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Adjoint Sensitivity Experiments of a Meso-β-scale Vortex in the Middle Reaches of the Yangtze River

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ABSTRACT

A relatively independent and small-scale heavy rainfall event occurred to the south of a slow eastward-moving meso-α-scale vortex. The analysis shows that a meso-β-scale system is heavily responsible for the intense precipitation. An attempt to simulate it met with some failures. In view of its small scale, short lifetime and relatively sparse observations at the initial time, an adjoint model was used to examine the sensitivity of the meso-β-scale vortex simulation with respect to initial conditions. The adjoint sensitivity indicates how small perturbations of initial model variables anywhere in the model domain can influence the central vorticity of the vortex. The largest sensitivity for both the wind and temperature perturbation is located below 700 hPa, especially at the low level. The largest sensitivity for the water vapor perturbation is located below 500 hPa, especially at the middle and low levels. The horizontal adjoint sensitivity for all variables is mainly located toward the upper reaches of the Yangtze River with respect to the simulated meso-β-scale system in Hunan and Jiangxi provinces with strong locality. The sensitivity shows that warm cyclonic perturbations in the upper reaches can have a great effect on the development of the meso-β-scale vortex. Based on adjoint sensitivity, forward sensitivity experiments were conducted to identify factors influencing the development of the meso-β-scale vortex and to explore ways of improving the prediction. A realistic prediction was achieved by using adjoint sensitivity to modify the initial conditions and implanting a warm cyclone at the initial time in the upper reaches of the river with respect to the meso-β-scale vortex, as is commonly done in tropical cyclone prediction.

Key words: mei-yu front heavy rainfall, meso-β-scale vortex, adjoint method, sensitivity experiment

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1. Introduction

The study of extratropical cyclogenesis has been the subject of many numerical model-based investigations. Often these have taken the form of sensitivity studies in which certain variables or parameterizations are altered to determine their effects on a forecast of a cyclone event. Adjoint methods provide a new and powerful approach to numerical sensitivity analysis in meteorology. An adjoint model can be used to identify regions where changes to variables or parameters have the largest impact on a selected forecast measure. In these regions of high sensitivity, small perturbations can grow rapidly and can strongly influence the growth of forecast error.

The earliest use of adjoint methods in meteorology should be attributed to Lorenz (1965), who investigated predictability using tangent-linear and adjoint operators. Hall et al. (1982), Lewis and Derber (1985), and Hall (1986) demonstrated that the adjoint approach could be used efficiently to evaluate parameter sensitivity in atmospheric models. More recently, the adjoints of primitive-equation meteorological models have been developed and used in sensitivity studies by Errico and Vukicevic (1992), Farrell and Moore (1992), Rabier et al. (1992), Errico et al. (1993), and Langland et al. (1995). These studies identified preferred regions for high sensitivity in the middle latitudes and have examined several forecast sensitivity measures. They had also demonstrated that adjoint sensitivity provides acceptable accuracy for describing the effects of perturbations in nonlinear models.

For sensitivity studies, the adjoint method has several advantages compared with conventional sensitivity tests performed in the forward sense. A single adjoint run can provide sensitivity to all model variables

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and parameters directly and efficiently. In an adjoint model, a forecast aspect should be selected as a control forecast measure at an earlier time. This allows identification of some important sensitivity effects.

The meso-β-scale system is regarded as one of the main heavy rainfall disturbances along the Meiyu front. In spite of its small scale and short lifetime, the meso-β-scale system has significant intensification effects on cumulus convection, and can bring heavy rainfall in favorable environmental conditions. It was found that some meso-α-scale systems consisted of meso-β-scale systems during the Meiyu process of 14–15 July 1979 through the analysis of satellite and radar data (Ninomiya et al., 1988). And 51 meso-β-scale systems were discovered during the intense precipitation process of 12–16 June 1991 (Yang et al., 1994). The horizontal scale of these systems is no more than 250 km, and the lifetime is about 5 hours. These small-scale systems formed three long-lifetime meso-α-scale systems through combination, respectively. Some of these meso-β-scale systems, triggered suddenly at the front of the main clouds, are very difficult to forecast. Convective instability and the confluence of water vapor in the low troposphere provide favorable environmental conditions for the development of meso-β-scale systems, and the forcing effects of terrain and mesoscale disturbance may be the trigger mechanisms of the meso-β-scale systems (Bei and Zhao, 2002). When a meso-α-scale vortex moved east and stagnated in the middle reaches of the Yangtze River at 1200 UTC 29 June 1999, a meso-β-scale vortex was established on the lee side of a mesoscale mountain, where westerly flow on the south of the meso-α-scale vortex converged with the southerly flow from a warm section, and this was successfully simulated using the Penn State/NCAR mesoscale model MM5 with four dimensional data assimilation (FDDA, Wang et al., 2003). But without FDDA, the simulation met with some failures. Considering the relatively sparse observations of mesoscale systems, the presence of pronounced mesoscale signals in the initial conditions is very important to the simulation (Wang and Gao, 2003). In an attempt to understand the causes of the forecast failures and to achieve an improved prediction, an adjoint model was used to examine the sensitivity of a meso-β-scale vortex simulation with respect to initial fields, and some sensitivity and forward experiments were conducted in the belief that major forecast errors can result from uncertainties in the initial conditions.

The model and experiment design are described in section 2. Section 3 gives a comparison between the analysis of the observations and the control experiment simulation. The adjoint analysis of the meso-β-scale vortex is discussed in section 4. Sections 5 and 6 describe the simulations of perturbed initial analysis fields and perturbed bogus soundings, respectively. Section 7 is a summary and discussion of this study.

2. Model and experiment design

The model used to simulate the meso-β-scale vortex is the Penn State/NCAR mesoscale model MM5. The model configuration includes a coarse mesh with a 30-km grid spacing and a fine mesh with a 10-km grid spacing. The domain size is 55×70 grid points for the outer, coarse domain, and 70×97 for the inner, fine domain covering the middle and lower reaches of the Yangtze River. There are 23 sigma levels set up in the vertical direction. The model employs the Grell cumulus convection parameterization for both the coarse and fine domains, the Blackadar High Resolution (BHR) Planetary Boundary-Layer (PBL) parameterization and mixed-phase ice scheme of precipitation physics, and cloud radiation scheme. The simulation is initialized at 0000 UTC 29 June 1999 and the forecast length for the MM5 run is 24 hours (i.e., the simulation ends at 0000 UTC 30 June 1999). The initial fields (IC) are provided by interpolation onto the mesoscale grid of the background $2.5^\circ \times 2.5^\circ$ latitude-longitude fields, produced by TOGA analysis. Three-hourly surface observations and 12-hourly upper-air sounding data are included through objective analysis to improve the initial fields.

The adjoint model is version 1 of the NCAR Mesoscale Adjoint Modeling System (MAMS1, Errico et al., 1994). MAMS consists of a nonlinear forecast model (NLM), associated tangent-linear model (TLM), and an adjoint model (ADJM). The nonlinear model is a regional, primitive-equation, sigma-coordinate, mesoscale forecast model that is based on the Penn State/NCAR mesoscale model. The tangent-linear model is derived by linearizing the NLM spatial and temporal operators. The adjoint model is the exact adjoint of the TLM. The ADJM solution represents, by definition, the gradients of a forecast aspect with respect to the input variables or parameters. The adjoint model configuration in this study only includes one mesh, the same as the coarse domain of the MM5 run. The sensitivity in the fine domain is interpolated from that in the coarse domain. To perform an adjoint run, a forecast measure (J) must be selected in advance. The adjoint model determines the sensitivity of this forecast measure with respect to initial perturbations. This forecast measure could be any variable including central pressure, central vorticity, and total amount of rainfall. Because the development of a meso-β-scale vortex was investigated in this case, the

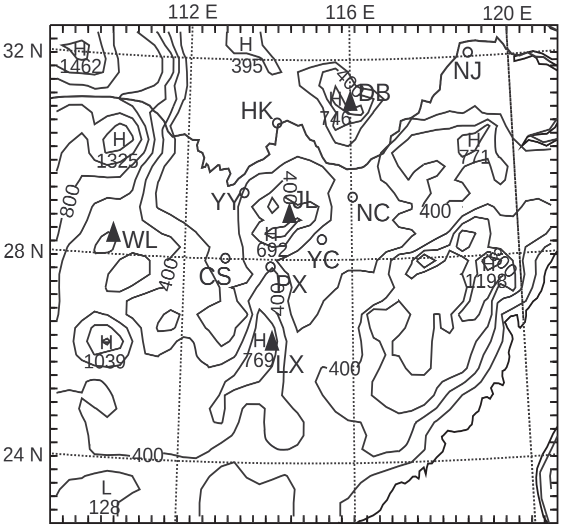

Fig. 1. Terrain in the middle and lower reaches of the Yangtze River, "DB", "JL", "LX", and "WL" represent Dabie, Jiuling, Luoxiao, and Wuling Mountains: and "NJ", "HK", "NC", "YC", "PX", "YY", and "CS" represent Nanjing, Hankou, Nanchang, Yichun, Pingxiang, Yueyang, and Changsha, respectively.

central vorticity of the vortex was selected as the forecast measure in the adjoint model.

