, the resclts of initialization and forecast, and comparison of forecasts obtained by coarse mesh and fine mesh versions of the model are also discussed.

2. Description of the model

The JMA fine mesh limited area forecast model has been suitably modified for the present study. Detail description of the model is given in Electronic Computation Centre, JMA (1983). The revised version of the model is briefly presented as follow :

The model equations are in (x, y, σ, t) coordinate system on Mercator projection. The domain of integration extends from equator to 40 deg. N and 50 deg. E to 120 deg. E. The horizontal area is resolved by the uniform grid distance of 220 km. In vertical there are six sigma levels corresponding to 950, 850, 700, 500, 300 and 150 mb. The lower and upper boundaries are placed at the bottom topography and at 100 mb respectively. The physical processes, *viz.*, large scale condensation, surface friction, sensible heat supply over the sea surface (the formulation is based on Kondo 1975), the parameterization of cumulus convection (Kuo 1974), dry convective adjustment (Krishnamurti *et al.* 1976) to remove superadiabatic lapse rate and horizontal and vertical diffusion (Electronic Computation Centre, JMA 1983) have been incorporated in the model. No radiative process is included in the model. The differential equations are converted to difference equations following Arakawa *et al.* (1974). The economical explicit scheme (Tatsumi 1983) has been used for the time integration.

The lateral boundary of the model is treated with one way interaction following the method proposed by Hovermale (Electronic Computation Centre, JMA, 1983), *i.e.*, the terms proportional to the Laplacian of the difference between the forecast values and the boundary values are added to the governing equations in the boundary region. The Laplacian operator ensures the effective damping of smaller scale differences. In the present experiment boundary values are provided by the 6 hourly forecast with the global spectral model (8 layer, T42 truncation).

As for the initialization, we do not know the well-established method for a tropical regional model. The non-linear normal mode initialization method for a global model is known to be effective in the tropical region. Accordingly, in the present experiment, we first initialized the global data with this method and then simply interpolated the results to obtain the initial fields for the limited area model. As a result, the resolution of the initial field of the experiment is not sufficiently high (2.5 degree latitude-longitude). From the view point of the suppression of the undesirable oscillation, this initialization procedure is found to be quite adequate. The amplitude of the gravity wave oscillation is so small that we hardly notice it. At the beginning of the integration, there are some oscillations of about 1 mb amplitude and with short period (1-2 hours). But these oscillations are damped very effectively by the time integration scheme.

3. Data

Data of two synoptic days, *viz.*, 4 and 7 July 1979 have been chosen as input to the model. The 4 July refers to the early stage of development of monsoon depression in the Bay of Bengal (Indian Ocean) and 7 July refers to the mature stage of the same depression. The purpose of selecting these two distinctly different stages of the same depression is to investigate whether the regional model is able to simulate the development of a weak cyclonic circulation into a depression with input of 4 July; and also to study the model prediction of movement, associated precipitation and structure of the mature monsoon depression with input of 7 July.

During the summer monsoon months, the depression is generally formed over the head Bay of Bengal (northern Indian Ocean) and propagates westward or northwestward over the Indian subcontinent. Normally heavy precipitations in the forward sector of the depression are observed.

On 4 July 1979, a weak cyclonic circulation was centred at 22 deg. N, 90 deg. E. The cyclonic circulation intensified into a depression on 6 July and developed into a major depression on 7 July. The centre of the depression on 7 July was located at 20 deg. N, 88 deg. E. A little movement was observed between 4 and 7 July, however, the system moved rapidly in westnorthwest direction during 7 and 9 July and subsequently weakened.

The grid point data of geopotential, msl pressure and horizontal wind components for both the synoptic days have been extracted from the FGGE-IIIb data sets. The precipitable water has been used to derive the moisture field. The FGGE-IIIb data sets are produced from level IIb data at European Centre for Medium Range Weather Forecast (Bengtsson *et al.* 1982) through three dimensional multi-variate optimum interpolation. In order to examine the quality of analyses for the present synoptic situations (4 and 7 July 1979) in the limited domain, the wind, temperature (derived from geopotential) and msl pressure of FGGE data sets are compared with the manual analyses. The manual analyses included the additional data collected during the MONEX-79 field phase. In general, there appears to be close agreement between the two analyses as far as the large scale fields are concerned; however, the msl pressure patterns show considerable discrepancies around the depression. Fig. 1 presents the msl pressure from both sets of analyses. The two sets of analyses as seen in Fig. 1 are quite different around the cyclonic circulation. The closed isobars in the msl pressure charts are completely missing in the FGGE analyses. The discrepancies in two analyses are quite understandable as the global analyses may not necessarily depict all fine aspects of weather systems particularly over the tropical belt where observational network is quite sparse.

