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EXPERIMENTAL STUDY OF THE ROLE OF INITIAL AND BOUNDARY CONDITIONS IN MESOSCALE NUMERICAL WEATHER PREDICTION

YAN Jing-hua (闫敬华)[1] , Detlev Majewski[2]

(1. *Guangzhou Institute of Tropical & Marine Meteorology, CMA, Guangzhou 510080 China; 2. Duetscher Wetterdinst, Offenbach, Germany*)

Abstract: Based on the real case of a frontal precipitation process affecting South China, 27 controlled numerical experiments was made for the effects of hydrostatic and non-hydrostatic effects, different driving models, combinations of initial/boundary conditions, updates of lateral values and initial time levels of forecast, on model predictions. Features about the impact of initial/boundary conditions on mesoscale numerical weather prediction (NWP) model are analyzed and discussed in detail. Some theoretically and practically valuable conclusions are drawn. It is found that the overall tendency of mesoscale NWP models is governed by its driving model, with the initial conditions showing remarkable impacts on mesoscale models for the first I0 hours of the predictions while leaving lateral boundary conditions to take care the period beyond; the latter affect the inner area of mesoscale predictions mainly through the propagation and movement of weather signals (waves) of different time scales; initial values of external model parameters such as soil moisture content may affect predictions of more longer time validity, while fast signals may be filtered away and only information with time scale 4 times as large as or more than the updated period of boundary values may be introduced, through lateral boundary, to mesoseale models, etc. Some results may be taken as important guidance on mesoseale model and its data a.ssimilation developments of the future.

Key words: numerical weather prediction, mesoseale, initial condition, boundary condition

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1 INTRODUCTION

Rapid progress has been made in numerical weather prediction (NWP) worldwide in recent years[1]. Regional high-resolution mesoscale numerical predictions are one of the general concerns and have been underway. It is certainly subject to initial and lateral boundary conditions, especially so when the issue is about high resolution, small domain and assimilation of detailed data. Many attempts have been made in the past to address it from various viewpoints. Staniforth (1990)[2] studies in detail the effects of boundary information on the inner section of a dependent-mesh model. Gong and Qiu[3] point out that in addition to initial errors, model errors and lateral boundary conditions are also important factors leading to forecasting errors in regional mesoscale models. By means of parallel experiments, Zhang et al[4] statistically illustrate the effects of different schemes of initial values on element forecasts. Chen et al. [5] study the effects of varying initial values on tropical cyclone forecasts. The role of initial boundary values is also shown in ensemble forecasts[6]. Nonetheless, problems, like poorer coherence and details and less complete coverage, still remain. The issue of very high resolution is not particularly addressed to meet the demands in current model development. With a model less than 10 km in resolution, the current work attempts to discuss how initial and lateral boundary conditions affect mesoscale models and

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Biography: YAN Jing-hua (1964 -), male, native from Yunnan Province, lead researcher, undertaking the study of numerical weather prediction.

sensitivity of the former by way of large-sample experiments using hydrostatic and non-hydrostatic effects, different driving models, combinations of initial/boundary conditions, updates of lateral values and initial time levels of forecast. The aim is to seek a relatively complete answer for use as technical foundations for the development and application mesoscale NWP and data assimilation systems.

2 INTRODUCTION TO A REAL CASE

As an experimental sample, a heavy rain was selected that took place in the yearly first raining season in the south of China. The frontal system in question affected Guangdong as it progressed southward across the province between the evening of March 24 and the morning of March 26, 2001, and resulted in a process of heavy rain, thunderstorm and gale in the central and southern parts of the province (figure omitted). It was typical of the season's heavy rain situation, in which a low-level cold high was advancing south while a upper-level westerly trough was heading east, with many convective cells and deep cloud clusters imbedded in the large-scale frontal rain bands. It was from severe convective systems of a-few-hourly scales that the heavy rain falls. Because of the frontal effect, air temperature dropped, humidity rose, air pressure increased and precipitation came and went.

