P2.9 ANALYSIS OF THE MESOSCALE PRECIPITATION BAND ASSOCIATED WITH THE 24 - 25 JANUARY 2000 STORM

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1. INTRODUCTION

On 24-25 January 2000, a major winter storm deposited as much as 20 inches of snow throughout portions of the eastern United States. This event was noteworthy as operational numerical weather prediction (NWP) model guidance for this cyclone was particularly poor, especially for lead times of 36 hours and longer. For shorter forecast lead times, while model guidance regarding the surface cyclone position and intensity at 1200 UTC on 25 January 2000 improved, guidance for the precipitation distribution remained poor. With lead times as short as 24 hours, forecasts of the surface cyclone and its associated precipitation were too far to the east.

The objectives of this study are to investigate the reasons for the poor numerical forecasts of the precipitation band associated with the event and to understand why improvements in the cyclone position and intensity were not associated with improvements in position of the precipitation band. First, the synoptic scale setting for the development will be described, including the evolution of the upper tropospheric features, and the associated rapid surface cyclogenesis. A diagnosis of the forcing for the precipitation band in association with the cyclone will be provided. Simulations of the event using version 3 of the Pennsylvania State University/National Center for Atmospheric Research Fifth Generation Mesoscale Model (hereafter, the MM5) will be described. An analysis of the model simulations will be provided showing the improved forecast in cyclone position and intensity, and the lack of appreciable improvement of the precipitation forecast. A description of the sensitivity of errors to model initial conditions will be provided using the MM5 adjoint modeling system. Finally, the growth of initial condition errors will be assessed through an evaluation of the structure and evolution of singular vectors calculated for a total energy norm.

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2. SYNOPTIC OVERVIEW

The precursor to the surface cyclone was an upper tropospheric trough that had crossed into the northwestern United States from southwestern Canada on 23 January. By 1200 UTC 24 January, the trough was advancing through the southeastern United States (Fig. 1). Surface cyclogenesis began in the Gulf of Mexico near the Florida panhandle at 0600 UTC 24 January. The surface cyclone crossed Florida and continued to intensify as it began to turn more northward. The most rapid deepening occurred between 2100 UTC 24 January and 1200 UTC 25 January as the cyclone moved northeastward along the southeast coastline of the United States from Florida to North Carolina.

As the surface cyclone was deepening rapidly, latent heat release linked with the heavy precipitation associated with the developing cyclone became increasingly important. This latent heating redistributed the potential vorticity (PV) by eroding the PV associated with the upper trough and increasing the PV in the middle and lower troposphere. Evidence for the destructive nature of the latent heating on the upper trough can be

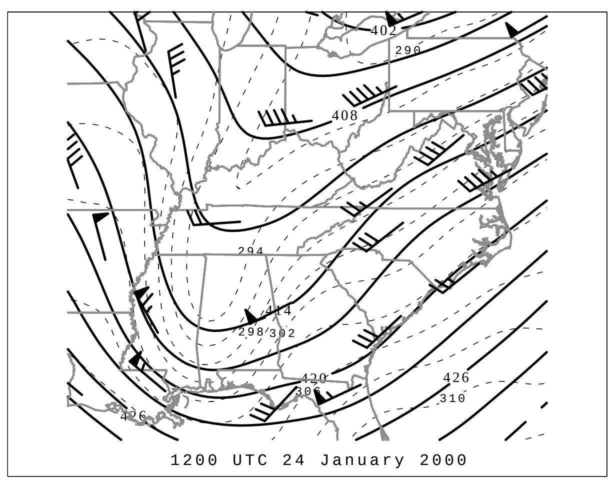

Figure 1. 600 hPa analysis of geopotential height (solid, interval 30 m), potential temperature (dashed, interval 2K), and wind (in knots) for 1200 UTC 24 January 2000.