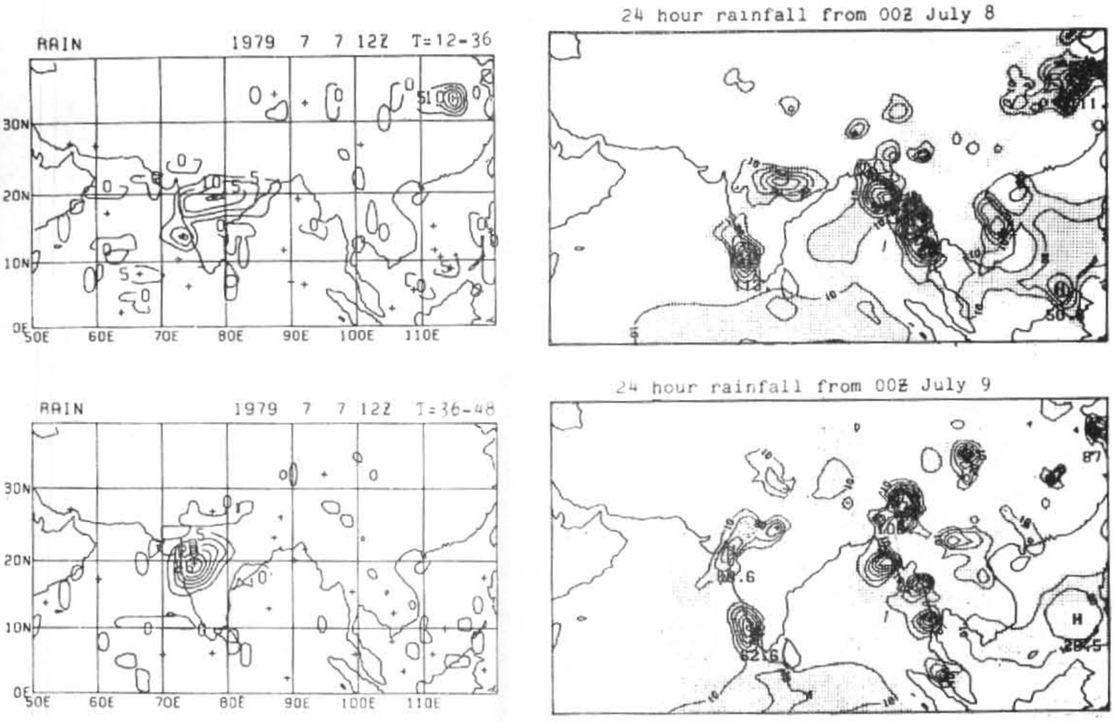


Fig. 5. Predicted and observed (Krishnamurti *et al.* 1983) 24-hour rainfall (mm). Note that the predicted rainfall for the period from 00 GMT, 9 July (bottom left panel) is 12-hour rainfall

As shown in Fig. 5, in the forecast from 7 July, the area of rainfall associated with the monsoon depression is predicted very well. The forecast amount of rainfall is less than the actual in 8 July and larger than the actual in 9 July. The orographic rainfalls along the west coast of India and Burma are missing in the forecast. In the forecast from 4 July, the agreement of the predicted area of rainfall associated with the monsoon depression with observation is not so good as the forecast from 7 July. This is probably closely related to the inadequate development of the disturbance in the model, and possibly to the initial moisture analysis.

4 (d). *Structure*

In order to examine further the quality of the forecast, we made vertical cross sections of the forecast fields. In general, the forecast structure of the monsoon depression is quite reasonable as shown in Fig. 6. The vorticity has maximum at around 850 mb. The upward motion is located several hundred kilometres ahead of the vortex centre. We also notice the cold core below 700 mb and warm core above it. These are the typical features of a monsoon depression revealed by observational studies (Krishnamurti *et al.* 1975; Godbole 1977). As for the moisture field, the geographical distribution is prominent, *i.e.,* relatively wet areas lie over the west coast of India and Burma, dry areas over the eastern part of the land and extremely dry area over Arabian desert. The presence of the moist area associated with the upward motion ahead of the monsoon depression is not clearly understood.

4 (e). *Development*

The forecast from 4 July is made to investigate whether the model is able to predict the rapid development of the disturbance. The initial and 48-hour forecast wind field at 850 mb are shown in Fig. 7 with the verification charts. The development of the monsoon depression correctly has been predicted by the model. The weak cyclonic flow at the initial time developed into a cyclonic circulation. The degree of intensification, however, is not sufficient. The predicted wind around the depression is much weaker than the actual. The figure shows that the cyclonic circulation already exists at the initial time in FGGE analysis. In the initialized field, this circulation is deformed into a flow with weak cyclonic curvature. This indicates that the initialization procedure for the present experiment is not sufficient enough for a limited area forecast.