In this paper, the simulation without initial perturbations is called the control experiment; the simulation with initial perturbations is called the sensitivity experiment. It should be noted that adjoint-derived perturbations do not necessarily show where errors in the initial conditions are, and neither does an adjoint result (i.e., pattern of sensitivity) necessarily indicate what locations or fields are the most important in producing the forecast. But since it does indicate where the sensitivity is greatest, it can provide information required to determine what is the most important factor.

3. Comparison of observations and control experiment simulation

3.1 *Analysis of the observed meso-α-scale vortex*

A meso-α-scale vortex developed and moved east along a shear line in the middle and lower reaches of the Yangtze River during 29–30 June 1999. Initially, a weak low appeared at the shear line at 850 hPa on the east side of Wulin Mountain (Fig. 1) in the northwest of Hunan province at 0000 UTC 29 June. The low moved northeast to Hankou and developed to be a meso-α-scale vortex at 1200 UTC 29 (Fig. 2a). After 12 h, the vortex moved to the west of Dabie Mountain, and slowed and stagnated over this area (Fig. 2b). Then the vortex appeared at suddenly Nanjing at 1200 UTC 30 June (not shown). There is no trough at 500 hPa, and the flow at 500 hPa is mainly westerly during the development of the meso-α-scale vortex. The eastward movement and development of this meso-α-scale vortex caused heavy rainfall in the lower reaches of the Yangtze River.

It should be noted that a relatively independent and small-scale heavy rainfall event (Fig. 3) occurred to the east of Jiuling Mountain, in the Boyang Lake plain, at the south of the meso-α-scale vortex, about 300 km away. The heavy rainfall moved northeast around the meso-α-scale vortex and merged at last into the main rain band to the east of the meso-α-scale vortex. The analysis of Blackbody Temperature (TBB) (not shown) shows that a meso-β-scale cloud cluster possibly caused this heavy rainfall event. But

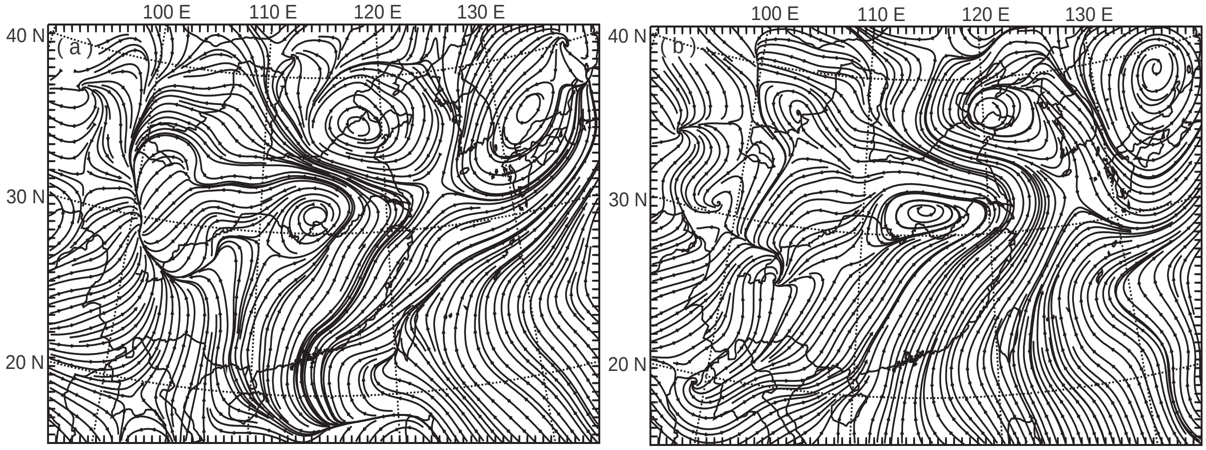

Fig. 2. The observed streamlines at 850 hPa at (a) 1200 UTC 29 June and (b) 0000 UTC 30 June 1999.

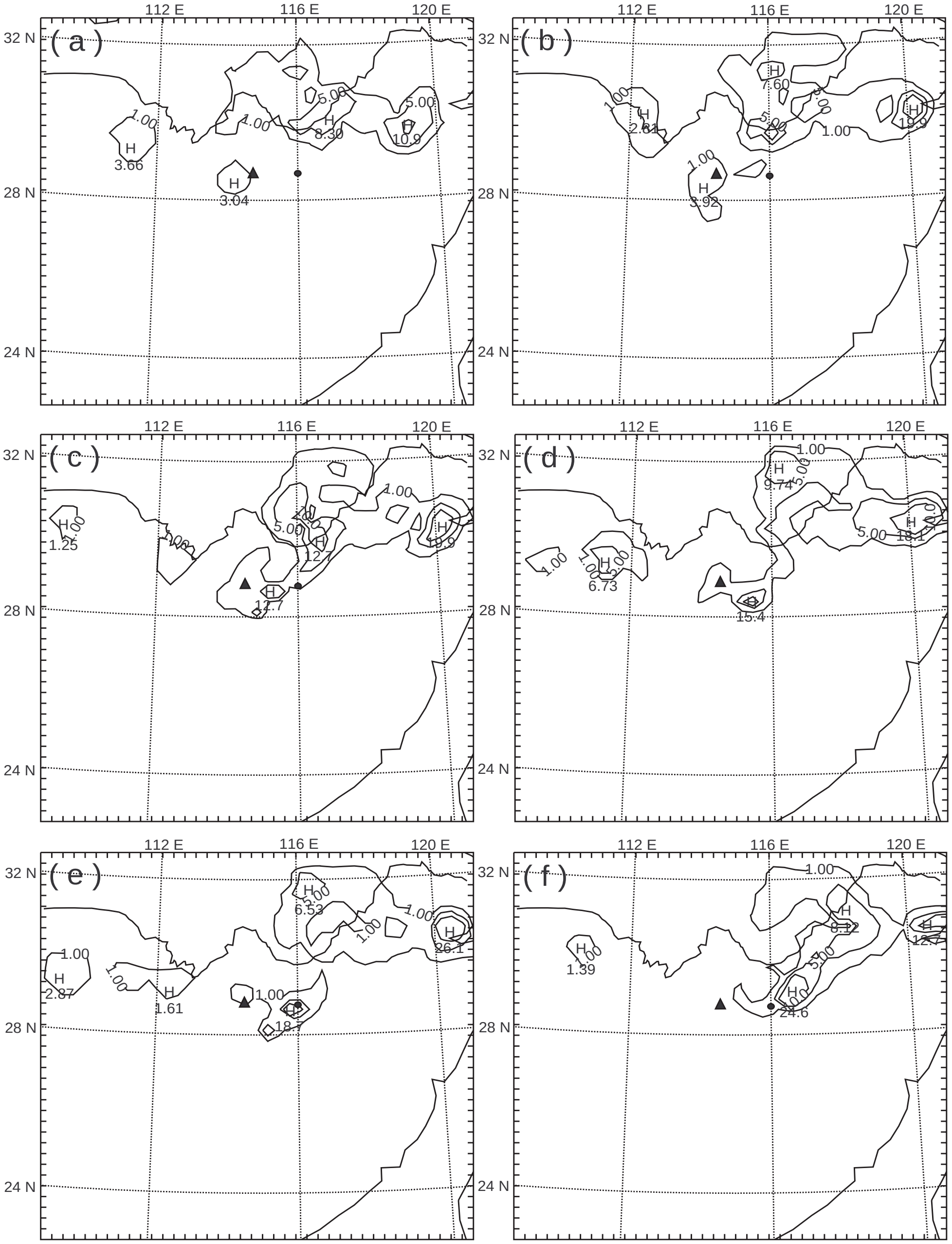

Fig. 3. Hourly observed precipitation (mm) of (a) 0600–0700 (b) 0700–0800 (c) 0800–0900 (d) 0900–1000 (e) 1000–1100 (f) 1100–1200 UTC 29 June, where the black triangle and black dot represent Jiuling Mountain and Nanchang, respectively.

there were no mesoscale signals in the analysis field from low to upper levels. So mesoscale simulations were conducted to try to reproduce the meso-β-scale vortex system and associated heavy rainfall.

