SENSITIVITY DIAGNOSIS OF THE 24-25 JANUARY 2000 STORM

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1. INTRODUCTION

On 24-25 January 2000, an intense winter storm deposited as much as 50 cm of snow throughout portions of the eastern United States. This event was noteworthy as operational numerical weather prediction (NWP) guidance was particularly poor for lead times as short as 36 hours. For shorter forecast lead times, while model guidance regarding the surface cyclone position and intensity at 1200 UTC 25 January 2000 improved, guidance for the distribution of the intense precipitation remained poor. With lead times as short as 24 hours, forecasts of the precipitation remained too far to the east, missing most of the precipitation that fell over the mid-Atlantic coastal states.

The objectives of this study are to investigate the reasons for the poor numerical forecasts, as well as to understand why improvements in forecasted cyclone position and intensity were not associated with improvements in the forecasted position of the intense precipitation band. A sensitivity study will allow us to calculate how a particular function of the NWP model forecast state (the response function, *R*), changes with respect to changes in the model control variables. These sensitivities, defined as the gradient of the response function with respect to the model control variables, are most efficiently calculated using the adjoint of an NWP model. By using various response functions related to both the forecasted cyclone and its associated vertical motion, we can investigate possible sources for the forecast error, as well as investigate why improvements in the forecasted surface cyclone were not necessarily associated with improved forecasts in the distribution of precipitation.

The synoptic setting for the development of the storm will be briefly described in section 2. In section 3, a description of the modeling system, its associated adjoint model and necessary modifications, as well as the data sets used in this study is presented. Section 4 contains a description of the sensitivity study, as well as examples of calculated forecast sensitivities. A description of future work may be found in section 5.

2. SYNOPTIC OVERVIEW

The precursor to the surface cyclone was an upper tropospheric short wave trough that had crossed into the northwest United States on 23 January. Surface cyclogenesis began once the upper level trough

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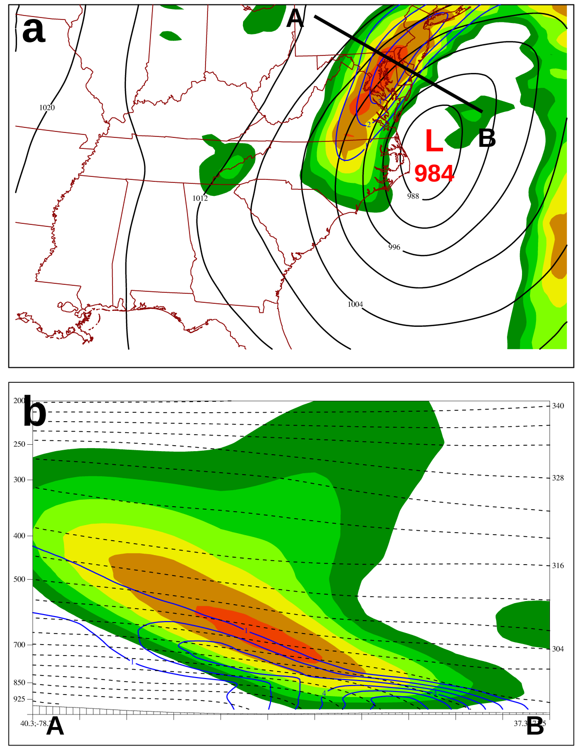

Figure 1. 1200 UTC 25 January 2000 analysis of (a) sea level pressure (black, interval 4 hPa), 700 hPa frontogenesis (blue, interval 1°C(1000km 3h)$^{-1}$ only positive values contoured), and vertical velocity omega (color filled, interval -2 μb s^{-1}, negative values only). Cross section (b) of frontogenesis (blue, interval 1°C(1000km 3h)$^{-1}$ only positive values contoured), vertical velocity omega (color filled, interval -2 μb s^{-1}, negative values only), and potential temperature (thin dashed, interval 3K) valid at same time. Line A-B on (a) denotes orientation of cross section for (b).