The vertical cross sections of the vorticity and the vertical motion field are presented in Fig. 8. The vorticity has maximum at 550 mb and is not intense at 850 mb. In the model, the intensification of the depression seems to occur at higher levels than the actual. It should be noted that the strongest vertical motion is located at the east and the west of the vortex centre and this is consistent with the slow westward movement of the disturbance.

5. Discussion of the results

We will discuss in this section three important aspects of the experiment, *i.e.*, the lateral boundary condition, the effect of increasing resolution and the role of cumulus convection.

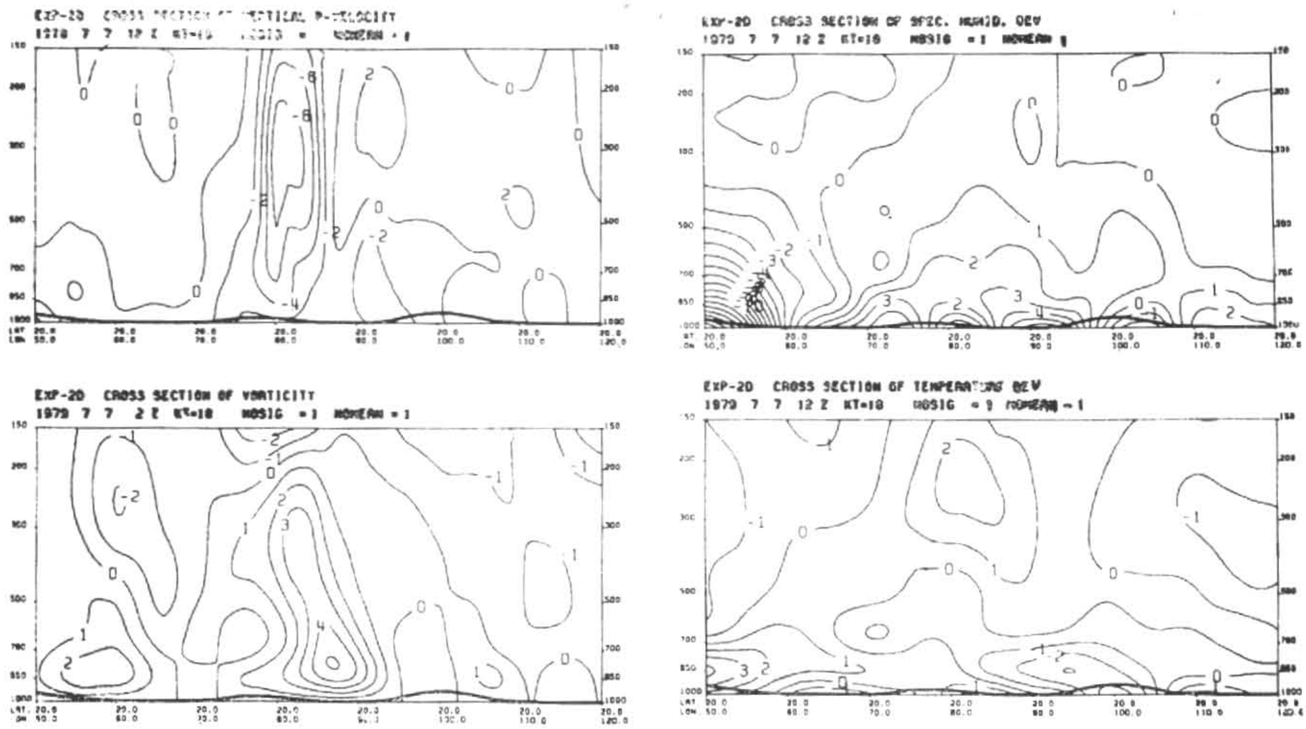


Fig. 6. Vertical cross sections along 20° N of predicted (at 18-hour) vertical p-velocity (top left), relative vorticity (bottom left), specific humidity deviation from its zonal mean (top right) and temperature deviation (bottom right) for 7 July case. Units are mb/hr, 10^{-5} sec^{-1}, g/kg and °C respectively

