Adjoint Sensitivity Study on Idealized Explosive Cyclogenesis

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ABSTRACT

The adjoint sensitivity related to explosive cyclogenesis in a conditionally unstable atmosphere is investigated in this study. The PSU/NCAR limited-area, nonhydrostatic primitive equation numerical model MM5 and its adjoint system are employed for numerical simulation and adjoint computation, respectively. To ensure the explosive development of a baroclinic wave, the forecast model is initialized with an idealized condition including an idealized two-dimensional baroclinic jet with a balanced three-dimensional moderate-amplitude disturbance, derived from a potential vorticity inversion technique. Firstly, the validity period of the tangent linear model for this idealized baroclinic wave case is discussed, considering different initial moisture distributions and a dry condition. Secondly, the 48-h forecast surface pressure center and the vertical component of the relative vorticity of the cyclone are selected as the response functions for adjoint computation in a dry and moist environment, respectively. The preliminary results show that the validity of the tangent linear assumption for this idealized baroclinic wave case can extend to 48 h with intense moist convection, and the validity period can last even longer in the dry adjoint integration. Adjoint sensitivity analysis indicates that the rapid development of the idealized baroclinic wave is sensitive to the initial wind and temperature perturbations around the steering level in the upstream. Moreover, the moist adjoint sensitivity can capture a secondary high sensitivity center in the upper troposphere, which cannot be depicted in the dry adjoint run.

Key words: baroclinic wave, explosive midlatitude cyclone, adjoint sensitivity, potential vorticity inversion

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1. Introduction

Explosive midlatitude cyclones, also called “bombs”, are rapidly developing midlatitude cyclones whose minimum surface pressure falls at least 1 hPa h⁻¹ for 24 h on average (Sanders and Gyakum, 1980). The development of a midlatitude cyclone is closely related to frontogenesis, and often causes heavy rainfall or snowfall. However, the forecasting of explosive cyclogenesis and the associated heavy rainfall/snowfall still has many challenges, due to the misrepresentation of diabatic processes in extratropical cyclones (Rodwell et al., 2013), and the nonlinear rapid development of initial errors caused mainly by moist instability (Zhang et al., 2002; Tan et al., 2004; Zhu and Thorpe, 2006). Therefore, it is worthwhile studying the sensitivity of explosive cyclogenesis to the initial perturbations with a moist process included via the adjoint method.

The adjoint method has been widely used in meteorology (e.g., Le Dimet and Talagrand, 1986), and sensitivity analysis is one of its basic applications. It is an efficient tool for studying the sensitivity of various aspects of forecasting to the initial state. In comparison to traditional sensitivity analysis, adjoint sensitivity analysis can directly answer the question “How sensitive is a model’s result to arbitrary input perturbations?” (Errico, 1997), and the adjoint model can obtain the sensitivity of certain special aspects of the forecast to all the initial variables on the whole model grid through only one model integration.

Many adjoint sensitivity studies have been con-
ducted for midlatitude cyclones. For example, Langland et al. (1995) calculated the adjoint sensitivity of an idealized midlatitude cyclone with only dry physics included, and found high sensitivity regions located in the baroclinic zone above the developing cyclone and in the middle and lower troposphere. Their subsequent work that included moist physics in the adjoint calculation showed that moist processes increased the sensitivity magnitude, but did not alter the primary spatial pattern of sensitivity; additionally, the cyclone intensity was sensitive to the vertical distribution of temperature perturbations (Langland et al., 1996). Recently, from an idealized cyclone study in a three-dimensional quasigeostrophic model, Kim and Beare (2011) found that the dynamical mechanism of cyclone development by adjoint sensitivity coincided with that of nonlinear sensitivity. Besides adjoint studies on idealized cyclones, many more real cases have also been examined to understand the dynamical processes or improve the forecasting of midlatitude cyclones, e.g., Atlantic cyclogenesis (Vukičević and Raeder, 1995; Zou et al., 1998), Mediterranean cyclone (Homar and Stensrud, 2004), and snowstorms caused by midlatitude cyclones (Langland et al., 2002; Kleist and Morgan, 2005a, b; Jung and Kim, 2009).