3.2 *Analysis of the control experiment simulation*

Because most meso-β-scale vortexes appear in the planetary layer at the beginning, we seek to emphasize the analysis of the development of the vortex in the low level. The simulation of the control experiment also shows the eastward-moving process of the meso-α-scale vortex along the Yangtze River. Initially (0000 UTC 29 June), a cyclonic convergence center appeared in the low level to the east of Changsha. This simulated center moved northeast and developed into a meso-α-scale vortex system.

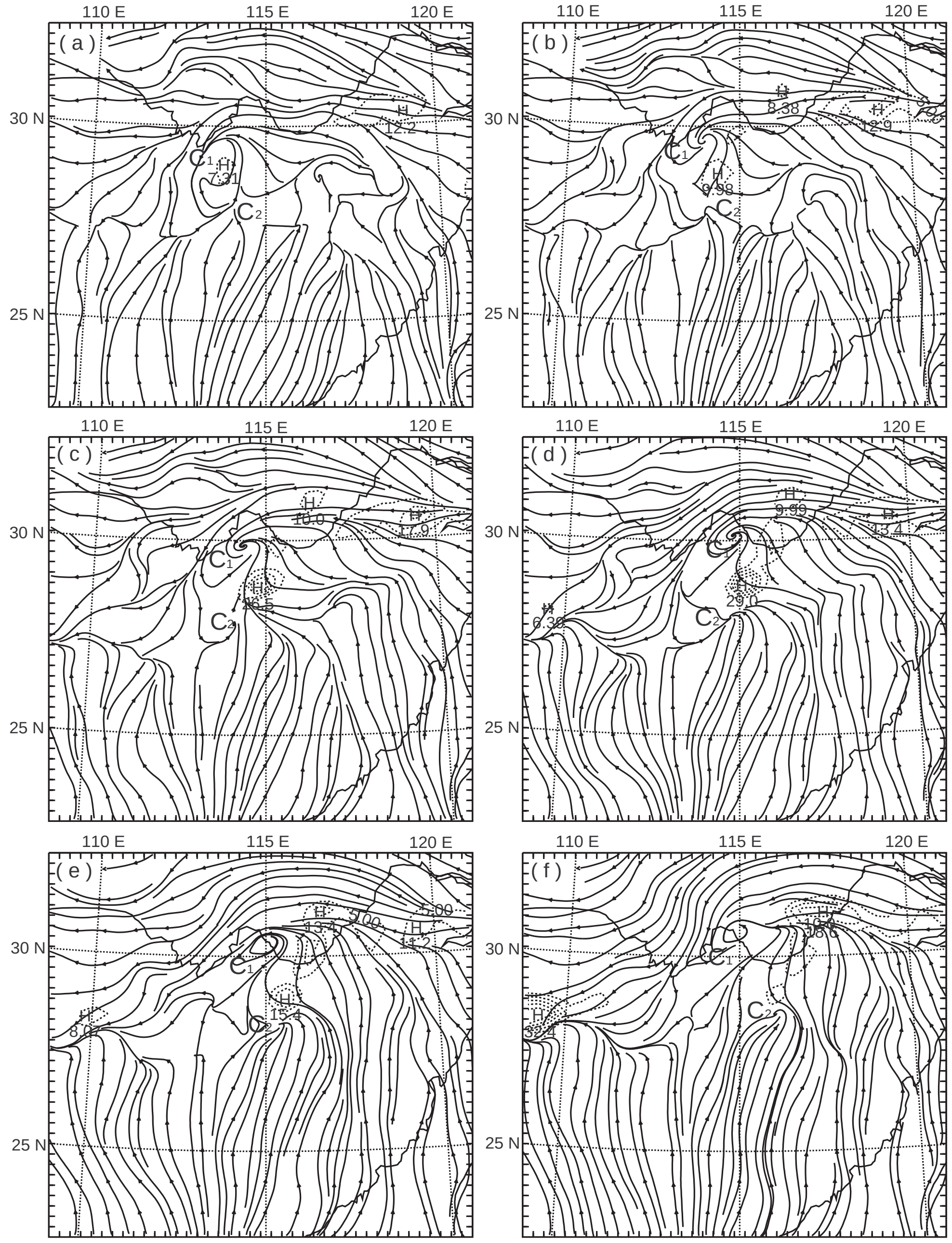

Fig. 4. The simulated streamlines at the 0.995 sigma level and hourly precipitation (mm, dashed) of the control experiment at (a) 08, (b) 10, (c) 12, (d) 14, (e) 16, and (f) 18 h, where "C_1" and "C_2" denote the meso-α-scale and meso-β-scale vortex respectively.

A meso-β-scale convergence center of southwesterly and southeasterly flow appeared to the south of the meso-α-scale vortex during its movement at 8 h (Fig. 4a). When the meso-α-scale vortex moved to the northeast of Yueyang, the meso-β-scale convergence center moved to Pingxiang in Jiangxi province, about 200 km south of the meso-α-scale vortex at 10 h (Fig. 4b). After 1400 UTC 29 June (Fig. 4d), the meso-β-scale convergence center was no longer being developed and began to weaken. The movement of intense precipitation to the northeast of the meso-β-scale system demonstrated the existence of this meso-β-scale system. But there was no closed cyclonic circulation of the meso-β-scale system in the stream field. So the simulation of the control experiment of the meso-β-scale vortex system met with some failures. The sim-

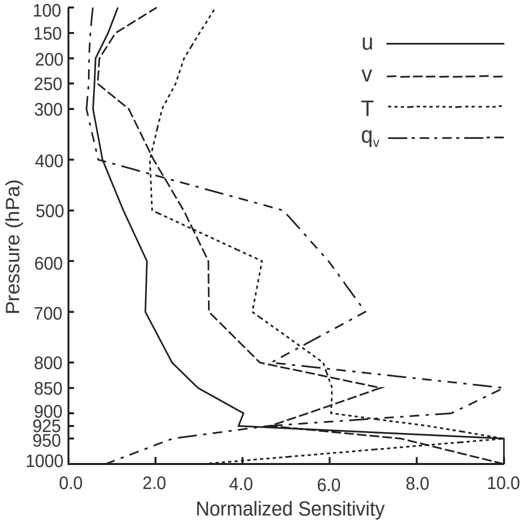

Fig. 5. Vertical profile of maximum normalized adjoint sensitivity (absolute) to zonal wind (solid), meridional wind (long dashed), temperature (short dashed), and water vapor (dot dashed) at the initial time.

ulated meso-β-scale vortex could not develop strongly enough. The MAMS was introduced to examine the sensitivity of the meso-β-scale vortex simulation with respect to the initial conditions to get some insight from the initial fields which strongly affect the simulation of the vortex. Some forward sensitivity experiments were conducted to test how the adjoint-based initial perturbations could influence the simulation of the meso-β-scale vortex.

4. Adjoint analysis of the meso-β-scale vortex with respect to initial fields

Without detailed observation data to identify the meso-β-scale vortex, the central vorticity of the simulated meso-β-scale vortex of the control experiment at the low level (sigma 0.91–0.97) at 1100 UTC 29 June, which was located to the southwest of the observed intense precipitation, was selected as the control forecast measure in the adjoint model. So the adjoint sensitivity indicates how small perturbations of initial model