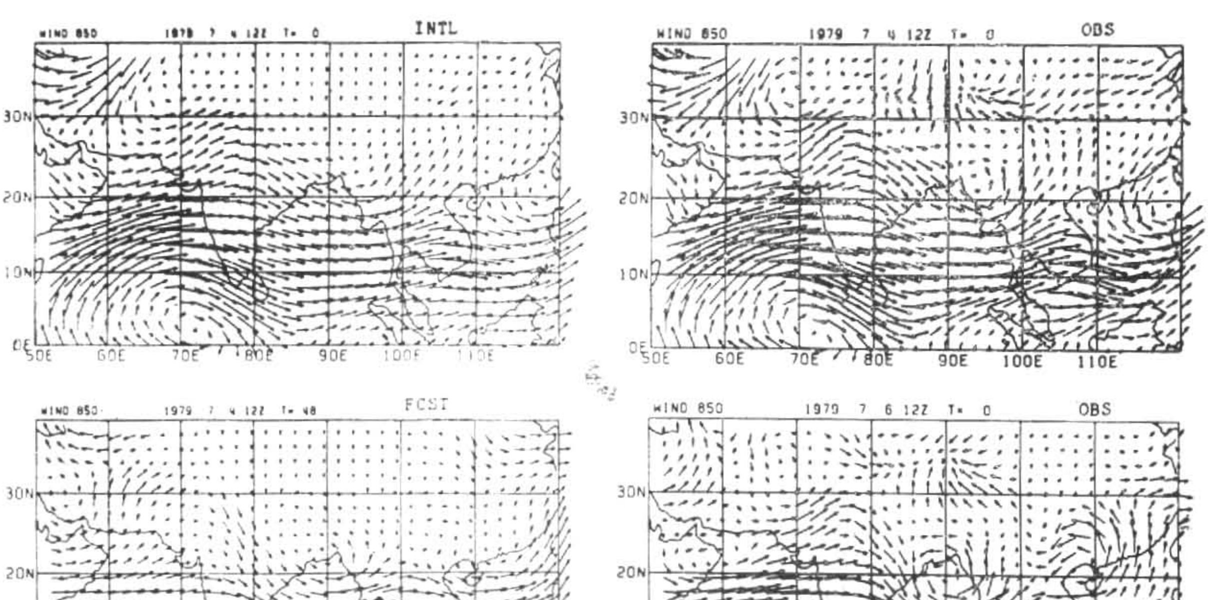


Fig. 7. Forecast and observed 850 mb wind field for the 4 July case. Unit is the same as in Fig. 3

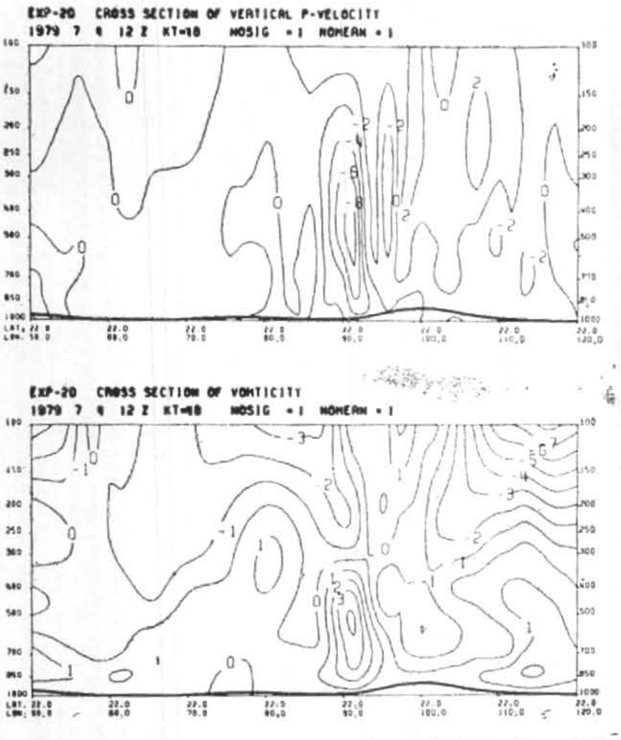


Fig. 8. Vertical cross sections along 22° N of predicted vertical p-velocity (top) and relative vorticity (bottom) for 4 July case (at 48-hour). Units are mb/hr and 10^{-6} sec^{-1}

5 (a). Lateral boundary values for the limited area model of the present experiment are provided by the forecast of the global model. This is probably the first attempt using this type of boundary condition for the limited area primitive equation model in the tropics. It is interesting to see the use of the forecast boundary produces the better forecast than the other boundaries such as the fixed value boundary.

In Fig. 9 the 48-hour forecast of 850 mb and 200 mb wind fields of the fixed value boundary experiment is shown. Comparing this figure with Fig. 3 and Fig. 4, we notice indeed some differences. But generally speaking the impact of the use of the forecast boundary is not always positive. Particularly the impact on the prediction of the monsoon depression is very little and on the southern bounday rather negative. Both boundaries give fairly good prediction. This indicates the efficiency of the Hovermale's boundary condition in low latitudes.

The good results of the fixed value boundary experiment partly come from the steadiness of the large scale tropical atmosphere. Since the synoptic situation of this experiment may happen to be very steady around the boundary regions, we should not conclude that the fixed value boundary is always useful in the tropical region. However, if we can use this boundary, it will make operational limited area forecasts easier.