The main aim of this study is to understand, through adjoint sensitivity analysis, the key processes that affect the explosive development of midlatitude cyclones, especially under the conditions of strong convection and heavy precipitation. To simulate the explosive development of an idealized midlatitude cyclone, we use an idealized condition including an idealized two-dimensional baroclinic jet with a balanced three-dimensional moderate-amplitude disturbance, derived from a potential vorticity (PV) inversion technique. In contrast to adding wind and temperature perturbations directly in the upper troposphere as in Langland et al. (1995), the initial condition generated from the PV inversion technique has initially balanced wind and temperature fields and high baroclinicity to ensure the explosive development of the synoptic-scale baroclinic wave. Furthermore, midlatitude cyclones are usually related to heavy rainfall and snowstorms; moist processes play an important role in the genesis and development of cyclones.

In this idealized simulation, a special initial moisture condition is added to generate the strong local moisture for the convection initiation and precipitation. Thus, we are able to evaluate the characteristics of the adjoint sensitivity related to the explosive development of this idealized midlatitude cyclone, as well as the influence of moist processes.

However, when moist physics plays a leading role, as well as the resolution increases, the tangent linear accuracy of the adjoint sensitivity will be greatly affected (Park and Droegemeier, 1997; Errico and Raeder, 1999; Ancell and Mass, 2006). Errico and Vukicevic (1992) showed that a good tangent linear approximation can remain valid for up to 1.5 days, but less in regions of explosive cyclogenesis. Moreover, Gilmour et al. (2001) indicated that the tangent linear approximation is usually valid for less than 1 day. Nevertheless, there are many applications of the adjoint method for mesoscale systems with remarkable moist processes, such as adjoint sensitivity studies on heavy rainfall (Soci et al., 2006; Chu and Tan, 2010), mesoscale vortex (Wang and Gao, 2006), and even tropical cyclones (Kim and Jung, 2006; Wu et al., 2007; Chu et al., 2011). Through changing the moisture content and distribution in the initial conditions, this paper discusses the valid duration of the tangent linear approximation under conditions of heavy precipitation for this idealized case.

The rest of the paper is organized as follows. Section 2 describes the numerical models, idealized initial conditions, and the experimental design. A brief overview of the idealized explosive cyclone is given in Section 3. Section 4 discusses the tangent linear assumption test and the selection of the response functions for the adjoint calculation. All the adjoint results are investigated in Section 5, followed by a summary in Section 6.

2. Numerical models, initial conditions, and experimental design

In this study, the non-hydrostatic mesoscale model MM5 (Grell et al., 1995; Dudhia et al., 1993) is
employed to simulate the baroclinic wave-frontal system, and the MM5 adjoint system (Zou et al., 1997) is used to calculate the adjoint sensitivity.

As in Tan et al. (2004), the initial condition is generated by giving a zonally invariant two-dimensional PV field and a three-dimensional PV perturbation; the boundary condition is specified as in Rotunno et al. (1994). By inverting the PV fields using the inversion technique, the baroclinic jet and potential temperature fields are obtained. The wind and potential temperature fields are therefore initially balanced, which ensures the fast development of the synoptic-scale baroclinic wave (Fig. 1a). The initial moisture field is also designed the same as in Tan et al. (2004). This initial distribution of moisture varies from a moist condition at the lowest level to a dry one above the height of 8 km (see Fig. 1b), producing a large horizontal moisture gradient in the lower to middle troposphere within the south region of the baroclinic zone. This distribution of moisture can generate large conditional instability, which is conducive to the initiation of convection and precipitation.

The domain of integration is rectangular, configured with 150 grid points in the $x$ direction and 70 in the $y$ direction. The horizontal grid resolution is 60 km and there are 20 vertical layers. The model is run with Cartesian coordinates and a constant Coriolis parameter. In the forecast model, the physical parameterization schemes are the Kuo cumulus parameterization, the Blackada planetary boundary layer scheme, and the simple ice phase microphysics scheme. The adjoint model uses the same parameterization schemes as the forecast model. Although this paper uses an idealized initial condition, it also uses a primitive equation model and complex parameterization schemes. Therefore, compared with simulating the cyclogenesis process with a simple dynamical model, this simulation is more realistic in its reflection of the effect of physical processes, such as diabatic heating.