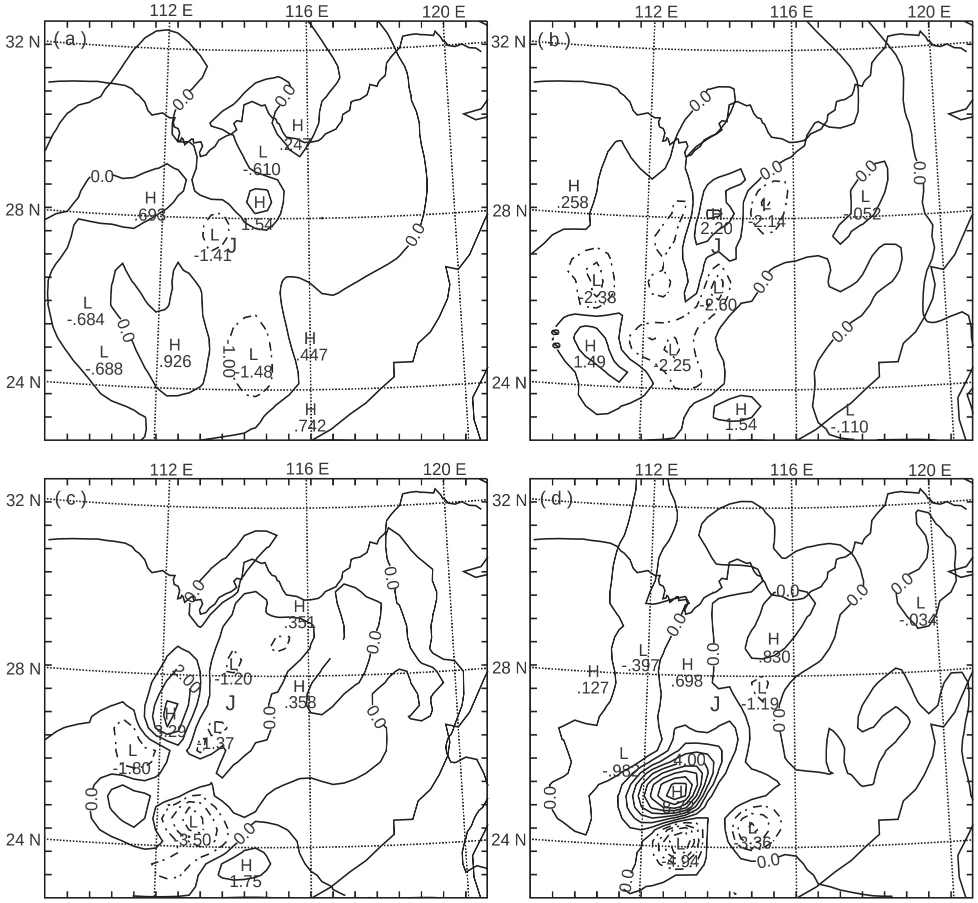

Fig. 6. Fields of normalized adjoint sensitivity to zonal wind at the initial time at (a) 700 hPa, (b) 850 hPa, (c) 900 hPa, (d) 1000 hPa, where "*J*" denotes the vorticity center selected as the control forecast measure in the adjoint model.

variables anywhere in the model domain can influence the central vorticity of the vortex.

Figure 5 gives a vertical profile of the maximum sensitivity (absolute) of the central vorticity with respect to wind components (u, v), temperature, and water vapor at the initial time. The adjoint sensitivity was normalized by the expression,

$$\frac{\partial J_{\rm norm}}{\partial x_{ijk}} = 10.0 \times \left|\frac{\partial J}{\partial x_{ijk}}\right| / \max\left|\frac{\partial J}{\partial x_{ijk}}\right| .$$

where J and x denote the simulated central vorticity and initial model variable respectively, and $\partial J/\partial x$ represents adjoint sensitivity. According to the figure, a large sensitivity to zonal wind is located below 700 hPa, especially below 950 hPa. A large sensitivity to meridional wind is also located below 700 hPa with two maximums at 1000 hPa and 850 hPa respectively. A large sensitivity to temperature is located below 600 hPa with a maximum at 950 hPa. A large sensitivity to water vapor is located below 500 hPa with two maximums at 850 hPa and 700 hPa respectively. Evidently, perturbations of a given size below 700 hPa for wind and temperature, and below 500 hPa for water vapor, have more influence on the meso-β-scale vortex, especially at the low level.

Figures 6, 7, 8, and 9 give the horizontal fields of adjoint sensitivity to initial wind components (u, v), temperature, and water vapor at four pressure levels (700, 850, 900, and 1000 hPa). The sensitivity values were also normalized by the expression,

$$\frac{\partial J_{\rm norm}}{\partial x_{ijk}} = 10.0 \times \frac{\partial J}{\partial x_{ijk}} / \max\left|\frac{\partial J}{\partial x_{ijk}}\right| .$$

The adjoint sensitivity to zonal wind (Fig. 6) is very divisional and scattered, with many little centers. A large sensitivity is mainly located to the south and west of the meso-β-scale vortex in Hunan province, from where the southwesterly and southeasterly flows came. There is a pair of positive and negative sensitivity centers from west to east on the southwest of Luoxiao Mountain, which appears to be a convergence of zonal wind in the sensitivity field.

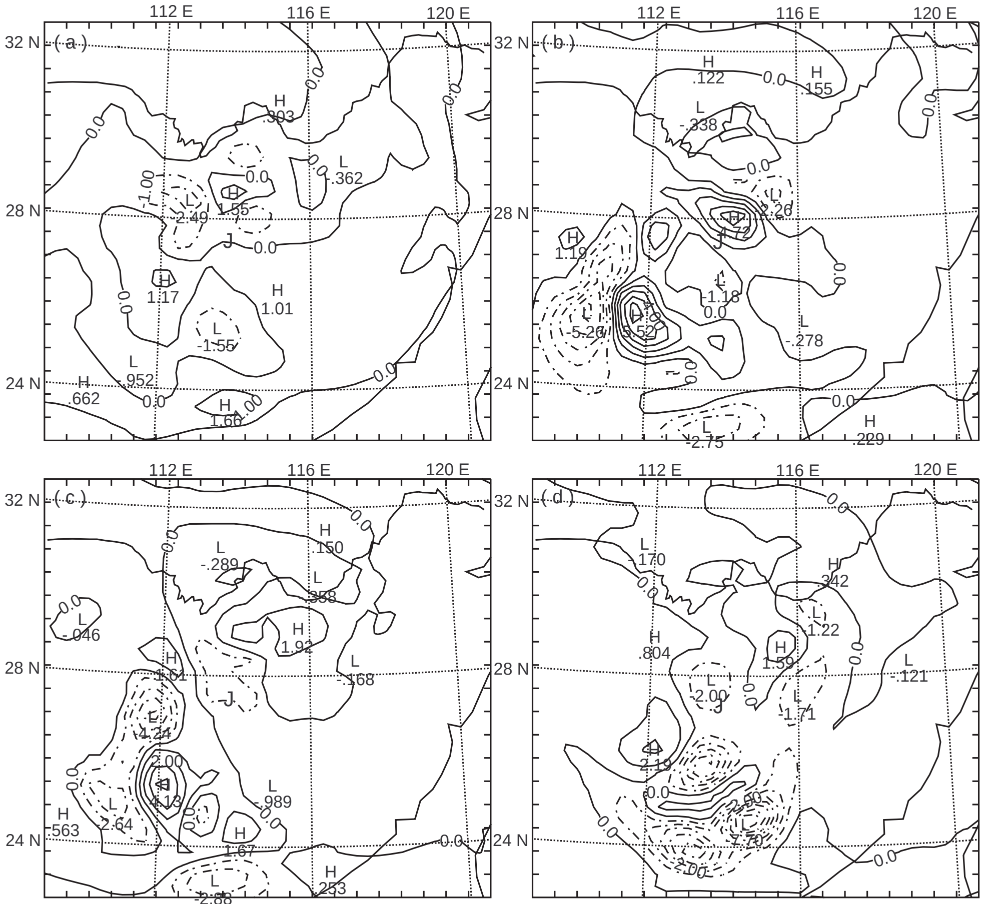

Fig. 7. Fields of normalized adjoint sensitivity to meridional wind at the initial time at (a) 700 hPa, (b) 850 hPa, (c) 900 hPa, and (d) 1000 hPa, where "J" denotes the vorticity center selected as the control forecast measure in the adjoint model.