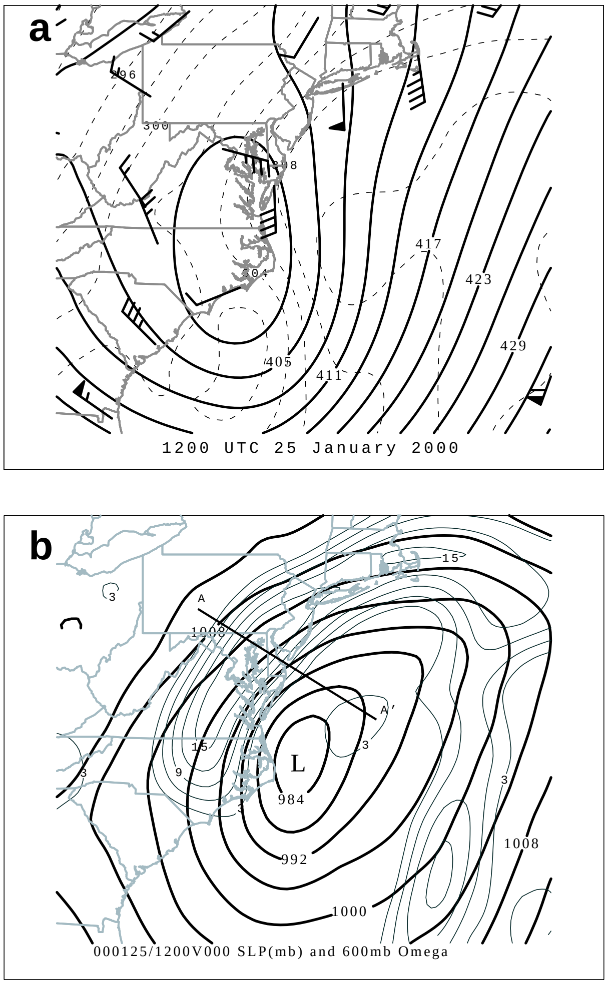

Figure 2. 1200 UTC January 25 (a) 600 hPa analysis as in Fig. 1, (b) sea level pressure analysis heavy solid, interval 4 hPa), and vertical velocity (thin solid, interval -3 μb s^{-1}). Line A-A' on (a) denotes the orientation of the cross section in Fig. 3.

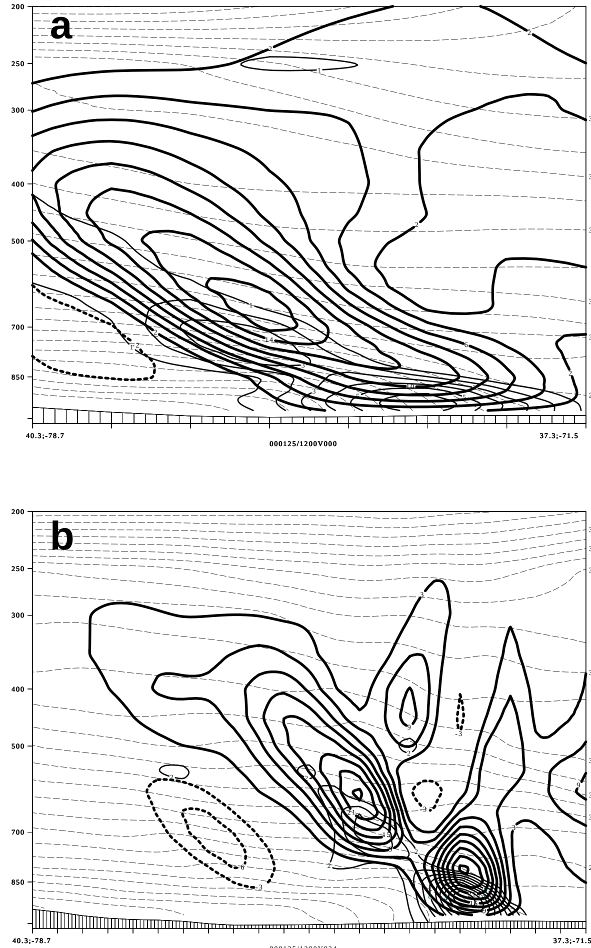

Figure 3. Cross sections of vertical velocity omega (heavy, interval -2 μb s^{-1}), frontogenesis (thin solid, interval 1^{o}C (100km 3h)$^{-1}$ only positive values contoured), and potential temperature (thin dashed, interval 3K) for (a) NCEP final analysis and (b) MM5 24 our forecast valid 1200 UTC January 25.

seen in the near disappearance of the thermal trough accompanying the geopotential trough (compare Figs. 1 and 2a).