Two numerical simulations are performed, i.e., a control experiment (CNTL), in which the initial maximum relative humidity ($\text{RH}_0$) is set to 70%; and a dry experiment (DRY), which is performed in a totally dry atmosphere with other configurations exactly the same as in CNTL.

Before the adjoint sensitivity computation, the accuracy of the tangent linear model (TLM) is evaluated. Firstly, we follow the method of Zou et al. (1997; Eqs. (3.15) and (3.16)) to verify the correctness of the TLM and adjoint model. Secondly, we compare the evolution of the initial perturbations in the nonlinear simulations and TLM integration. The initial perturbations consist of random, zero-mean Gaussian noise added in the temperature field with the standard deviation being set to 0.2 K. To investigate the impact of moist processes on the accuracy of the TLM, this test is carried out in conditions of dry, fake-dry (no latent heating), and different initial water content from

**Fig. 1.** (a) Vertical cross-section of initial zonal velocity (thick contours; interval: 10 m s$^{-1}$; maximum: 51.59 m s$^{-1}$) and potential temperature (thin contours; interval: 4 K). (b) Vertical distribution of the initial relative humidity for the control experiment ($\text{RH}_0 = 70\%$; interval: 10%).
RH₀ = 70% to RH₀ = 90%. Table 1 lists the names and settings of each experiment.

**Table 1.** Experimental settings for the tangent linear assumption

| Experiment name | Moisture content |
|-----------------|------------------|
| RH70            | RH₀ = 70%        |
| RH80            | RH₀ = 80%        |
| RH90            | RH₀ = 90%        |
| DRY             | No moisture      |
| FDRY            | RH₀ = 70%, no latent heating |

Note: standard deviation of initial temperature perturbations is set to 0.2 K.

3. Explosive development of the simulated baroclinic wave

The baroclinic initial perturbation experiences explosive growth both in the moist and dry simulations (Fig. 2). During the first 7 h, the baroclinic wave begins to intensify in both CNTL and DRY, and there is almost no difference between these two simulations, since convection has not yet imposed any notable effect on the development of the cyclone. Thereafter, the minimum surface pressure in DRY maintains at 985 hPa for about 10 h, from hours 8 to 18 of the simulation. Meanwhile, the surface low in CNTL begins to intensify, causing a large difference in surface pressure simulations. At hour 33, the difference reaches a peak of 11 hPa, and then reduces to about 9 hPa. At hour 48, the minimum surface pressure in DRY and CNTL is 954 and 946 hPa, respectively. It is obvious that the moist processes help the explosive growth of the idealized midlatitude cyclone.

The evolution of the pressure and surface potential temperature fields in DRY and CNTL are also quite different, as shown in Figs. 3 and 4, respectively. The surface cyclone in CNTL moves and develops faster than that in DRY. Zhang and Tan (2007) provided a detailed description of these features. Figure 3 shows the cyclone’s frontal structure during its initial (Fig. 3a) and fast intensification (Figs. 3b and 3c) stages in DRY, which reveals the typical features of the baroclinic wave-frontal system. For example, the cyclone is located in a broad baroclinic zone, and the cold front is roughly perpendicular to the warm front forming a “T-bone” structure (Fig. 3b). As the cyclone develops into its mature stage, the western section of the warm front bends around the low cyclonically, forming a “bent-back” structure (Fig. 3c). In CNTL, precipitation is produced in the early stage (Fig. 4a); and with the development of the cyclone,

![Fig. 2. Temporal evolution of minimum surface pressure in CNTL (dashed line) and DRY (solid line).](image)

![Fig. 3. Evolution of the cyclone’s surface pressure (solid contours; interval: 5 hPa) and surface potential temperature (dashed lines; interval: 4 K) in experiment DRY at hours (a) 24, (b) 36, and (c) 48 of the simulation.](image)
the intensity and range of the precipitation increase (Figs. 4b and 4c), indicating the existence of strong moist convection near the frontal zone. Up to hour 48 of the simulation, the surface low center and warm front are both stronger in CNTL than in DRY. It is clear that moist processes not only produce a large amount of precipitation, but also influence the structure, intensification, and movement of this idealized midlatitude cyclone.