3 BRIEF INTRODUCTION TO THE EXPERIMENT MODEL AND INITIAL AND LATERAL BOUNDARY CONDITIONS

Two mesoscale models, a statistic model (HRM) and a non-statistic model (LM), are used in the experiment. They both have the same scheme of physical processes and resolution (7 km and 30 layers are taken in the experiment). The model has a domain covering 104°-117.5°E, 17°-29°N, and distributes in meshes of 217×193 gridpoints on each of the layers.

The non-static model LM (a local one) is operational and mesoscale at the Weather Bureau of Germany, which mainly deals with the mesoscale-β and mesoscale-γ issues. Being a full-elastic primitive equations model, it uses the spherical coordinates with rotating latitude/longitude in the horizontal direction but a generalized topography-dependent coordinate in the vertical. Physical processes include a 4th order linear horizontal dissipation scheme, which has been corrected topographically in terms of the dissipation of total heat, and takes into account the mesh-scale precipitation that has the micro-physical cloud effects. Following the Tiedtke's convection parameterization scheme for mass flux (1989), the Louis scheme is used for vertical dissipation in the near-surface layer and the 2nd order planetary boundary layer scheme of Mellor and Yamada (1974) the longwave and shortwave flux twin-flow radiation scheme of Ritter Geleyn (1992), which includes complete cloud-radiation feedback, and the three-layer soil model of Jacobsen and Heise, which contains the vegetation effect, are used for layers above it.

The static model HRM (of high resolution) is an operational mesoscale model previously used at the German weather bureau, which deals with mainly the mesoscale-α and mesoscale-β issues, with resolution varying from 28 km to 6 km. Being a primitive equations and static model, it uses a mixed coordinates in the vertical direction and its horizontal coordinates and physical processes scheme are identical with the LM, together with an implicit initialization scheme that is adiabatic, non-linear and normal. As a well-tested model, HRM is being run routinely at the Guangzhou Regional Meteorological Center[7] and a number of countries and regions.

In the experiment, the mesoscale model was nested with the global model through Davies' scheme (1976) of physical quantity relaxation, which has 8 circles of boundary buffer zone[7]. Two sets of initial and lateral boundary conditions and associated combinations were used.

One set of the data was provided by GME, a global operational model of the German weather bureau, known as the GME data. The model's horizontal mesh structure is of icsahedral-dexagonal to help minimize the mesh transformation on a global scale. It has a horizontal resolution of about 60 km and vertically layered into 30 levels. The physical scheme used in the model is basically the same as that in the ECMWF. The model initial values are from a 6-hourly four-dimension assimilation scheme for optimum interpolation cycles. The cycle and assimilation have been going on ever since the cold-start in 1985. An initialization technique of increment digital filter is also used. As shown in multiple comparisons and analyses, the assimilation system is of fine quality, which is illustrated in detail in [8].

The other set of data is from the ECMWF. For sufficiently high density in space and time and complete information of all model elements, the analyzed field of the ECMWF is used as the initial value for integration of 72 h with the GME to have output of methods about nested boundary information. Experts in the German Weather Bureau have shown through experiment studies that the general agreement between the GME and ECMWF models in terms of model physics contributes to insignificant difference in the 72-h forecasts between them, even though they use the same initial boundary conditions. The data is to be referred to as EC data.

4 EXPERIMENT SCHEMES

With regard to a frontal precipitation process that affected the south of China, twenty-seven contrast experiments were made based on the needs for analysis of the initial and lateral boundary values. Tab.1 gives the experiment schemes and what they are meant to achieve. For the mesoscale model, the horizontal resolution is 0.0625° (~7 km) and there are 31 vertical layers.

As controls, Exps. (1) - (8) are also used to study the sensitivity of non-static processes and the consistence in the conclusions drawn with different initial times. By altering the combination of initial and lateral values, Exps.(17) - (20) study their roles. Exps.(21) - (27) are designed to see what effect the lateral values will have and how sensitive they will be in response to different periods updating the values.