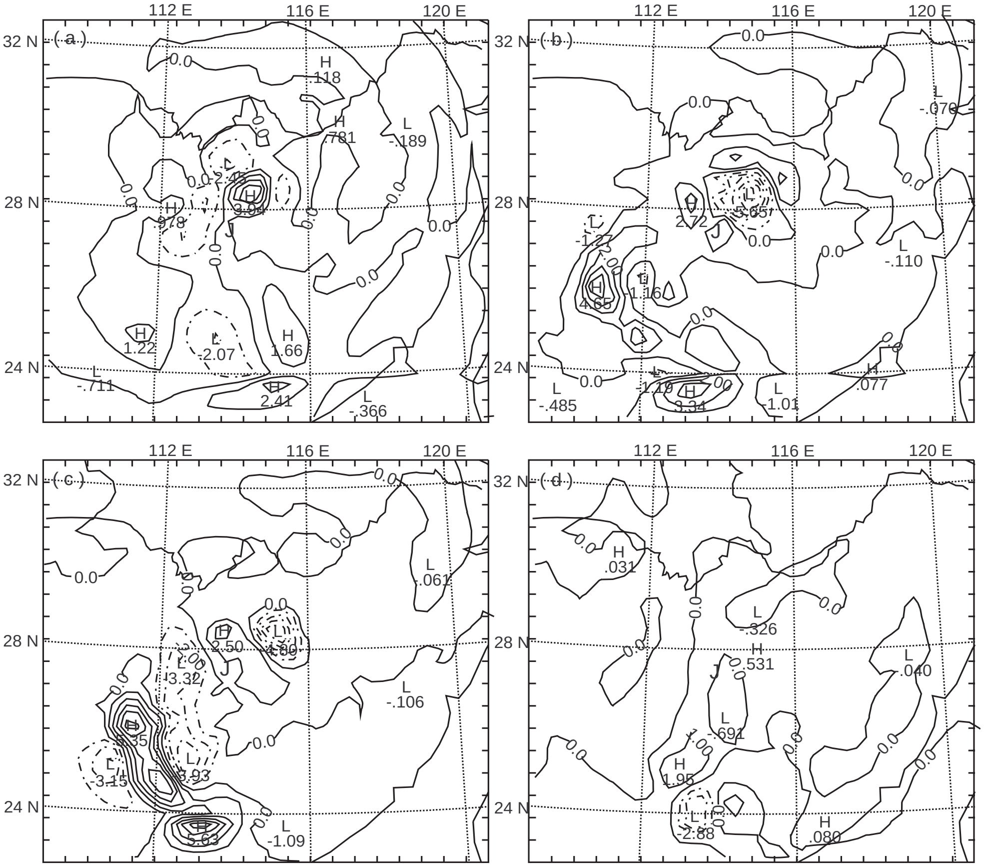

Fig. 8. Fields of normalized adjoint sensitivity to temperature at the initial time at (a) 700 hPa, (b) 850 hPa, (c) 900 hPa, and (d) 1000 hPa, where “J” denotes the vorticity center selected as the control forecast measure in the adjoint model.

The adjoint sensitivity to meridional wind (Fig. 7) in the west of Hunan province is mainly negative, and that in the east of Hunan is mainly positive, which means that the initial meridional perturbations in the west (east) of Hunan would have a negative (positive) effect on the simulated central vorticity. The positive sensitivity to meridional wind in the east and negative sensitivity in the west would form cyclonic shear in the sensitivity field. The cyclonic shear is just located to the southwest of Luoxiao Mountain, 300 km southwest of the meso-β-scale vortex, the same as the convergence of sensitivity to zonal wind. This means that, with the eastward movement of the whole system, the intensification of convergence and cyclonic shear of the initial wind would have a positive effect on the development of the meso-β-scale vortex.

The adjoint sensitivity to initial temperature (Fig. 8) is also mainly located to the southwest of the meso-β-scale vortex. This characteristic corresponds with the adjoint sensitivity to the zonal and meridional wind, especially in the upper reaches of the Yangtze River with respect to the meso-β-scale vortex in the center and southwest of Hunan province, where the positive adjoint sensitivity to temperature, convergence and cyclonic shear of the adjoint sensitivity to wind are located. The adjoint sensitivity to water vapor (Fig. 9) is mainly located to the north and west of the meso-β-scale vortex in Hunan and Jiangxi provinces, with positive values to the west and northwest of the vortex in Hunan province and negative values to the northeast of the vortex in Jiangxi province. So the adjoint sensitivity of the meso-β-scale vortex with respect to initial variables is locally located in Hunan and Jiangxi provinces, in the upper reaches of the Yangtze River with respect to the meso-β-scale vortex.

5. Results of the sensitivity experiments

5.1 *The Sensitivity experiments*

5.1.1 *Adjoint-based perturbations in initial fields*

Based on adjoint sensitivity, perturbation of any initial variable α is determined from the expression:

$$\Delta\alpha = \alpha_{\rm sc} \cdot \frac{\dfrac{\partial J}{\partial \alpha_{ijk}}}{\max\left|\dfrac{\partial J}{\partial \alpha_{ijk}}\right|} ,$$

where $\alpha_{\rm sc}$ denotes an arbitrary constant scaling factor, which indicates the maximum value of perturbation. The scaling factors employed in this study are 8 m s^{-1} for u and v, and 4 K for T (abbreviated as V8T4). In view of wet hydrostatic stability and supersaturation in the initial fields, perturbations of water vapor could not be added to the initial fields directly. Another method of adding perturbations, namely the bogus sounding perturbation, is introduced in section 6 to examine the effects of initial water vapor perturbation.

Figure 10 gives the wind perturbation vector and speed added to the initial fields directly at four sigma levels (0.870, 0.910, 0.945, and 0.970) based on the V8T4 scaling. Similar to the adjoint sensitivity, a cyclonic perturbation circulation is located at the southwest to the meso-β-scale vortex in Hunan province at the 0.870, 0.910, and 0.945 sigma levels, with the other large perturbations also mainly in Hunan province. The positive initial temperature perturbation (not shown) corresponds with the cyclonic perturbation to form a warm cyclonic perturbation circulation with a small scale.

5.1.2 *Analysis of the experiment with perturbed initial fields*

Similar to the control experiment, the sensitivity experiment also simulated successfully the eastward movement and stagnation of the meso-α-scale vortex and the meso-β-scale vortex process to its south. When the meso-α-scale vortex moved east, a meso-β-scale convergence center of southwesterly and southeasterly flow formed to the north of Pingxiang in Jiangxi province at 8 h (Fig. 11a). The convergence center developed into a closed cyclonic circulation at

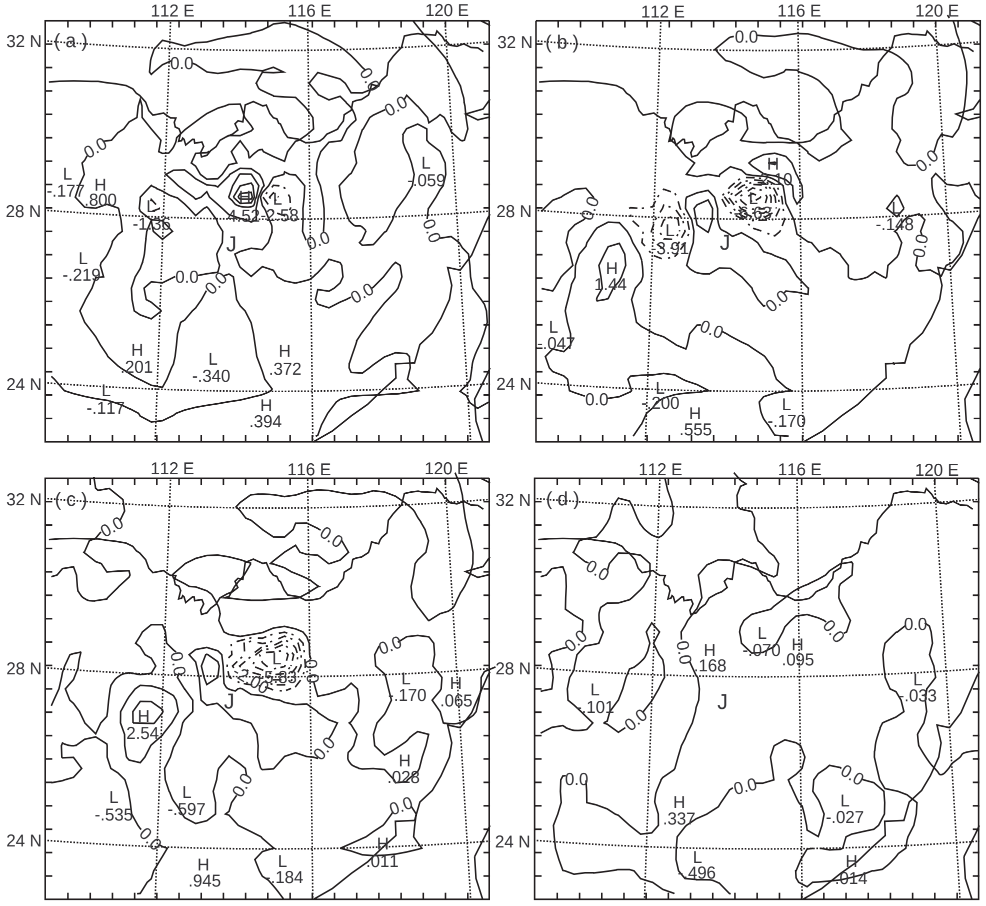

Fig. 9. Fields of normalized adjoint sensitivity to water vapor at the initial time at (a) 700 hPa, (b) 850 hPa, (c) 900 hPa, and (d) 1000 hPa, where "J" denotes the vorticity center selected as the control forecast measure in the adjoint model.