4. Tangent linear assumption and the response functions

4.1 Validation of the tangent linear assumption

Before computing the adjoint sensitivity, an evaluation of the TLM and adjoint model correspondence is carried out to make sure that the adjoint sensitivity is a good approximation of the nonlinear sensitivity. We compare the TLM solutions with the difference between pairs of control and perturbed nonlinear forecasts using the same settings. The correlation between the nonlinear and tangent linear temperature perturbations during the 48-h simulation at 6-h intervals is shown in Fig. 5; all correlation coefficients are statistically significant at the 0.005 level by using a Student’s t-test. In general, the correlation gradually decreases with integration time in all the tests. However, the dry and moist tests perform very differently. In the dry test, the correlation decreases quite slowly, and remains at a value of 0.965 even after 48 h of integration. On the contrary, the correlation decreases rather rapidly when moist physics is included. The correlation decreases with increased initial moisture, with the coefficients falling below 0.8 after 47 and 37 h of integration in RH80 and RH90, respectively (Fig. 5). The results from the fake-dry test (RH = 70%) are similar to that of the dry test, indicating that the nonlinear effect is mainly due to the release of latent heat from non-adiabatic processes. To qualitatively describe the agreement between the nonlinear perturbations and tangent linear perturbations, Figs. 6a and 6b show the 48-h forecast of the perturbations from experiment RH70. It can be seen that after 48 h of integration, the distribution, spatial scale, and amplitudes of the nonlinear and tangent linear perturba-

Fig. 4. As in Fig. 3, but for CNTL. Color-shading indicates the 6-h accumulated precipitation.

Fig. 5. Evolution of the correlation ($p < 0.005$) between nonlinear and tangent linear temperature perturbations for dry adjoint integration (DRY); fake-dry adjoint integration (FDRY; RH$_0$ = 70%); moist adjoint integration with RH$_0$ = 70% (RH70), 80% (RH80), and 90% (RH90).
The above quantitative and qualitative evaluation shows that, although moist physics will hamper the tangent linear assumption, the tangent linear model can still simulate the nonlinear evolution of initial perturbations during a 48-h integration under moderate water content (RH = 70%). As addressed in Section 3, heavy precipitation occurs at around hour 24 of the forecast in CNTL (RH = 70%). Therefore, the CNTL simulation is chosen as the background for the adjoint calculation here. On the one hand, the model can simulate the explosive development of the idealized cyclone, as well as the active convection and heavy rainfall; on the other hand, the tangent linear assumption can still be valid during the 48-h integration. All these factors make it possible and reasonable to investigate the adjoint sensitivity of this rapidly developing idealized cyclone with moist physics included.

4.2 Response functions

To perform an adjoint-model run, a predefined forecast measure, called a response function, must be selected in advance. The response function must be derivable for model control variables, and the gradients of the response function with respect to the model state variables at the forecast time serve as the initial conditions for the adjoint model integration. In this study, two response functions related to the intensity of the midlatitude cyclone are selected for the adjoint calculation: 48-h simulated minimum surface pressure ($J_1$; Fig. 8) and the vertical component of relative vorticity over the vorticity center ($J_2$; Fig. 7).

5. Adjoint sensitivity analysis

5.1 Minimum surface pressure sensitivity ($J_1$)

After 48 h of adjoint integration, the sensitivity of $J_1$ with respect to the model initial conditions at all model levels is obtained. For example, Fig. 8 shows the horizontal distributions of the initial meridional wind sensitivity at 700 hPa in the dry and moist adjoint runs, respectively. It can be seen that, in both the moist and dry adjoint runs, the largest sensitivity is mainly located in the upstream baroclinic zone (Fig. 8). Moreover, 700-hPa meridional wind sensitivities show a cyclonic pattern, with a dipole of positive and negative sensitivity centers in a northeast–southwest direction.
westward orientation (Fig. 8). The sensitivity to zonal wind also shows a cyclonic pattern (figures omitted). This sensitivity distribution means that cyclonic wind perturbations added over the sensitive region would lead to an increase of 48-h forecast minimum surface pressure, i.e., a weakening of the cyclone’s intensity, and vice versa. There is a remarkable difference between the dry and moist adjoint runs: the magnitude of the moist adjoint sensitivity is much larger than the dry adjoint sensitivity, and there is another weaker sensitive region located to the east of the primary sensitive region in the moist adjoint run (Fig. 8). This difference indicates that the cyclogenesis in the moist simulation is more complicated than that in the dry simulation, since not only the initial perturbations in the upstream region, but also those near the 48-h cyclone center, can substantially impact the 48-h forecast intensity.