reached the northeastern Gulf of Mexico at 0600 UTC 24 January. The surface cyclone then proceeded to cross Florida and continued to intensify as it began to make a northward turn. The most rapid deepening occurred between 2100 UTC 24 January and 1200 UTC 25 January as the surface cyclone moved northeastward along the southeast coastline of the United States from Florida to North Carolina. By 1200 UTC 25 January (near the time of peak intensity of the surface cyclone), a sea level pressure minimum of 984 hPa was located just off the coast of Cape Hatteras, North Carolina (Fig. 1a). 1200 UTC 25 January was also the time which the heaviest precipitation was falling

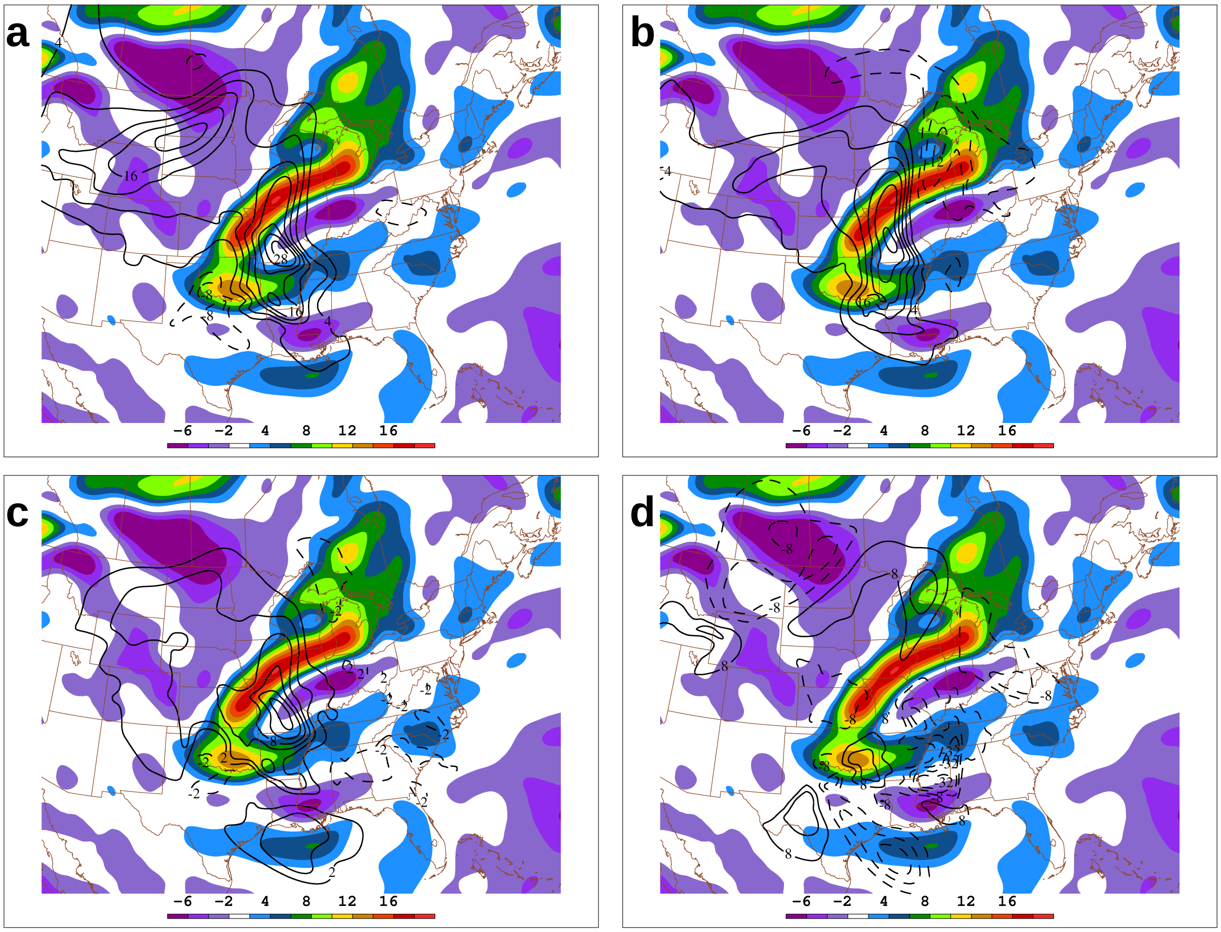

Figure 2. 36h sensitivity gradients (with respect to the initial distribution of 500 hPa relative vorticity) valid at 0000 UTC 24 January 2000 for (a) $-R_1$ (interval $4\text{x}10^5$ Jskg^{-1}), (b) R_2 (interval $4\text{x}10^7$ s^{-1}s), (c) R_3 (interval $2\text{x}10^{-11}$ K^{2}m^{-2}), and (d) R_4 (interval $8\text{x}10^1$ m). For the sensitivity gradients, the zero contour been omitted, positive values are solid, and negative values are dashed. Also plotted is the 500 hPa relative vorticity valid at the same time (color filled, fill interval $2\text{x}10^{-5}$ s^{-1}).

throughout the mid-Atlantic United States. The primary ‘forcing’ mechanism for the 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. A cross section through the maximum vertical velocities at 1200 UTC 25 January (Fig. 1b), indicates that the upward vertical motion is coupled with positive frontogenesis, extending up into the middle troposphere, tilting westward with height.

3. MODEL CONFIGURATION AND DATA

Sensitivity calculations were performed using the MM5 Adjoint Modeling System (Zou et al. 1997). The Tangent Linear Model and the corresponding adjoint of the MM5 include simple physical parameterizations:

- Horizontal and vertical diffusion
- Dry convective adjustment
- Bulk aerodynamic surface flux parameterization
- Grell cumulus parameterization scheme