Tab.1 Brief Introduction to experiment schemes

No.	Date (UTC)	Models	Initial	Boundary	Int-bdy	Goals*
1-8	01032300 01032312 01032400 01032412	LM/HRM	GME	GME	3h	C N T
9-16	01032300 01032312 01032400 01032412	LM/HRM	EC	EC	3h	C B N T
17-18	01032400	LM/HRM	EC	GME	3h	I B N
19-20	01032400	LM/HRM	GME	EC	3h	I B N
21-23	01032400	LM	GME	GME	6/12/24h	B N
24-27	01032400	HRM	GME	GME	1/6/12/24h	B N

Note: N: non-hydrostatic; C: control; T: initial times; B: boundary data; I: initial data

5 ANALYSIS OF THE RESULTS

5.1 *The relationship between the driving model and mesoscale model*

The contrast analysis is conducted using the results from Exps.(1) - (8), in which the driving model is the GME, the global model of the German weather bureau. As shown in the study, the mesoscale model generally tends to agree with the driving model in terms of the spatial distribution and main variation trends, whether or not the model is static or when the forecast initiates. Variations of temperature and pressure as shown in Fig.1 are such instances.

It is known from the figure that the overall tendency for element forecasts by the mesoscale model (HRM, LM, Exps. 5 & 6) is in general agreement with that of the driving model (GME), in which the unrealistically high temperature forecast by LM for mid-day of the twenty-fourth was mainly resulted from its depicting of the heat-island effect of Guangzhou, all too excessively, while the observation was carried out in near suburb where there is no significant heat-island effect. Similar situations are also with humidity and wind (figures omitted). It is indicative that for the mesoscale model, the overall forecast tendency is dependent on its driving model via the initial and lateral boundary values and the forecast quality is much subject to that of the driving model; a good background prediction by the latter is required if the mesoscale model gives accurate and detailed forecasts.

As study reveals, however, the mesoscale model can give more detailed and accurate forecasts, more important variations and disturbance information, based on the background of the driving model. As shown in Fig.1a, the mesoscale model well reflects the fact that temperature rapidly falls as a consequence of the passage of a cold front in the early morning of the 25^{th} before increasing again, which is totally not reproduced by the driving model. In Fig.1b, the driving model fails to depict the pressure peaks in the morning of the 25^{th} but the mesoscale model can. Similar adjustments are found with the elements of wind and precipitation (figures omitted).

In addition, the driving model is too slow in estimating the location of rain bands and precipitation centers while the mesoscale model makes significant modification to the location to nudge the forecast towards reality. For instance, in the 24-48-h precipitation forecast for 00Z March 23^{rd}, the front edge of the main rain band is about 150 km farther behind than observation, according to the GME forecast while it is close to reality with the LM (figure omitted).

It is also found in the analysis that large illusive precipitation can sometimes be caused in some of the unstable areas on the lateral boundary of the mesoscale model, due to incomplete match between the driving model and the high-resolution one, though no significant effect is found on the inner model zone (figure omitted).

5.2 *The role of initial and lateral values in mesoscale models*

It is found from comprehensive analysis Exps.(1) – (20) that the influential information from the lateral boundary can be quickly transmitted to the inner zone of the mesoscale model to replace the initial model values to become the steering forecast tendency of the model. In other words, the initial boundary values can influence about the first 10 hours of model forecast but the lateral information will take its place over the remaining time. Take the element forecast at Guangzhou weather station to illustrate the point.

Fig.2 gives the comparisons of humidity and pressure at the Guangzhou weather station between 0300, 1100, 1700 and 1900 (L.T.), which shows that within the first 18 hours (for humidity) and 14 hours (for pressure) of the forecast, discrete phenomena are not found in individual schemes of lateral values, in which no spin-up occurs with the EC scheme 12 hours before the forecast while it is observed with individual schemes of lateral boundary values. It is seen in the figure that the hollow points (GME lateral values) and solid points (EC lateral values) are in two different groups, with significant difference between them, or, the two being in a discrete state. The difference in humidity increases with the validity duration, separating into two completely independent groups after 55 hours (there has been identical phenomenon with temperature). The air pressure is split into two groups after 14 hours. It shows that the overall forecast tendency of the inner zone of the mesoscale model depends on the performance of the lateral boundary values, which are governing mainly within the first dozen or more hours, a feature most pronouncedly shown in the dynamic element of pressure.

