On the Numerical Weather Forecasts between Hydrostatic and Nonhydrostatic Systems from the NCEP Regional Spectral Model

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Abstract

The emergence of a nonhydrostatic model for operational use is fostered at some operational centers due to the improvement of advanced numerical method in the nonhydrostatic modeling and the support of sufficient computer resource. However, the questions related to use hydrostatic and nonhydrostatic models for numerical weather forecast; such as, the optimal resolution to use a nonhydrostatic model, or the nonhydrostatic effect in a coarse resolution, are not clear answered. The recently upgraded NCEP regional spectral model (RSM) with hydrostatic and nonhydrostatic options is tried to use for this application. With the same model numerics and structure for both options except model dynamics, it provides us clear comparisons and indications to the answers.

Two month parallel tests of nonhydrostatic option of RSM with 50 km and 10 km are examined. The results from these parallel runs show that the differences between the hydrostatic and nonhydrostatic RSM are mostly over mountain areas, even in a coarse resolution as 50 km. It suggests that the nonhydrostatic effect in the coarse resolution may not be negligible over mountains. In the 10-km resolution, some cases show remarkable differences after two day forecasts nearby mountains. It may imply the nonlinear growth from both systems can be significant difference in 10 km resolution. Thus, the optimal resolution for running a nonhydrostatic model may not be easily determined by a static scale analysis.

1. Introduction

The fully compressible nonhydrostatic mesoscale spectral model in hydrostatic sigma coordinates (Juang, 1992) have been implemented into the NCEP hydrostatic Regional Spectral Model (RSM) (Juang and Kanamitsu, 1994) with modifications. The major modification is to change the external-provided time-dependent hydrostatic coordinate (one case shown in Juang, 1992) to have an internal-determined time-dependent hydrostatic coordinate. It becomes the same as hydrostatic RSM which has internal-determined time-dependent hydrostatic coordinate. Thus, with the same perturbation method, spectral computation and semi-implicit scheme, both systems should clearly have the difference only in dynamics with either the nonhydrostatic system or the hydrostatic approximation.

Most of the operational centers are intended to use a nonhydrostatic model for their mesoscale weather forecasts. But there are several questions related to use hydrostatic and nonhydrostatic models for numerical weather forecasts are not clear answered from our community. For examples, what is the optimal resolution to use a nonhydrostatic model? Is the hydrostatic model unable to forecast the weather in high resolution? Is the nonhydrostatic effect negligible in a coarse resolution? Using the same model structure and numerics except the dynamics with or without a hydrostatic approximation such as the NCEP hydrostatic and nonhydrostatic regional spectral model, we might have some chances to answer some of the questions here.

In this report, the modified nonhydrostatic model will be described, the different methods for both options will be provided, and some case results from its experimental daily weather forecast will be presented. The summary and conclusion will be given, possibly to answer some of the questions. For simplicity, the nonhydrostatic regional spectral model which is also called the nonhydrostatic mesoscale spectral model will be referred as MSM, and the hydrostatic regional spectral model will be referred as RSM.

2. Model description

The assumption of time-dependent hydrostatic sigma coordinates in Juang (1992) is found to be suitable for use in a daily weather forecast model, and it is the basic approach for NCEP nonhydrostatic mesoscale spectral model. In term of coordinate, this model is different from the hydrostatic sigma coordinate of MM5 (Dudhia, 1993) which uses time-independent hydrostatic coordinate. Instead of using time-dependent hydrostatic coordinate which is determined from the outer coarse grid system as in Juang (1992), it was implemented with modifications by using the entire fully compressible nonhydrostatic system to determine the hydrostatic coordinate through the mass conservation of the coordinate as hydrostatic model does.

This modification makes it close to the system of Laprise (1992) which is used by Bubnova et al (1995) with extra effort in dealing with numerical instability. The numerical instability may be related to the definition of the hydrostatic coordinate as pointed out by Gallus and Rancic (1996). In terms of the definition of the hydrostatic relation, nonhydrostatic field is used by Laprise's system, so that the instability may come from the coordinate, and it becomes difficult to deal. MSM uses hydrostatic fields to define hydrostatic relationship (see Juang, 1992), so that the instability from the coordinate can be avoided.