To investigate the vertical distribution of adjoint sensitivity, cross-sections are made along the line AB in Fig. 8a. Figure 9 shows the sensitivity of $J_1$ with respect to the zonal wind component ($\partial J_1/\partial u$), meridional wind component ($\partial J_1/\partial v$), and temperature field ($\partial J_1/\partial T$) in the dry and moist adjoint runs, respectively. In general, the vertical distribution of all the adjoint sensitivities presents a westward tilt, both in the dry and moist adjoint runs (Fig. 9). The maximum sensitivity is located between 600 and 800 hPa, whereas the moist maximum sensitivity center is slightly higher than the dry one. It should be noted that the height of the maximum sensitivity center coincides with the steering level according to the definition of Hoskins et al. (1985), at which level the speed of the basic zonal flow and the baroclinic wave are the same. Since the speed of basic flow is the same in the dry and moist simulations, while the moist baroclinic wave moves faster than the dry baroclinic wave, the steering level is therefore slightly higher in the moist simulations. This is probably the reason why the moist maximum sensitivity center is higher than the dry one. Moreover, the magnitude of the moist sensitivity is about 2–4 times larger than that of the dry sensitivity, which is related to the amplifying effect of latent heat release reported by Errico and Raeder (1999).

Another remarkable difference lies in the upper troposphere. It can be seen that there is a much weaker wind sensitivity dipole between 400 and 200 hPa in the moist adjoint run (Figs. 9b and 9d), while the dry wind sensitivity is mainly confined below 400 hPa (Figs. 9a and 9c). It should be noted that this upper-level wind sensitivity dipole has a reverse phase with the main primary sensitivity dipole in the lower troposphere. The patterns of $-\partial J_1/\partial v$ and $-\partial J_1/\partial u$ indicate low-level convergence and upper-level divergence, which are beneficial for strengthening of the cyclone (decrease in $J_1$). The existence of upper-level sensitivity in the moist adjoint run is ascribed to the latent heat release, which can enhance the vertical motion, strengthen the low-level convergence, and cause upper-level divergence. Therefore, the moist adjoint sensitivity can capture a secondary high sensitive center in the upper troposphere, which cannot be depicted in the dry adjoint run.

Figure 10 depicts the vertical profiles of the to-

![Figure 8](image-url)
Fig. 9. Cross-sections along the line AB in Fig. 8a of the sensitivity of $J_1$ with respect to the (a, b) initial zonal wind ($10^{-4}$ hPa m s$^{-1}$; contour interval: 5), (c, d) initial meridional wind ($10^{-4}$ hPa m s$^{-1}$; contour interval: 2.5), and (e, f) initial temperature ($10^{-3}$ hPa K$^{-1}$; contour interval: 3), respectively. Panels (a, c, e) show the dry adjoint integration and (b, d, f) the moist adjoint integration.

total sensitivity of the 48-h forecast $J_1$ to different initial variables in the dry and moist adjoint runs, respectively. As with the characteristics in Fig. 9, the total sensitivity is mainly concentrated in the mid-to-lower troposphere. It can also be seen that the moist processes not only enhance the magnitude of sensitivity,
but also extend the sensitivity to higher model levels (Fig. 10).