The "overall forecast tendency" as studied here refers to the trend of synoptic variation over a vast area without local effect of specific weather systems. For synoptic regimes with long life cycles, such as the tropical cyclone, their initial value may be the information that affects long-validity forecasts, but it is mainly felt around the synoptic systems that possess enormous energy. According to relevant studies[5, 6], the initial values of tropical cyclones can affect forecasts with long periods of validity.

From the distance between the station and the model boundary, we can estimate that the velocity with which the lateral values influence inward is 12 (thermodynamic variable) – 16 (dynamic variable) m/s, which is equivalent to the mean velocity of the atmospheric motion for middle and lower levels and the speed of atmospheric longwave (at the synoptic scale), faster than the inertial internal wave (about 9 m/s at 24°N). In the meantime, gravitational waves that are related with the lateral values (fast waves) are largely absent, indicating that the lateral values are transmitting in ways other than the gravitational wave and suggesting an efficient nested model scheme[9] in filtering out illusive gravitational wave effect that is caused by possible unmatched lateral values. In other words, the lateral values affect the inner model zone mainly through the transportation and movement of synoptic waves. It will be shown (Fig.6) that the information introduced via the lateral boundary contains all time scales besides long-period processes.

From the comparison of forecast precipitation fields, we have a clearer picture that shows various effects of the initial and lateral boundary values. As shown in the comparison of the 6-hourly fields for Exps.1 – 20, the precipitation forecasts are generally consistent with those of the controls for the first 12 hours, with the initial values unchanged but lateral values varying. The forecasts are then basically consistent with those for the controls operating with the lateral values varying.

In summary, the forecasts are mainly dependent on the initial values for the first 12 hours but on the lateral values for the rest. In contrast, with the lateral values unchanged but initial values varying, however, the precipitation forecasts for the first 12 hours are largely consistent with those of the controls for individual initial values; the forecasts are more or less in line with those of the controls for individual lateral values. The foregoing view has once again been confirmed. Fig.3 compares the 0-6-h and 24-30-h precipitation predicted by the GME control, EC control and EC control but with GME initial values (as in Exp.19). It is seen that the 0-6-h precipitation in Exp.(19) has the distribution consistent with the GME (the left bottom panel versus the left upper one) while 24-30-h precipitation shows consistence with the EC (the left bottom panel versus right middle one). From the results of the figures and tables of a parallel comparison study shown in [4], we can also see clearly that the initial values mainly have their impact on the model for the first 12 hours, a supporting evidence for the current paper.

The study, however, also suggests much stronger and longer (up to 48 hours and more) initial value effect. As shown in Fig.4, large difference is found in the HRM comparison of 24-48-h precipitation forecasts using unchanged lateral values versus varying initial values, with the precipitation over the eastern Guangdong much larger with the EC initial value than with the GME initial value.

With more detailed analysis, we find that the above difference is mainly caused by much lower initial values of soil moisture content in the scheme of EC scheme, which then significantly increases the diurnal temperature predicted (The difference is the maximum in eastern Guangdong with preceding maximum temperature higher than that with the GME scheme by 2°C to 4°C, figure omitted). With temperature getting higher, the instability will become stronger and 24-48-h precipitation will get strengthened.