In this case of internal-determined hydrostatic coordinate, the mass of the coordinates is conserved so that upper sponge layers or radiative top boundary conditions used in most of the nonhydrostatic model are not necessary in the resolution of interested here, coarser than 10 km. An example of this is shown in Fig. 1 of Juang (1996) in a vertical cross section of temperature over the high mountains. The same conclusion is obtained for other fields.

The perturbation method and spectral computation in the RSM (Juang and Kanamitsu, 1994) are used in the MSM. The time filter, semi-implicit and horizontal diffusion for the perturbation used in the RSM are adopted in the MSM as well. Instead of using equal weighted coefficients for semi-implicit integration as in Juang and Kanamitsu (1994), a forward-time-weighted semi-implicit scheme is implemented for MSM. From the sensitivity tests (not shown here), it is found that larger forward-time-weighted coefficient has to be used by MSM to obtain a stable integration with the same time step as RSM. The larger forward-time-weighted coefficient makes integration stable but less effect the results.

All the model physics used for the RSM have been modified to be suitable for the nonhydrostatic MSM. The hydrostatic relation used in the model physics code is eliminated. Temperature changes the thickness explicitly in the hydrostatic system, but it should change the pressure explicitly in the nonhydrostatic system. In other word, we are dealing model physics on constant pressure surface in hydrostatic system, and on constant height in nonhydrostatic system.

The model physics used in both models are identical. They are short wave and long wave radiation with cloud interaction, soil model, high resolution PBL, gravity wave drag, simplified Arakawa and Shubert Scheme, shallow convection and large scale precipitation. Details of the model equations, numerical techniques and modified model physics will be published later (Juang, 1997).

3. Results

The MSM is used to make daily weather forecasts in parallel with the 50 km RSM over North America and in Parallel with the 10 km RSM over Hawaii for the 00 z cycle only. The results from the MSM (the non-hydrostatic RSM) do not display much difference at 50 km in terms of synoptical scale waves as compared to the RSM except over mountain areas. Fig. 1 shows an example for 48-hr forecast from 0000 UTC 5 June 1996 from both model options. The sea -level pressure over mountain area or nearby shows much difference between MSM and RSM.

For hydrostatic model, it used to produce low pressure center over the high mountains and shown after the extrapolation to mean sea level pressure, for example here in Fig. 1 b. And from the nonhydrostatic model with the same extrapolation, the highs and lows are shown over the mountain areas, see Fig. 1 a, which provides a better guidance of the evolving system. In other word, the systematic error of low pressure over mountains is removed.

Another systematic error of the hydrostatic model is that the system tends to move faster while it is closer to the Rockies. After day by day comparison, it indicates that nonhydrostatic system provides a slower movement while close to the mountain as shown for an example in Fig. 1. And over all, the nonhydrostatic option of the model does predict the synoptic scale system well from daily results.

Fig. 2 shows the validation from the NCEP surface analysis for Fig. 1, it is clear shown that there is a high pressure center over the border of Montana and Wyoming, which is not shown in RSM but in MSM, even it is too high in MSM. And the low pressure center over the west panhandle of Texas is well predicted by MSM, not RSM. For the movement system close to the west coast. Let's select the isobaric of 1016 hPa for example, it is west of 120° W in MSM as well-predicted as compared to analysis, but RSM is shown much more east-ward and across to the 120° W.

For Hawaii (at 10 km), there are more differences between RSM and MSM in all fields because it shows more mesoscale features. It is difficult to get an observation to validate the results, but we can show how differences there from out results, and how well they are predicted should be left to some further studies with observations.

Fig. 3 shows an example of comparison between MSM and RSM on 850 hPa streamline after 24 hr forecast. It is found that the MSM provides much more freedom for the flow over mountains. Thus, the northern part of the leeside vortex moves farther away as compared to RSM. After 48 hr forecast, in Fig. 4, they become significant difference, even their large scale flow which provides by the global model is the same. MSM shows more and larger disturbance to the lee side than those of the RSM. In this case, it is a dynamical induced feature because there is no precipitation nearby the mountain.

4. Conclusion

The nonhydrostatic MSM was coded into the hydrostatic RSM to be a nonhydrostatic option in the RSM. The model physics in the RSM has been modified to be used in either hydrostatic or nonhydrostatic modes. Thus, it reduces the effort in maintenance because both share not only the same model physics but also most of the dynamic routines. And it provides not only possibly for operation use, but also for research purposes, such as used in this studies.