Differences between the two experiments gradually grow with time as the difference between the two boundary values increases. But even after 48-hour of integration, as shown in Fig. 10, the difference in the inner part of the domain is small enough. Fig. 11 depicts the difference of vorticity and divergence between the two experiments. The large difference of vorticity is seen near the northern boundary at 200 mb. The difference is also large at the westerly jet of 850 mb. But in general, in the region away from the boundary the difference of vorticity is quite small. The difference of divergence is also small in the inner region. But we notice somewhat large difference at northern India. Since this area is the area of heavy rainfall associated with the monsoon depression, the difference of divergence at this area may be related to the difference of the convective activity in this region in the two experiments. Indeed, the amount of rainfall is 15% larger in the forecast boundary experiment. The convective activity, which might be sensitive to the divergence field, seems to enhance the small difference of divergence due to the different boundaries.

5(b). *Effect of resolution*

The obvious advantage of the use of a limited area model is that the higher resolution is obtained compared with global or hemispheric model with the same computer resources. Fig. 12 shows the 48-hour forecast of 850 mb wind field and rainfall by the global model which provided the lateral boundary values to the limited area model. Comparing this figure with Fig. 3 and Fig. 5, the improvement of the forecast by the use of the limited area model is clear. The horizontal distance of the Gaussian grid, on which the physical processes are computed, of the global spectral model is about 300 km, whereas the grid distance of the limited area model is about 200 km.

To investigate the effect of further increase of the resolution, the experiment with 110 km grid resolution was carried out. The number of vertical levels are also increased from six to twelve. The 48-hour forecast of 850 mb wind field with the higher resolution model is shown in Fig. 13(a). The westward movement of the depression in the high resolution model is a little slower than the low resolution model and agrees closer with observation. In general, however, the difference between the two forecasts is not large. One of the reasons of this small difference is the low resolution of the initial field, as the initial fields of the both experiments are obtained by the interpolation from the initial field of the global model, the resolution of which is 2.5 degrees latitude-longitude.

5 (c). *The role of cumulus convection*

Observational and numerical studies (Krishnamurti *et al.* 1975, 1976) and the linear instability analysis (Shukla 1978) show that the cumulus convections play an important role in the maintenance, development and the westward movement of the monsoon depression.

In order to see the role of cumulus convection in the present study, an experiment with dry model was performed for the 7 July case. As shown in Fig. 13(b) the dry model failed to predict the maintenance and the proper westward movement of the depression.

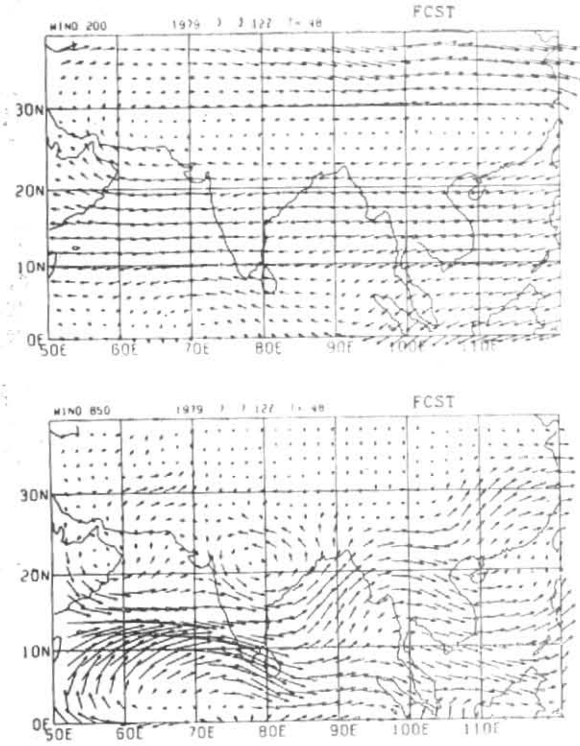


Fig. 9. 200 mb and 850 mb wind field predicted by the model with fixed value boundary. Units are the same as in Figs. 3 & 4.