By 1200 UTC 25 January (near the time of maximum intensity of the cyclone), the surface cyclone had deepened to 980 hPa and was located just off the coast of Cape Hatteras, North Carolina (Fig. 2b). 1200 UTC 25 January was also the time in which the heaviest precipitation was falling throughout the mid-Atlantic United States. The surface cyclone deepened to a minimum of 976 hPa as it continued its northward movement. The surface cyclone finally began to weaken off of the New Jersey coast at 1800 UTC 25 January.

The surface cyclogenesis was able to begin once the upper level trough reached the Gulf of Mexico and Western Atlantic. The primary 'forcing' mechanism for vertical motion and concomitant precipitation over the Mid Atlantic appears to have been frontogenesis. The most intense vertical velocities at 1200 UTC 25 January could be found near 600 hPa, north and west of the surface cyclone. As the 600 hPa trough intensified and eventually became cut off at 1200 UTC January 25 (Fig 2a), the flow became more diffluent over the mid-Atlantic. Such a configuration of wind and temperature was frontogenetical. A cross section (orientation shown on Fig. 2b) through the maximum vertical velocities at 1200 UTC 25 January (Fig. 3a), indicates that the upward vertical motion is coupled with positive frontogenesis, extending from the surface to the middle troposphere, tilting westward with height over the surface and mid-tropospheric frontal zone.

3. MODEL CONFIGURATION

Using the MM5, simulations of 60, 48, 36, 24, and 12 hours ending at 1200 UTC 25 January 2000 were performed. The key components to the MM5 setup for the simulations are as follows:

- Initial and boundary conditions taken from the NCEP Eta Model
- Sea surface temperatures taken from the ECMWF analyses

• Single domain with 30 km horizontal resolution and 23 vertical levels
• Grell cumulus parameterization
• MRF (Hong and Pan 1996) boundary layer scheme
• Explicit moisture scheme with ice (Dudhia, 1989)

For brevity, the discussion to follow will focus primarily on the 24 hour simulation.

The upper trough was poorly forecast in the 24 hour MM5 simulation. While the trough was nearly in the correct position, its minimum height was 30 meters too high (Fig. 4a). How the model handles latent heating may have been important, which would also explain the disorganized nature of the middle tropospheric trough in the simulation. The 600 hPa vertical velocity fields (Fig. 4b) share many of the same characteristics as the analysis. A cross section constructed between the same two points as in Fig. 2 shows that the upward vertical motion is primarily associated with positive frontogenesis in the model simulation (Fig. 3), but much further to the east. The model simulation captures the westward tilt with height of the vertical motion and frontogenesis.

The model forecast of the cyclone position and intensity at 1200 UTC 25 January improved with shorter lead times. With lead times 36 hours and less, the simulations were able to produce sea level pressure minima