It is not clear whether or not we have to pay extra computation resources to run the nonhydrostatic model for resolution such as 50 km or 10 km here, which is required about 50% more computation cost in MSM than RSM, however, the systematic error of hydrostatic model over terrain may be improved in 50 km by the nonhydrostatic version. And it may imply that nonhydrostatic effect can not be ignored in coarse resolution as 50 km.

It can be computed by linear scale analysis to find out that 10-km resolution over Hawaii Island should not in a nonhydrostatic regime (not shown here), however, the nonlinear growth of the nonhydrostatic effect from the model clearly show significant from MSM, thus it has much more difference between MSM and RSM than in 50 km resolutions. It implies that the static scale analysis may not be a proper method to determine the optimal scale for running a nonhydrostatic model because it can not illustrate the nonlinear growth from a nonhydrostatic model.

Even though this study does not answer all the questions and more works have to be done, the nonhydrostatic option of the RSM demonstrates a useful tool to do further investigations.

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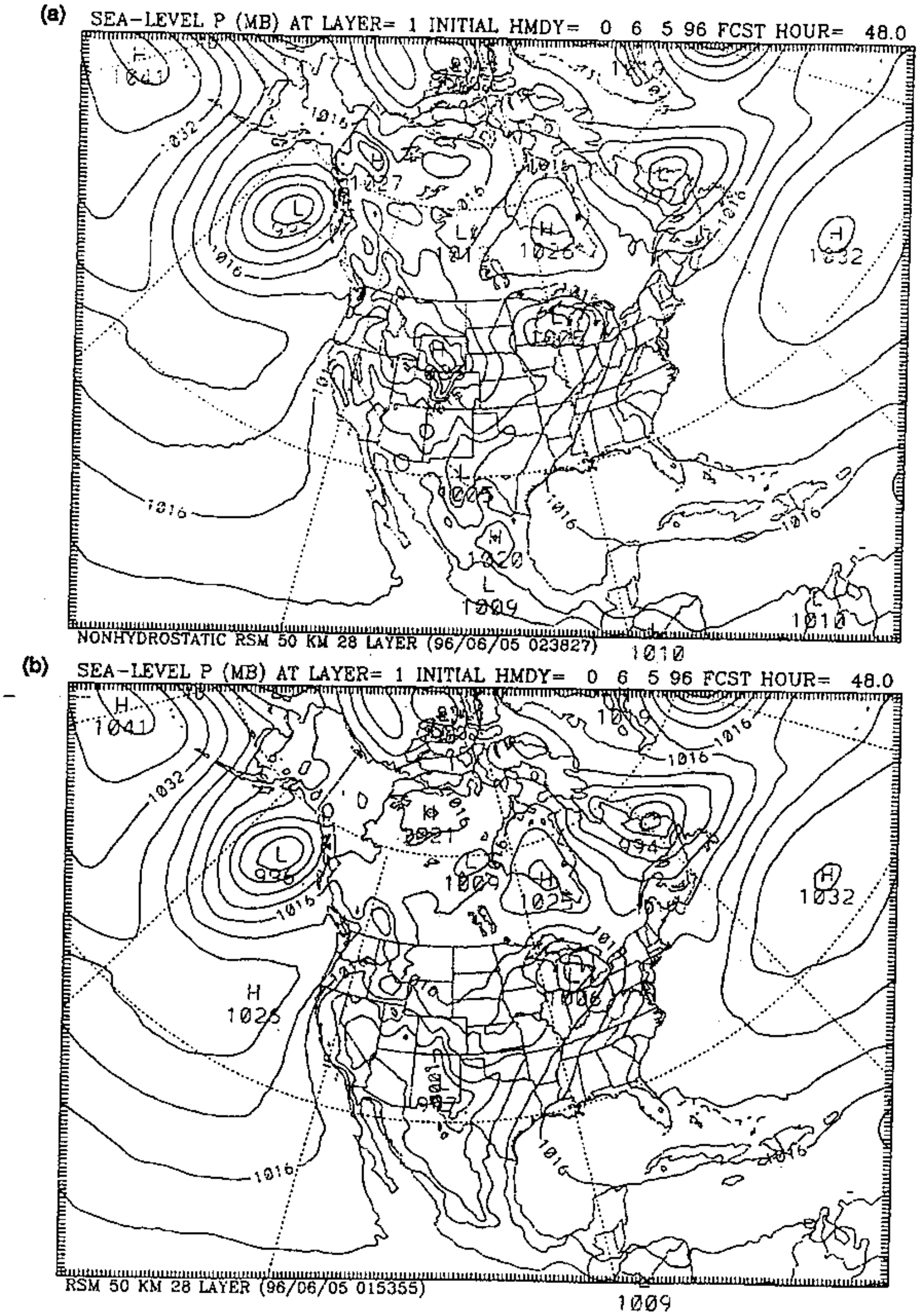