Fig.5 gives the difference in moisture content for the surface layer of soil (0 – 10 cm) between the GME and EC initial values, which is much smaller with the latter. It mainly attributes to the difference in the assimilation process. As shown in some studies, precipitation in preceding periods can affect soil moisture content over a long time scale. For some of the international models like ECMWF, NCEP, JMA and GME, the National Meteorological Center of China and NCEP have compared and analyzed forecasts of precipitation over China and North America. The results have shown that the GME model tops in forecasting accuracy for both regions, which reflects from one side the desired quality of soil moisture content in GME. Ever since the cold start-up in 1985, the 4-dimension assimilation system has been working in cycles in the GME and has been giving relatively realistic assimilation fields of soil moisture content. Particularly, the EC initial values used in the current experiment is calculated entirely for its own purpose. The assimilation field of the ECMWF differs greatly because the assimilation is not long or specialized enough.

5.3 *The effect of updating period of lateral values*

As the atmospheric driving model contains information on various scales, it is important to decide on the periods in which the lateral values are updated during the nesting to ensure the introduction of important information and forecasting efficiency. As shown in comparisons of Exps.(21) – (27) and relevant control experiments, the optimum period is 3 hours or less for updating the lateral values. When it is between 6 and 12 hours, small difference begins to appear though there is not much change in the general situation and quantity values, and it becomes much more significant when the period is 24 hours. It mainly displays as changes in the key sectors of the rain bands, large increase in rainfall and illusive precipitation that is caused by noise (figure omitted). For temperature and humidity, the updating period is between 1 and 12 hours, with no directional changes in the evolution and characteristics of forecast temperature and humidity for the inner model zone. It reflects real processes. When it is 24 hours, the overall tendency is reproduced but significant changes have taken place in the quantity values and variation characteristics (figure omitted). For pressure (Fig.6), however, the model can well predict all information about the variation, including semidiurnal period, when the information of lateral values begin to affect the inner zone and the updating period is between 1 and 3 hours. When the updating period is 6 hours, semidiurnal oscillations cannot be predicted but variation trends and amplitudes that are caused by cold front weather can be known in advance. When it is 12 hours, semidiurnal oscillations cannot be predicted but variation trends and amplitudes can be foretold qualitatively, though not very well with short time scale, like that in the mid-day of the 25th. When it is 24 hours, neither semidiurnal oscillations nor synoptic processes can be predicted, except for long-term smoothed trend of evolution.

It can be then known from the analysis that the model introduces through the boundary information on time scales four times larger than or as large as the updating period of the lateral values and filters information faster than it. It is then clear that the effect of lateral values and their updating period is obvious on the model's forecasting capability and varying-time-scale information can be incorporated to the model by selecting the right, yet various, updating period. For the large-scale, long-period processes found in frontal movement as discussed in the current work, an updating period within 12 hours, which basically describes the phase variation during a frontal process, is sufficient in predicting precipitation. The rules given above should be followed to choose sufficiently short periods to probe processes with meso-and fine- scales so that element forecasts can be improved using mesoscale models. In the meantime, the updating periods for lateral values are not necessarily very short to avoid negative effects possibly caused by unimportant high-frequency information. As shown in the experiments done in [10], the updating periods are not too long or too short. It is also revealed from the analysis based on Fig.6 that the semidiurnal oscillation of pressure widely existing in low latitudes may not be essential for precipitation.