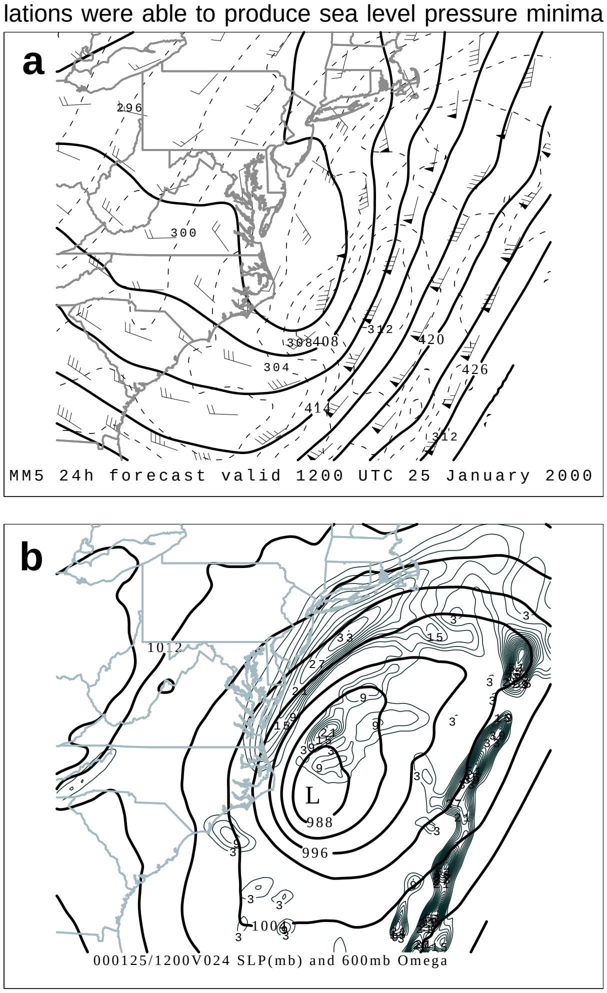

Figure 4. As in Fig. 2, except for 24 h MM5 forecast valid at 1200 UTC 25 January.

within 100 km of the analyzed minimum at 1200 UTC 25 January (Fig. 5). In addition, the simulations deepened the surface cyclone to within a few millibars. However, there is no systematic improvement of the model forecasted precipitation. In fact, it appears that the precipitation forecast was degraded between the 48 (Fig. 5d) and 36 hour (Fig. 5c) simulations. This result suggests that the processes involved in the forcing for the vertical motion are not necessarily directly related to the cyclone position and intensity.

4. SENSITIVITY STUDY and SINGULAR VECTORS

4.1 Motivation

A sensitivity study involves calculating how a particular function of a forecast state of a model (called the *response function*) changes with respect to changes in the initial or boundary conditions of that model. This calculation, which results in a gradient of the response function with respect to the initial (or boundary conditions) can in principle be used to evaluate how changes in the initial model state will effect the response function at the final time. To the extent that the forecast errors for the 24 - 25 January 2000 event are related to errors in specification of the initial conditions and not to model error due to physical parameterizations or model resolution, it is possible to identify what changes to the initial or boundary conditions for the model forecasts would reduce the forecast error. Based on the discussion above, it appears that the forecasts of the cyclone position (or intensity) and forecasts of the precipitation (or vertical motion) do not share the same forecast sensitivities. As a consequence, attempts to identify a set of 'optimal' initial conditions for an improved forecast of the cyclone intensity or position will not necessarily lead to improvements in the precipitation forecast.

An adjoint model is an efficient tool to calculate the sensitivity of a response to changes in the initial or boundary conditions (Errico, 1997). In order to develop the adjoint of a forecast model, the tangent linear model (TLM) of that forecast model must first be developed. The adjoint is then simply the transpose of the TLM. The adjoint model takes as its input the gradient of the response function at the final forecast time, and then integrates this gradient backward to the initial time. The output of the adjoint model is then the sensitivity of the selected forecast response function to the initial conditions.

In this study, we make use of the MM5 adjoint modeling system (Zou et al., 1997) to calculate the sensitivities of a set of model forecast response functions with respect to the initial state of the model. The TLM and corresponding adjoint of the MM5 include simple physical parameterizations:

• Horizontal and vertical diffusion
• Dry convective adjustment
• Bulk aerodynamic surface flux parameterization.
• Kuo and Grell cumulus parameterization schemes

The adjoint model will be integrated ('backwards') about a moist basic state derived from an MM5 forecast which utilizes more complete model physics.