All of the sensitivities to be described were calculated with this system by integrating the adjoint model “backwards in time” (without considering the moisture) about a moist basic state derived from a non-hydrostatic MM5 non-linear forecast which utilized more sophisticated physics. All non-linear ‘forward’ integrations were initialized using the National Center for Environmental Prediction’s final analyses.

In order to remove non-physical oscillations in the output of a time-dependent adjoint model, modifications to the adjoint model code (Zou et al. 2001) were required to output the time evolving sensitivity fields.

4. SENSITIVITY STUDY

For this case, we are particularly interested in understanding why improvements in the forecasted cyclone (position and intensity) were not necessarily associated with improvements in the vertical motion and precipitation forecast. We perform a sensitivity study using the adjoint modeling system, considering four relevant response functions:

- R_1: Energy-weighted forecast error (in a region encompassing the cyclone at verification time)
- R_2: Lower tropospheric circulation about a box (in same region as energy-weighted error calculation)
- R_3: 700 hPa horizontal frontogenesis (in a region extending from central North Carolina to New Jersey)
- R_4: Vertical motion in a region similar to that defined for response function R_3.

Response function R_2 was chosen because it is a measure of cyclone intensity, while R_3 and R_4 were chosen as they are related to the dynamics governing the precipitation. R_1 contains aspects of the other three response functions, as there were errors in both the forecasted surface cyclone and vertical motion. The gradients of these four response functions with respect to the initial conditions for a 36h forecast valid 1200 UTC 25 January as well as their time evolution were calculated. In addition to calculating sensitivities with respect to the model control variables, sensitivities with respect to derived variables such as relative vorticity and geopotential were also computed.