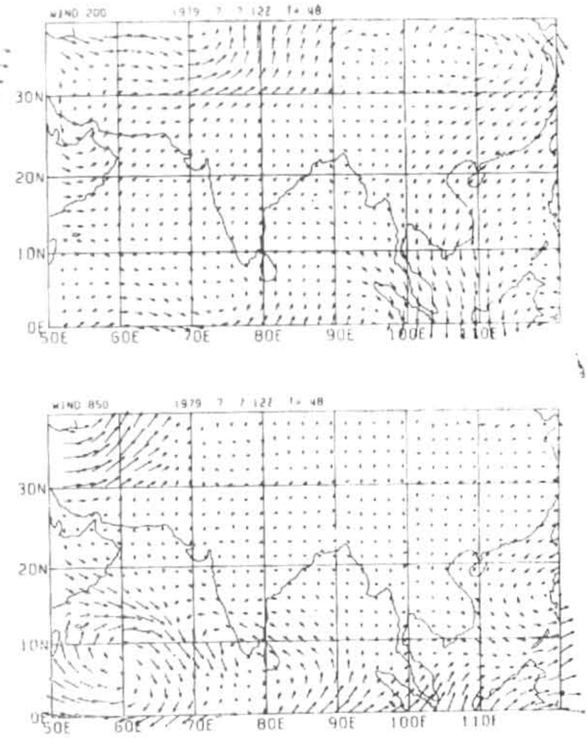


Fig 10. The difference of the predicted wind field at 48-hr between the experiments with forecast boundary and with fixed value boundary. Units are the same as in Figs. 3 & 4

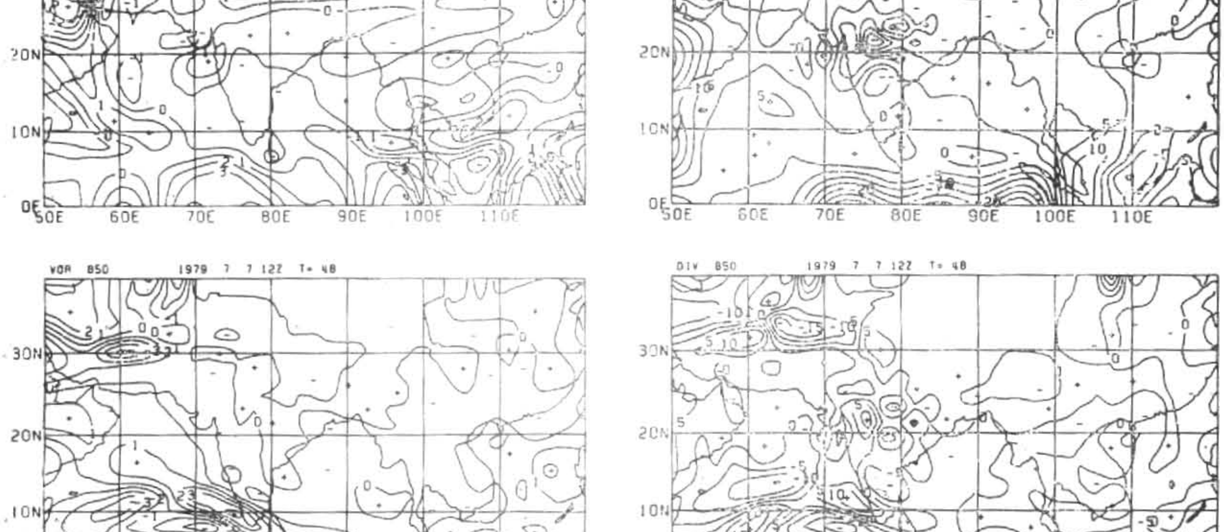


Fig. 11. The difference of the predicted vorticity (left) and divergence (right) at 48-hr between the experiments with forecast boundary and with fixed value boundary. Units are 10^{-5} sec^{-1} and 10^{-6} sec^{-1}, respectively