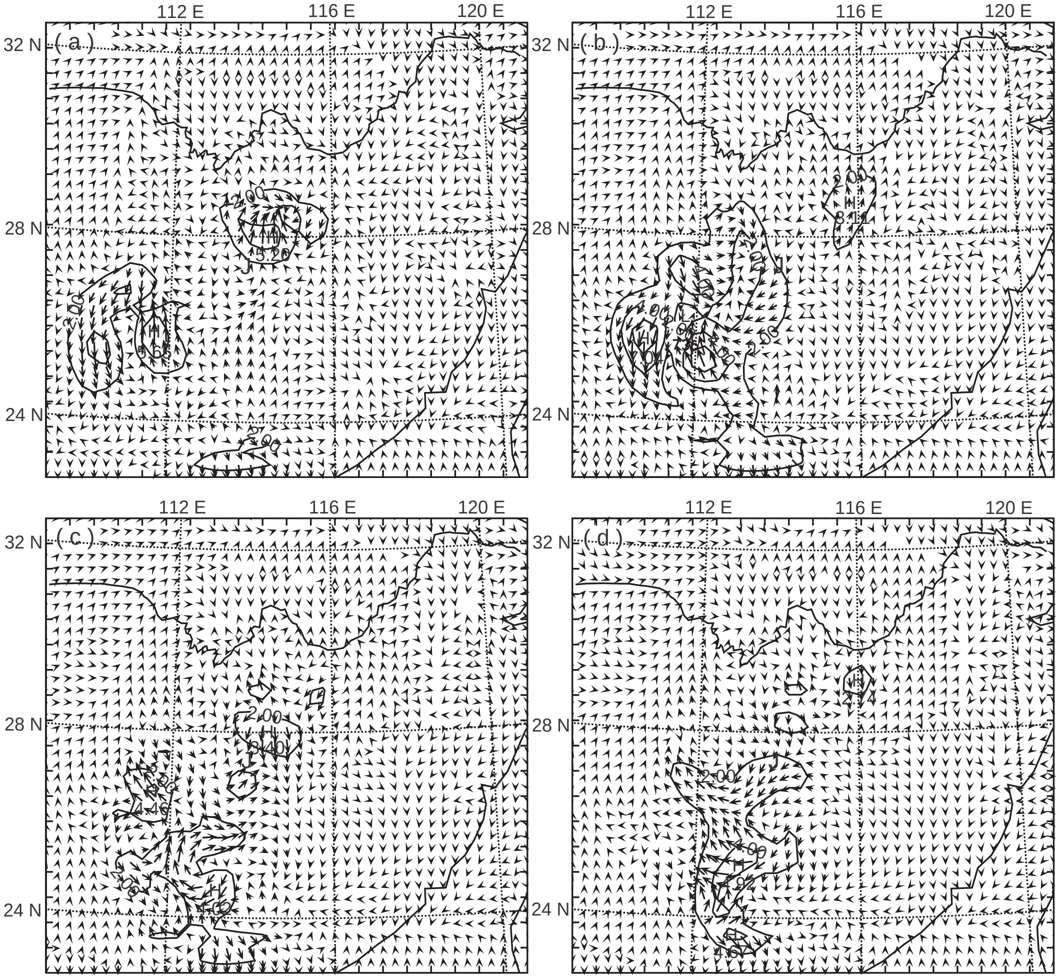

Fig. 10. Perturbation wind vector and speed (m s^{-1}, solid) added to initial fields directly at the (a) 0.870, (b) 0.910, (c) 0.945, and (d) 0.970 sigma levels, where "J" denotes the vorticity center selected as the control forecast measure in the adjoint model.

12 h (Fig. 11c). But after its formation, the closed cyclone began to weaken and moved east with the meso-α-scale vortex. At 14 h (Fig. 11d), the cyclone weakened into a cyclonic convergence center at Yichun, and began to occlude over the south of Nanchang at 16 h (Fig. 11e). The simulation also produced intense precipitation with strong locality to the northeast of the meso-β-scale cyclone. Compared with the control experiment, the simulated meso-β-scale vortex of the sensitivity experiment was intensified greatly, and a closed cyclonic circulation appeared in the stream field at 12 h, which did not appear in control experiment. This can be also verified in the vorticity field, where the central vorticity of the cyclone in the sensitivity experiment is about 21.2×10^{-5} s^{-1}, while that in the control experiment is only 18.0×10^{-5} s^{-1} (not shown). So the simulation of the sensitivity experiment, with a warm cyclonic perturbation circulation added to initial fields in the upper reaches of the Yangtze River with respect to the meso-β-scale cyclone, met with mixed success in simulating the development of the meso-β-scale cyclone to some extent.

5.2 *The sensitivity experiment with bogus sounding perturbations*

Considering the small scale of the meso-β-scale system and the relatively lower horizontal resolution of the conventional observation data, 9 bogus stations (Fig. 12a) were set up in the high adjoint sensitivity areas where perturbations would have a great influence on the simulation of the meso-β-scale vortex. The sounding data of the bogus stations was interpolated from the objective analysis fields. Adjoint-based perturbations were added to bogus soundings according to the V8T4 scaling, including the sounding of dew point (water vapor in the model, and the constant scaling

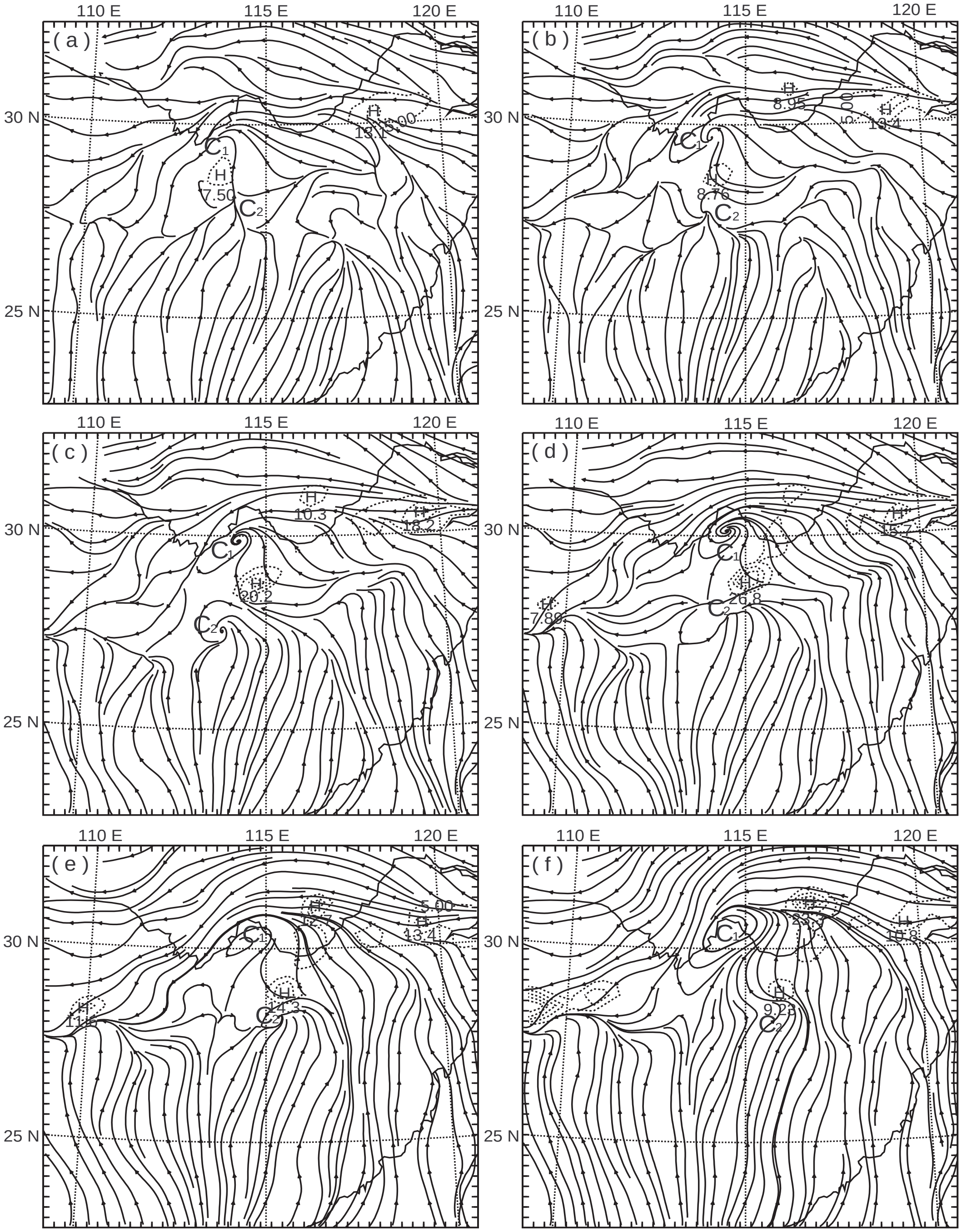

Fig. 11. The simulated streamlines at the 0.995 sigma level and hourly precipitation (mm, dashed) of the sensitivity experiment with perturbations added directly at (a) 08, (b) 10, (c) 12, (d) 14, (e) 16, and (f) 18 h, where "C_1" and "C_2" denote the meso-α-scale and meso-β-scale vortex respectively.