The sensitivity gradients with respect to relative vorticity for all four response functions have their greatest magnitude in the vicinity of the upper trough (Fig. 2). Gradients of R_1, R_2, and R_3 (Figs. 2a, b, and c) indicate that positive perturbations in the analyzed relative vorticity over Missouri, just downstream of the upper trough will lead to a reduction of the forecast error, as well as in increase in the lower tropospheric circulation and 700 hPa horizontal frontogenesis (for this interpretation and for the most direct comparison, the gradient with respect to R_1 has been multiplied by negative one). This would imply that such a perturbation would produce a more intense cyclone as well as increase the 'forcing' for the precipitation in the desired regions. Although, not all of the largest sensitivities are associated with the main upper trough, as R_1 and R_3 have relatively large sensitivities over North and South Dakota. However, there are often significant differences in sensitivity gradients when considering multiple response functions. It should be expected that perturbations that would lead to an increase in frontogenesis would also lead to an increase in the vertical motion forecast. For example, it is counterintuitive that placing a positive perturbation in the analyzed relative vorticity south of Louisiana would lead to an increase in the forecast of frontogenesis, but would at the same time lead to a decrease in the forecasted vertical velocities (Fig. 2c and d). It is also noteworthy that sensitivity gradients for R_4 are significantly different in most locations, when compared with sensitivities for the other three response functions.

5. FUTURE WORK

Further comparison of the forecast sensitivity gradients and their time evolution will need to be done, in order to better understand why improvements in the forecast of the cyclone aren't necessarily associated with improvements in the vertical motion forecast. For completeness, we hope to investigate the sensitivity gradients with respect to distributions of potential vorticity (this gradient can be derived via the use of the adjoint of a potential vorticity inversion operator). Sensitivity gradients for the energy-weighted error response function can be used to create an optimal analysis, which is intended to minimize the forecast error. Figure 3 shows the results of running the non-linear model forward when initializing from an 'optimal initial condition'. This forecast is much improved from the same model integration initialized from operational analyses (not shown), in terms of both the surface cyclone and the distribution of vertical motion. Comparing the evolution of this corrected forecast in conjunction with singular vector calculations will allow us to further investigate the growth of initial errors for this case. The assumption of dry, linear dynamics will be evaluated to determine the validity of these assumptions for this study.

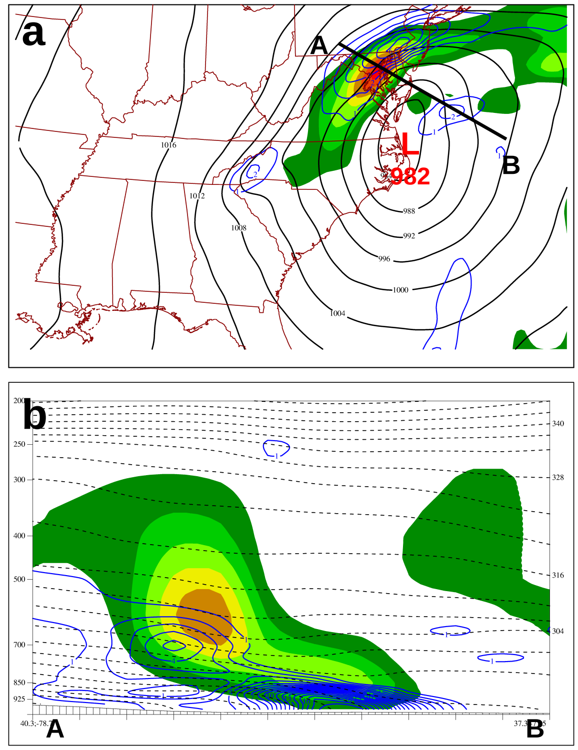

Figure 3. 36h forecast valid at 1200 UTC 25 January 2000 of (a) sea level pressure (black, interval 4 hPa), 700 hPa frontogenesis (blue, interval $1^{o}C(1000km\ 3h)^{-1}$ only positive values contoured), and vertical velocity omega (color filled, interval -6 μb s^{-1}, negative values only). Cross section (b) of frontogenesis (blue, interval $1^{o}C(1000km\ 3h)^{-1}$ only positive values contoured), vertical velocity omega (color filled, interval -2 μb s^{-1}, negative values only), and potential temperature (thin dashed, interval 3K) valid at same time. Line A-B on (a) denotes orientation of cross section for (b).

6. REFERENCES

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Acknowledgements

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