To further explore the inherent connection between temperature sensitivity and wind sensitivity, Fig. 11 presents the cross-sections of temperature sensitivity in the moist adjoint run along the lines CD and EF through the maximum sensitivity centers in Fig. 8b. Firstly, the moist sensitivity tilts northward with height. Secondly, to the west of the trough there is a positive sensitivity gradient with negative sensitivity in the south and positive sensitivity in the north, whereas the sensitivity to the east of the trough shows an inverse pattern. Thirdly, there is an inherent connection between temperature sensitivity and wind sensitivity. Supposing we have an initial temperature and wind perturbations with the same pattern as that of $-\partial J_1/\partial u$, $-\partial J_1/\partial v$, and $-\partial J_1/\partial T$, the temperature gradient and zonal wind will increase to the east of the trough and decrease to the west of the trough, which is consistent with the thermal wind relation. Furthermore, both the cold advection to the west of the trough and warm advection to the east of the trough will be enhanced. Such initial perturbations will be beneficial for the explosive cyclogenesis process. From the above analysis, the adjoint sensitivity with moist processes included indicates that proper settings of initial temperature and wind perturbations near the steering level will enhance the explosive development of the baroclinic wave.

**Fig. 10.** Vertical profiles of the total adjoint sensitivity of the 48-h forecast minimum surface pressure $J_1$ with respect to the initial temperature ($T$; hPa K$^{-1}$) and horizontal wind fields ($u$, $v$; hPa (m s$^{-1}$)$^{-1}$): (a) dry adjoint integration and (b) moist adjoint integration.

**Fig. 11.** Cross-sections along the lines (a) CD and (b) EF in Fig. 8b of the sensitivity of $J_1$ with respect to the initial temperature in the moist adjoint integration ($10^{-3}$ hPa K$^{-1}$; contour interval: 3).
5.2 Vertical component of relative vorticity sensitivity ($J_2$)

Besides the minimum surface pressure, the vertical component of relative vorticity is also related to the intensity of the midlatitude cyclone. It should be noted that a decrease in $J_1$ is usually associated with an increase in $J_2$; therefore, the pattern of sensitivity to $J_1$ and $J_2$ should present opposite phases. As an example, Fig. 12 shows the cross-sections of the meridional wind sensitivity ($\partial J_2/\partial v$) along the line AB in Fig. 8a in the dry and moist adjoint runs, respectively. In general, the characteristics of meridional wind sensitivity ($\partial J_2/\partial v$) are quite similar to those of $\partial J_1/\partial v$, except for the reverse of phase (Figs. 8c and 8d). Moreover, the difference between the dry and moist sensitivity of $J_2$ is more remarkable than that of $J_1$, because vorticity has a stronger correlation with latent heat release than minimum surface pressure. The sensitivity of $J_2$ with respect to the other initial variables also possesses similar characteristics, but with a reverse phase, as $J_1$ (figures omitted). However, it is worth noting that the response functions are defined at different model levels, whereas the sensitivity of them both maximizes around the steering level. These results further highlight the importance of mid-to-lower initial perturbations on the development of this idealized baroclinic wave.

6. Summary

This study investigates the adjoint sensitivity related to an idealized explosive cyclogenesis by using a PV inversion technique and MM5 adjoint system. First, the initial condition is generated by superposing an idealized two-dimensional baroclinic jet with a three-dimensional perturbation. The wind and potential temperature fields are obtained by inverting the PV field with the inversion technique. Thus, they are initially balanced, which ensures the rapid development of the synoptic-scale baroclinic wave. Second, the validity period of the TLM for this idealized baroclinic wave case is discussed, considering different initial moisture distributions and a dry condition. Lastly, two response functions (the 48-h forecast surface pressure center and the vertical component of relative vorticity of the cyclone) are selected for the adjoint computation. The conclusions can be summarized as follows.

(1) The validity of the tangent linear assumption for this idealized baroclinic wave case can extend to 48 h with intense moist convection, and the validity period can last even longer in the dry adjoint integration.

(2) The explosive development of the idealized baroclinic wave is sensitive to the initial wind and temperature perturbations around the steering level in the

![Fig. 12. Cross-sections along the line AB in Fig. 8a of the sensitivity of $J_2$ with respect to the initial meridional wind: (a) dry adjoint integration and (b) moist adjoint integration (contour interval: 0.01 m$^{-1}$).](image-url)
upstream baroclinic zone.

(3) The moist adjoint sensitivity can capture a secondary high sensitivity center in the upper troposphere, which cannot be depicted in the dry adjoint run.

Future work will focus on the rapid development process of explosive midlatitude cyclones through a real case study.

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