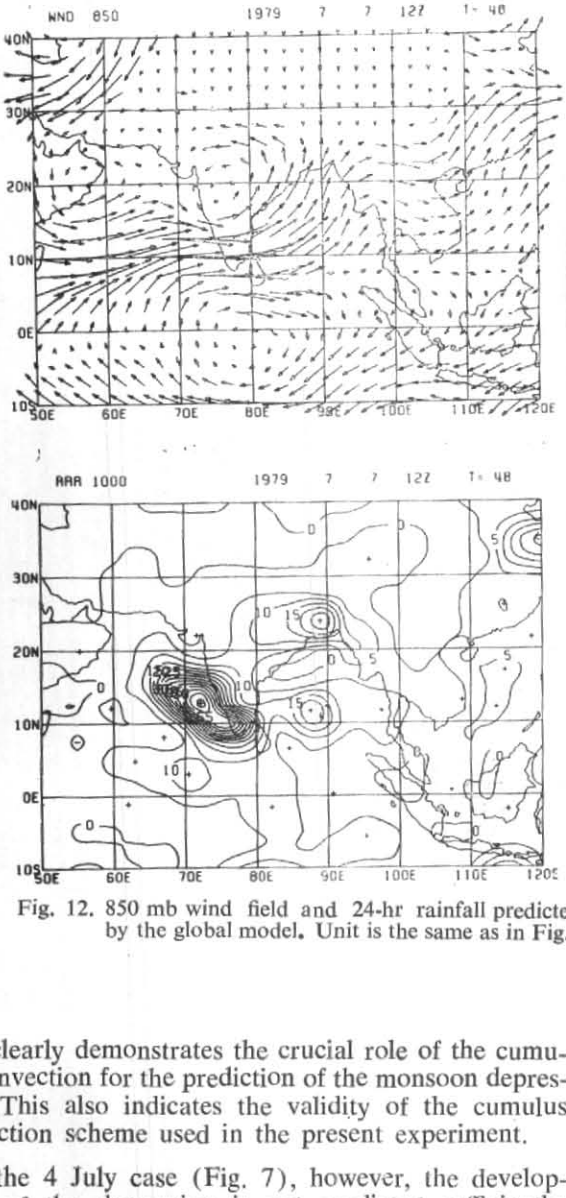
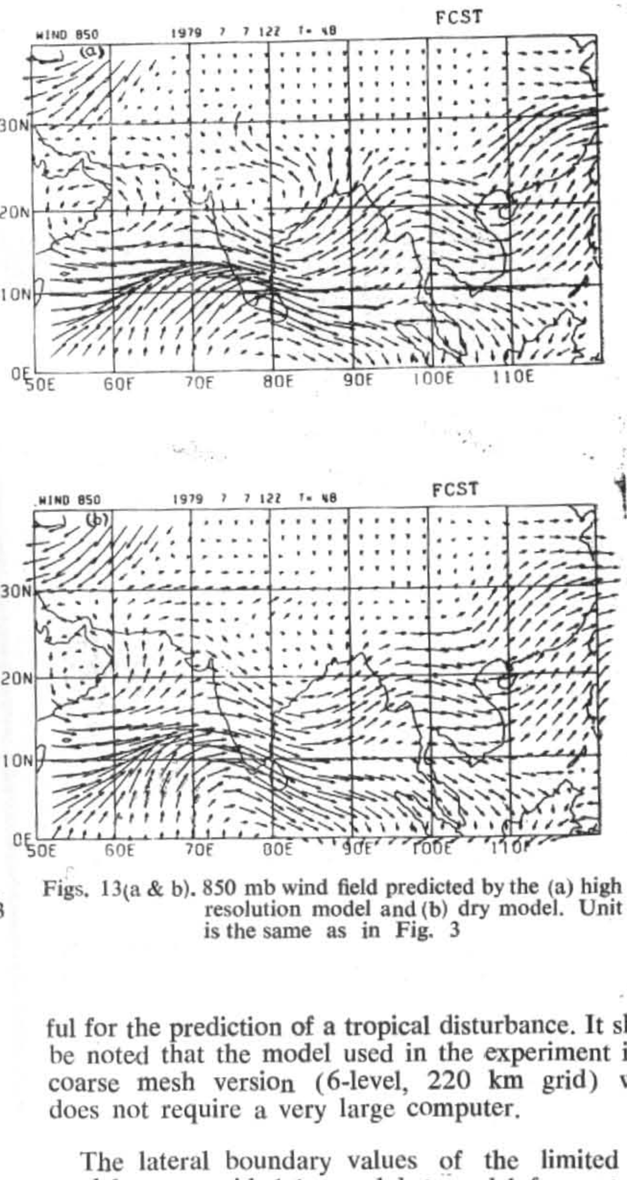


Fig. 12. 850 mb wind field and 24-hr rainfall predicted by the global model. Unit is the same as in Fig. 3



Figs. 13(a & b). 850 mb wind field predicted by the (a) high resolution model and (b) dry model. Unit is the same as in Fig. 3

This clearly demonstrates the crucial role of the cumulus convection for the prediction of the monsoon depression. This also indicates the validity of the cumulus convection scheme used in the present experiment.

In the 4 July case (Fig. 7), however, the development of the depression is not predicted sufficiently. One reason for this might be the inadequate resolution of the initial field. Another possible reason may be that the cumulus convection in the model may not work well for the development of the monsoon depression in this case. In the 4 July case, the prediction of rainfall is not as good as that of 7 July case. Since the role of cumulus convection in the development of monsoon depression in the early stage is not well understood at present, further investigation of the mechanism of the development is needed.

6. Summary and conclusions

JMA operational limited area model is successfully applied to the prediction experiment of a monsoon depression. The maintenance and movement of the monsoon depression and the associated rainfall area are predicted well. The development of the depression in the early stage is also predicted. The experiment demonstrates that the limited area model is quite useful for the prediction of a tropical disturbance. It should be noted that the model used in the experiment is the coarse mesh version (6-level, 220 km grid) which does not require a very large computer.

The lateral boundary values of the limited area model are provided by a global model forecast. This boundary condition is found to work well in the tropics with the use of the Hovermale's scheme. An additional experiment with fixed value boundary is also made. The monsoon depression is predicted well also with this boundary. In general, the difference of the forecasts due to the different boundaries is small in the inner part of the domain even after 48 hours integration. However, the result of experiment suggests that the small difference in the divergence field might affect considerably on the convective activity in the model.