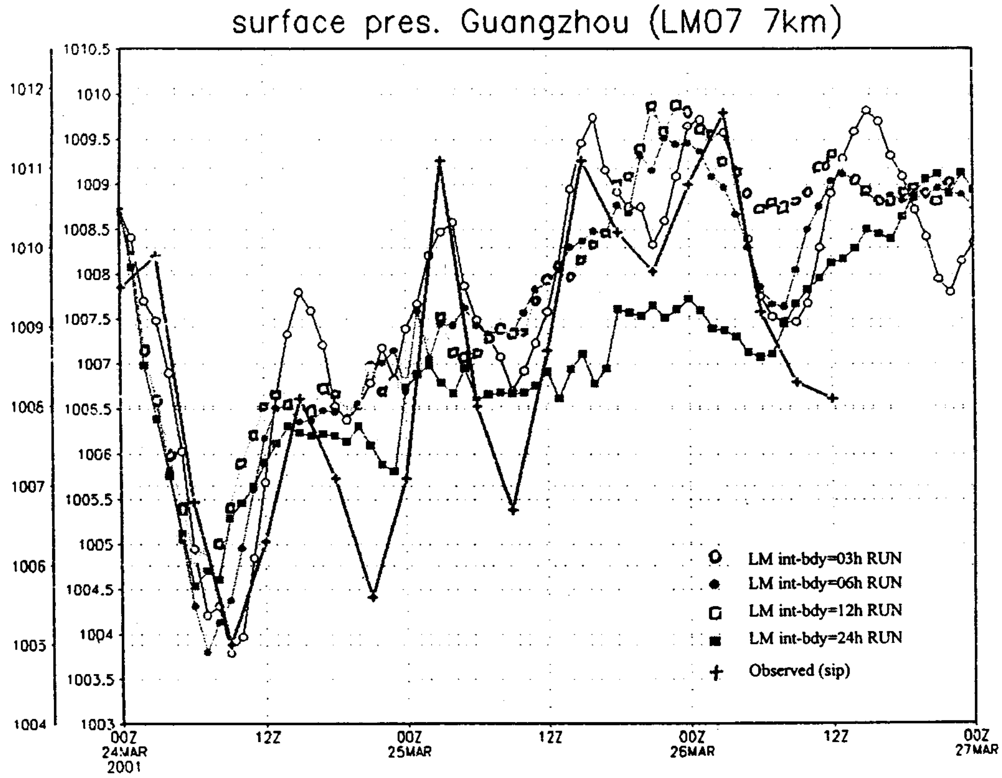

Fig.6 0-72-h pressure forecasts for the Guangzhou weather station by LM using varying updating periods for lateral values.

6 CONCLUDING REMARKS

(1) The overall tendency of mesoscale model forecasts depends on its own driving model, for the accuracy of whose general circulation background forecast determines the quality of the fine forecast of mesoscale models.

(2) On the basis of the driving model background, the mesoscale makes more detailed and accurate forecasts, gives more important variations and information of perturbation and even supplements to some extent directional tendencies in the driving model (like slow movement of rain bands).

(3) In some of the unstable zones of the lateral boundary in mesoscale models, large illusive precipitation and perturbation may be resulted from incomplete match between the driving model and high-resolution model, though the effect is insignificant for the inner model zone.

(4) As the lateral boundary information transmits rapidly towards the inner model zone, the initial values only affect the first 10 hours of forecast by the mesoscale model while the lateral boundary information becomes a determining factor for the rest of the forecast tendency. When we use fine data assimilation technique to make high-resolution numerical forecasts, it is necessary to focus on short-term rolling warnings and forecasts based on specific characteristics of the initial and lateral boundary role.

(5) The lateral values are transmitting to the inner zone at speeds of 12 –16 m/s, equivalent to the mean speed of the atmospheric motion at mid-and lower- layers and the speed at which the atmospheric longwave (on the frontal scale) travels. In other words, the effect is realized through the transportation and movement of synoptic information (wave) of various time scales rather than the transportation of high-frequency gravity waves.

(6) Sometimes the effect of initial values can be felt for as long as 48 hours and more, mainly because of the contribution from external parameters of the model like initial soil moisture content. It is then seen that initial values also affect long-validity forecasts. In particular, not only conventional elements but also external parameters like soil moisture content and snow cover must be properly dealt with in the assimilation of initial values. For synoptic systems with long life cycles and huge energy, the effect of initial values can last over a long time, though mainly on local weather around the systems.

(7) The model introduces through the boundary information on time scales four times larger than or as large as the updating period of the lateral values and filters information faster than it. By selecting various periods to update the boundary, information on different time scales can be introduced and unimportant high-frequency noise filtered. For large-scale long-term frontal processes, updating periods within 12 hours are sufficient enough to reflect major features of the processes. For processes that are on meso- and fine- scales and of fast waves, the periods must be sufficiently short to improve element forecasts using mesoscale models.

(8) The semidiurnal oscillation of pressure widely existing in low latitudes may not be essential for precipitation.

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