factor for the initial water vapor perturbation was 5g kg^{-1}). Then the perturbed soundings were reanalyzed to create new initial fields, that is, the sounding perturbations were analyzed objectively on the grid and added to the original initial fields. The aim is to investigate how perturbations in high sensitivity areas can affect the simulation of the meso-β-scale vortex.

Figure 12 gives the perturbation wind vector and speed on the grid according to the bogus sounding perturbations. A cyclonic perturbation circulation appears in Guangdong and Hunan provinces in the perturbation vector field, similar to the perturbations

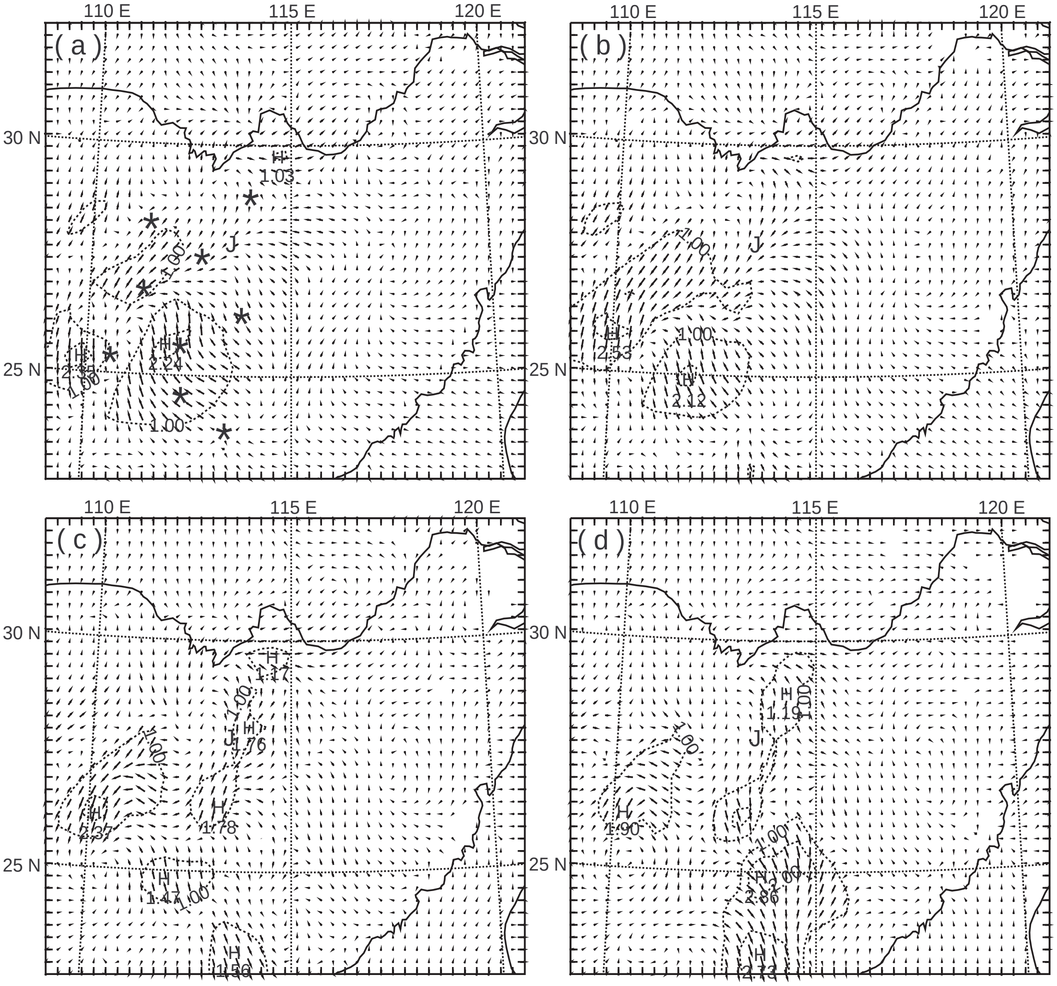

Fig. 12. Perturbation wind vector and speed (m s^{-1}, dashed) at the (a) 0.870, (b) 0.910, (c) 0.945, and (d) 0.970 sigma levels according to bogus sounding perturbations, where the "*" in (a) denotes the added bogus stations and "*J*" denotes the vorticity center selected as the control forecast measure in the adjoint model.

added to the initial fields directly, with a small wind perturbation in other areas. There is a relatively large negative temperature perturbation center (not shown) in Hunan and Jiangxi provinces, and positive centers in the southwest of Hunan, in Guangdong, and in the northeast of Guangxi province. The water vapor perturbation (not shown) is similar to the temperature perturbation, with a large negative perturbation center in the northeast of Hunan and the northwest of Jiangxi province, and a positive center in the southwest of Hunan and the northeast of Guangxi province.

The analysis of the sensitivity experiment with bogus sounding perturbations shows that there is also significant improvement in the simulation of the meso-β-scale vortex. Similarly, a convergence center of southwesterly and southeasterly flow appeared to the northeast of Pingxiang to the south of the meso-α-scale vortex at 8 h (Fig. 13a). The convergence center developed into a closed cyclonic circulation at 12 h (Fig. 13c). Then the cyclone moved east to Yichun and weakened into a cyclonic convergence center at 14 h (Fig. 13d). The convergence center began to occlude over the southwest of Nanchang at 16 h (Fig. 13e), and there was only a cyclonic curvature in the stream field at 18 h (Fig. 13f). It is evident that the formation and development process of the simulated meso-β-scale vortex is complete, a closed cyclonic circulation also appeared, with local intense precipitation to the northeast of the vortex during its movement. But the intensity of the simulated vortex is much weaker than that in the sensitivity experiment with perturbations added directly. The reason is probably related to the method of bogus sounding perturbations. Because the low number of bogus perturbations were not able to