Fig. 1 48 hr forecast of mean sea level pressure in hPa over North America from 0000 UTC 5 June 1996 by (a) nonhydrostatic RSM and (b) hydrostatic RSM, with contour interval of 4 hPa.

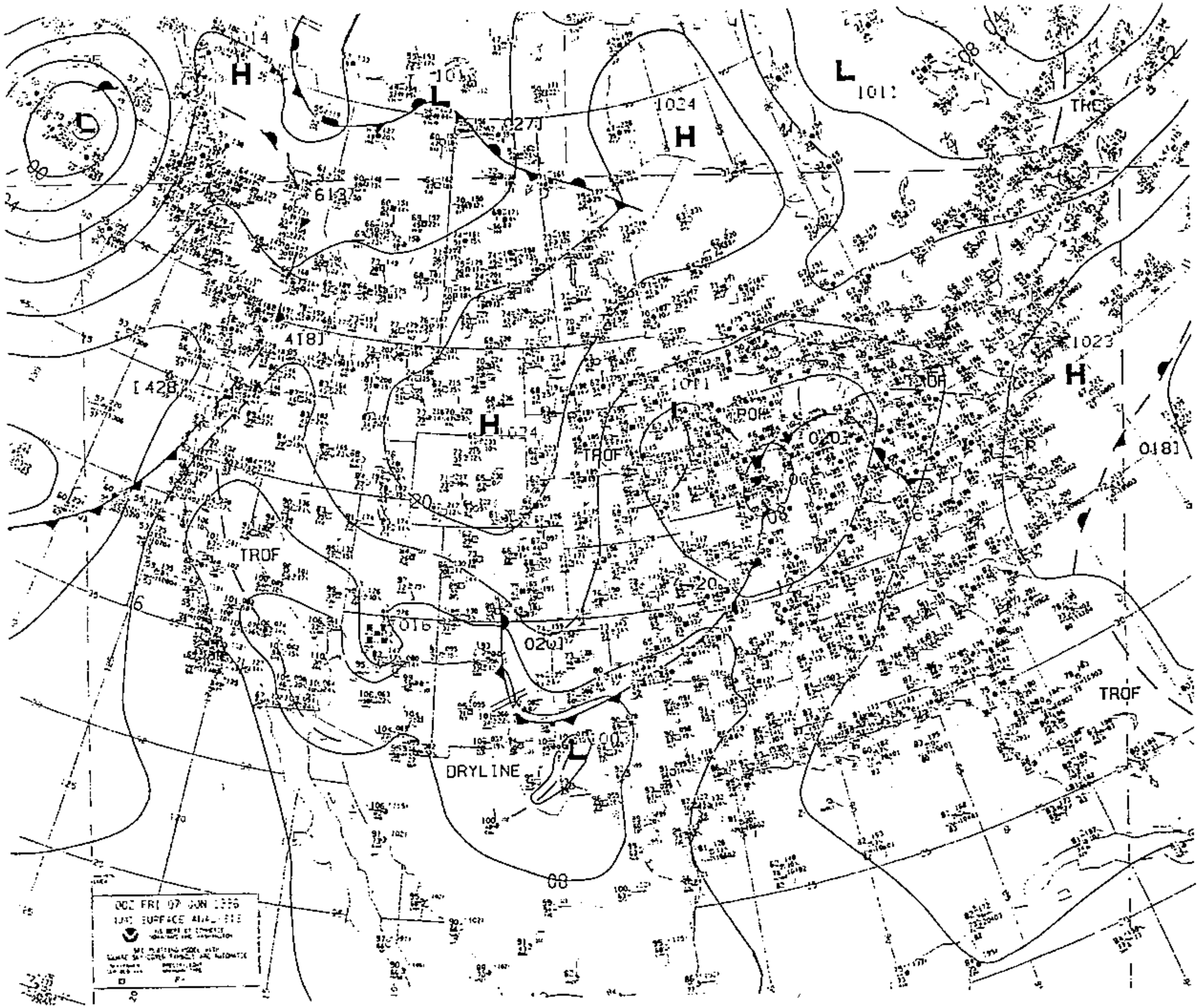

Fig. 2 The NCEP surface analysis on 0000 UTC 7 June 1996 for validation to Fig. 1, with contour interval of 4 hPa for mean sea level pressure.