In the present experiment, the balanced initial field is obtained by the global normal mode initialization. This procedure is found to be adequate to suppress the undesirable gravity wave oscillations but not suitable to obtain the high resolution initial field for a limited area model. Recently the normal mode initialization method for a regional model is being developed (Brier 1982) and we can expect to apply it to a tropical regional model.

It is found that FGGE-III b analysis is quite adequate as an initial field for the limited area forecast model. But finer analysis with higher resolution model is expected to improve the forecast further.

Acknowledgements

The authors wish to express their thanks to Dr. M. Kanamitsu for his guidance and encouragement throughout the experiment and for his valuable comments on the manuscript. The authors are deeply indebted to Mr. Y. Tatsumi who provided the JMA operational limited area model. One of the authors (S. S. Singh) wishes to thank the WMO and the Government of India for the award of WMO Fellowship under UNDP Country Programme which enabled him to carry out this work at JMA, Tokyo, Japan.

References

Arakawa, A. and Mintz, Y., 1974, 'The UCLA Atmospheric General Circulation model' (with the participation of A. Katayama, J.W. Kim, W. Schubert, T. Tokioka, M. Schlesinger, W. Chao, D. Randall and S. Lord). Notes distributed at the Workshop, 25 March-4 April 1974.

Bengtsson, L., Kanamitsu, M., Kallberg, P. and Upalla, S., 1982, 'FGGE-4 dimensional data assimilation at ECMWF', *Bull. Am. met. Soc.*, **63**., pp. 29-43.

Brier, S., 1982, 'Nonlinear normal mode initialization of a limited area model,' *Mon. Weath. Rev.*, **110**, pp. 1166-1186.

Chen, J.H. and Miyakoda, K., 1974. 'A nested grid computation for the barotropic free surface atmosphere, *Mon. Weath. Rev.*, **102**, pp. 181-190.

Das, P.K. and Bedi, H.S., 1978, 'The inclusion of Himalayas in a primitive equation model', *Indian J. Met. Hydrol. Geophys.*, **29**, pp. 375-383.

Davies, H.C., 1976, 'A lateral boundary formulation for multi-level prediction models', *Quart. J. R. met. Soc.*, **102**, pp. 405-418.

Electronic Computation Centre, JMA, 1983, 'Outline of operational numerical weather prediction at Japan Meteorological Agency', Appendix to Periodic Report on Numerical weather Prediction, pp. 33-48.

Godbole, R.V., 1977, 'The composite structure of the monsoon depression', *Tellus*, **29**, pp. 25-40.

Kondo, J., 1975, 'Air-sea bulk transfer coefficients in diabatic conditions', *Boundary-layer Met.*, **9**, pp. 91-112.

Krishnamurti, T.N., Kanamitsu, M., Godbole, R., Chang, C.B., Carr, F. and Chow, J.H., 1975, 'Study of a monsoon depression (I) Synoptic structure', *J. met. Soc. Japan*, **53**, pp. 227-239.

Krishnamurti, T.N., Kanamitsu, M., Godbole, R., Chang, C.B., Carr, F. and Chow, J.H., 1976, 'Study of a monsoon depression (II) Dynamic structure, *J. met. Soc. Japan*, **54**, pp. 208-225.

Krishnamurti, T.N., Cocke, S., Pasch, R. and Low-Nam, S., 1983, 'Precipitation estimates from raingauge and satellite observations Summer MONEX', FSU Report No. 83-7.

Kuo, H.L., 1974, 'Further studies of the parameterization of the influence of cumulus convection on large scale flow', *J. atmos. Sci.*, **31**, pp. 1232-1240.

Price, G.V. and MacPherson, A.K., 1973, 'A numerical weather forecasting method using cubic splines on a variable mesh', *J. appl. Met.*, **12**, pp. 1102-1113.

Shukla, J., 1978, 'CISK-barotropic-baroclinic instability and growth of monsoon depressions, *J. atmos. Sci.*, **35**, pp. 495-508.

Sikka, D.R., Singh, S.S. and Rajamani, S., 1980, 'An analysis-prediction experiment--A case study with a monsoon depression in the Bay of Bengal', Results of Summer Monex Field Phase Research (Part A), FGGE operations report, **9**, pp. 151-159.

Tatsumi, Y., 1983, 'An economical explicit time integration scheme for primitive model', *J. met. Soc. Japan*, **61**, pp. 269-288.

Williamson, D.L. and Browning, G.L., 1974, 'Formulation of the lateral boundary conditions for the NCAR limited area model', *J. appl. Met.*, **13**, pp. 8-16.