4.2 Discussion of future work

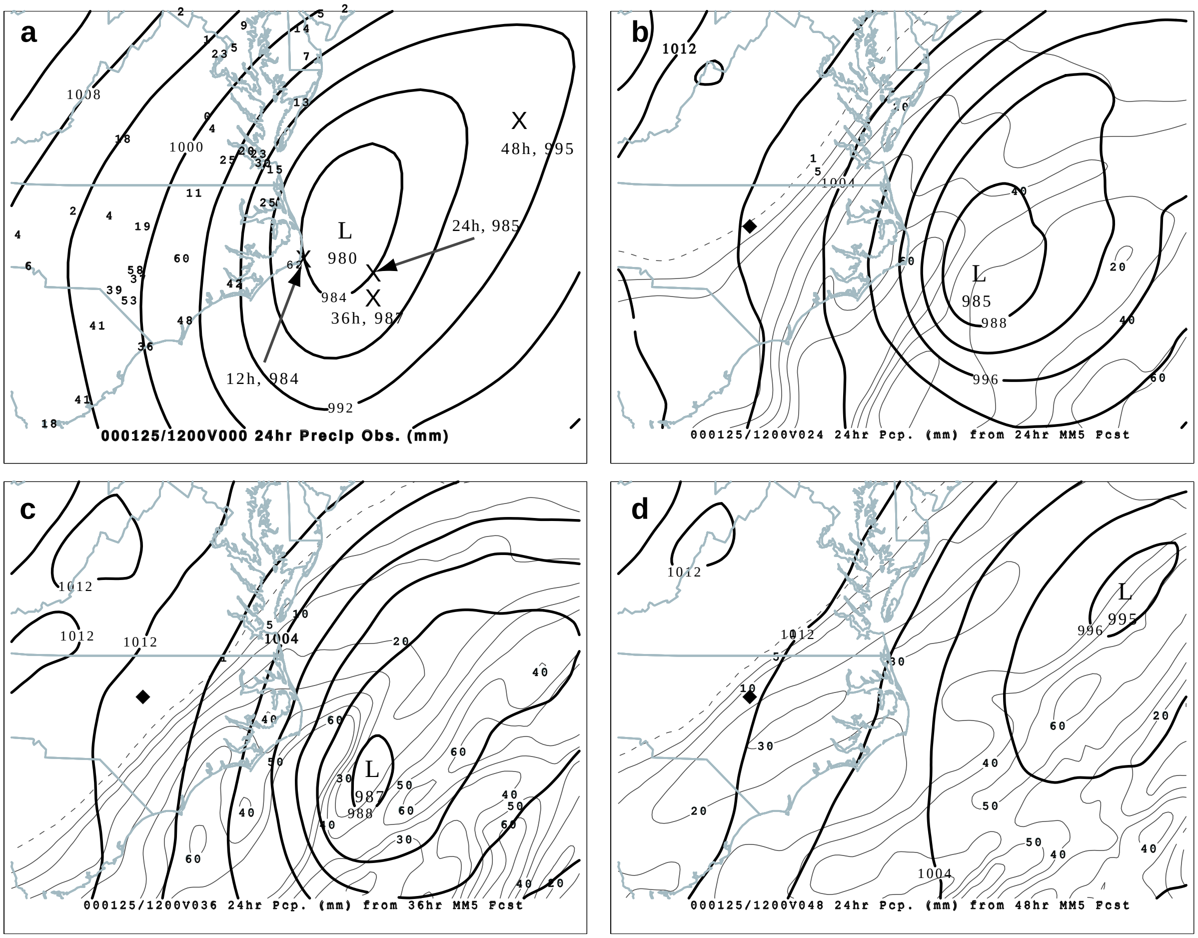

Figure 5. (a) Mean sea level pressure analysis (contour interval 4 hPa) for 1200 UTC January 2000 and observed 24 h precipitation ending at the same time; (b) 24 h, (c) 36 h, and (d) 48 h forecasts of mean sea level pressure (heavy contour, interval 4 hPa) and 24 hour accumulated precipitation valid for 1200 UTC January. X's in panel (a) identify the location of the cyclone center in the 12h, 24h, 36h, and 48h forecasts.

We are interested in understanding why improvements in the forecast of the cyclone (position and intensity) were not linked with improvements in the precipitation/vertical motion forecast. Relevant response functions to consider for cyclone intensity are the pressure perturbation in the model's lowest layer or the circulation about a box enclosing the cyclone. Other response functions that will be considered are related to the vertical motion. Two possible candidates are the model forecast of vertical motion over an area or within some volume, or the model forecast of frontogenesis. We propose to compare the sensitivities of these response functions with respect to the initial model state.

In addition to evaluating the sensitivities of the set of response functions, we will also investigate the growth of initial analysis errors by determining that portion of the analysis errors that projects onto the leading singular vectors of the basic state flow used in the TLM and adjoint model integrations.

The assumptions of dry, linear dynamics will be evaluated to determine the validity of these assumptions for this study.

5. REFERENCES

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