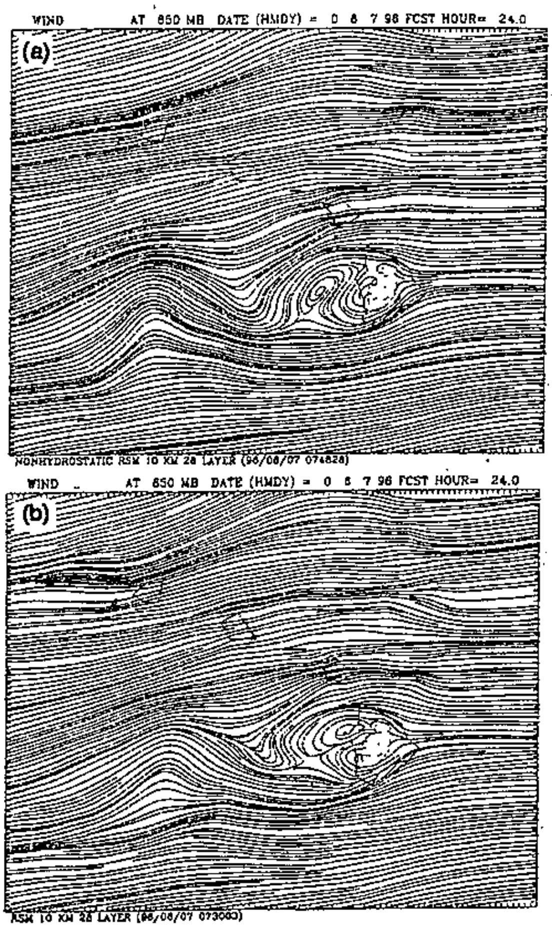

Fig. 3 24 hr forecast of streamline on 850 MB with initial date of 0000 UTC 7 June 1996 for (a) nonhydrostatic RSM and (b) hydrostatic RSM over Hawaii in 10 km resolutions.

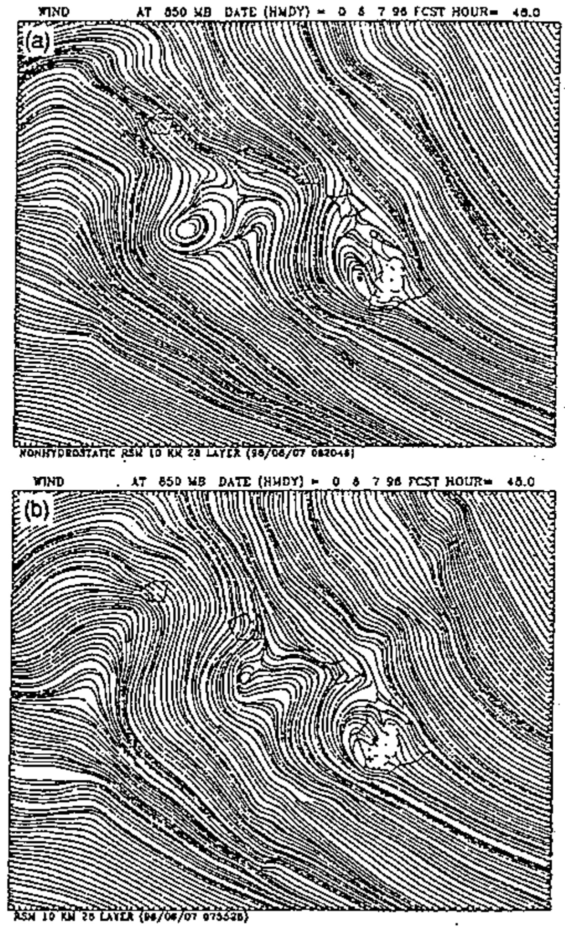

Fig. 4 The same as Fig. 3, except 48 hr forecast.