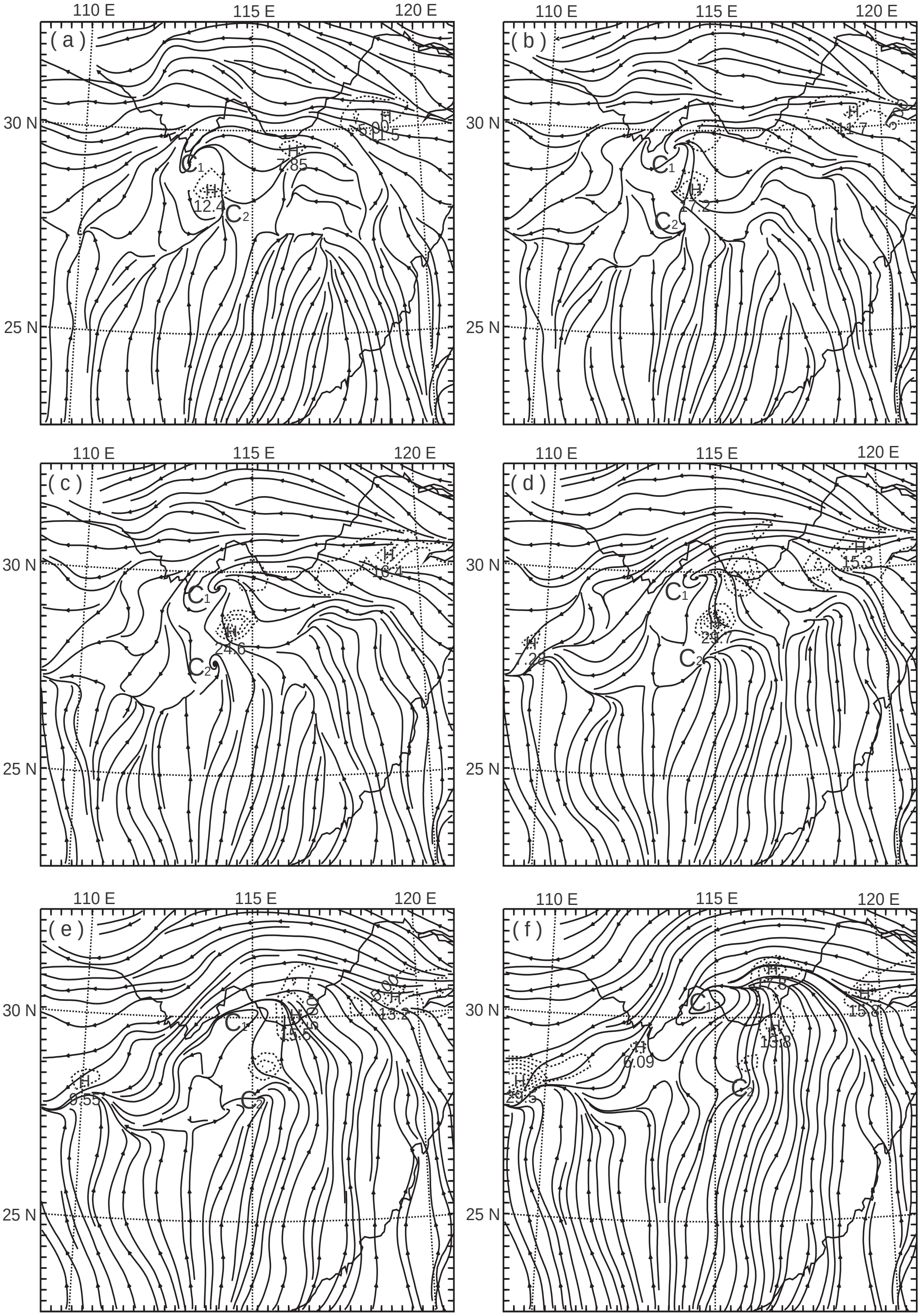

Fig. 13. The simulated streamlines at the 0.995 sigma level and hourly precipitation (mm, dashed) of the sensitivity experiment with bogus sounding perturbations at (a) 08, (b) 10, (c) 12, (d) 14, (e) 16, and (f) 18 h, where “C_1” and “C_2” denote the meso-α-scale and meso-β-scale vortex, respectively.

comprise the adjoint sensitivity field completely, positive perturbations may be replaced at some negative sensitivity areas through objective analysis, and this may have a negative influence on the simulated vortex.

6. Summary and discussion

Because of its small scale and short lifetime, the mesoscale model has some limits in simulating the formation and development of a meso-β-scale vortex in the middle reaches of the Yangtze River. Adjoint sensitivity has been examined in this study for a meso-β-scale vortex to the south of an eastward-moving meso-α-scale vortex. The adjoint method efficiently determines the sensitivity of a forecast aspect to perturbations of model variables at earlier times in a forecast. In this case, the sensitivity describes how perturbations at the initial time can intensify the central vorticity of a meso-β-scale vortex. An adjoint-sensitivity pattern, by itself, does not provide information about the relative importance of anomalies or perturbations in the forecast. Rather, the sensitivity shows how the forecast feature can be modified in various alternative forecasts. It is possible to consider the effects of hypothetical perturbations using adjoint sensitivity.

The Penn State/NCAR mesoscale model MM5 was employed to simulate the meso-β-scale vortex, and the adjoint sensitivity of the vortex at the 11th hour of the simulation with respect to initial fields was examined using MAMS (Mesoscale Adjoint Modeling System). The sensitivity indicates that the largest sensitivity for both the wind and temperature perturbation is located below 700 hPa, especially in the low level. The largest sensitivity for the water vapor perturbation is located below 500 hPa, especially in the middle and low levels. The horizontal adjoint sensitivity for all variables is mainly located in the upper reaches of the Yangtze River with respect to the simulated meso-β-scale system in Hunan and Jiangxi provinces with a small scale. The sensitivity shows that warm cyclonic perturbations in the upper reaches can have a great effect on the development of the meso-β-scale vortex.

When a warm cyclonic perturbation was added to the initial fields, based on adjoint sensitivity, in the upper reaches of the Yangtze River with respect to the meso-β-scale vortex, the simulated vortex was intensified greatly and a closed meso-β-scale cyclonic circulation was able to form in the stream field, and this did not appear in the control experiment. Perturbations added to bogus soundings in key areas were also able to improve the simulation of the vortex circulation, with weaker intensity than that in sensitivity experiment with perturbations added directly.

It should be noted, in closing, that the precipitation simulation was not improved significantly in the sensitivity experiments compared with observed precipitation. It was found that the precipitation forecast could be improved in a sensitivity experiment where precipitation is selected as the forecast measure in the adjoint model, but the vortex simulation could not be improved. When both central vorticity and precipitation were selected as forecast measures together, neither the vortex nor the precipitation simulation could be improved in the sensitivity experiment. The adjoint analysis in this paper focused on vorticity and the first half of the period of the meso-β-scale vortex. Investigation is still required with regard to precipitation and the second half of the period when the meso-β-scale cyclone forms and begins to weaken. And the adjoint-sensitivity results remain for further study to verify the generality for other meso-β-scale vortexes.

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REFERENCES

Bei Naifang, and Zhao Sixiong, 2002: Mesoscale analysis of sudden heavy rainfall systems during the second Meiyu process at 1998. *Chinese J. Atmos. Sci.*, **26**(4), 526–540.

Errico, R. M., K. Raeder, and T. Vukicevic, 1994: Mesoscale Adjoint Modeling System Version 1(MAMS1). NCAR Tech. Note, NCAR/TN-410+IA.

Errico, R. M., and T.Vukicevic, 1992: Sensitivity analysis using an adjoint of the PSU-NCAR mesoscale model. *Mon. Wea. Rev.*, **120**, 1644–1660.

Errico, R. M., T. Vukicevic, and K. Raeder, 1993: Comparison of initial and lateral boundary condition sensitivity for a limited-area model. *Tellus*, **45A**, 539–557.

Farrell, B. F., and A. M. Moore, 1992: An adjoint model for obtaining the most rapidly growing perturbation to oceanic flows. *J. Phys. Ocean.*, **22**, 338–349.

Hall, M. C. G., 1986: Application of adjoint sensitivity theory to an atmospheric general circulation model. *J. Atmos. Sci.*, **43**, 2644–2651.

Hall, M. C. G., D. G. Cacuci, and M. E. Schlesinger, 1982: Sensitivity analysis of a radiative convective model by the adjoint method. *J. Atmos. Sci.*, **39**, 2083–2056.

Langland, R. H., R. L. Elsberry, and R. M. Errico, 1995: Evaluation of physical process in an idealized extratropical cyclone using adjoint sensitivity. *Quart. J. Roy. Meteor. Soc.*, **121**, 1349–1386.

Lewis, J. H., and J. C. Derber, 1985: The use of adjoint equations to solve a variational adjustment problem with advective constraints. *Tellus*, **37A**, 309–322.

Lorenz, E. N., 1965: A study of predictability of a 28-variable atmospheric model. *Tellus*, **17**, 321–333.

Ninomiya, K., T. Akiyama, and M. Ikawa, 1988: Evolution and fine structure of a long-lived meso-α-scale convective system in Baiu frontal zone, Part I: Evolution and meso-β-scale characteristics. *J. Meteor. Soc.*, **66**, 331–350.

Rabier, F., and P. Courtier, 1992: Four-dimensional assimilation in the presence of baroclinic instability. *Quart. J. Roy. Meteor. Soc.*, **118**, 649–672.

Rabier, F., P. Courtier, and O. Talagrand, 1992: An application of adjoint models to sensitivity analysis. *Beiträge Physik der Atmosphäre*, **65**, 177–192.

Wang Zhi, and Gao Kun, 2003: Sensitivity experiments of an eastward-moving southwest vortex to initial perturbations. *Adv. Atmos. Sci.*, **20**(4), 638–649.

Wang Zhi, Zhai Guoqing, and Gao Kun, 2003: Analysis and numerical simulation of a meso-β-scale vortex in the middle reaches of the Yangtze River. *Acta Meteorologica Sinica*, **61**(1), 66–77.

Yang Jinxi, Fen Zhixian, and Zheng Huanhuan, 1994: Mesoscale analysis of heavy rainfall in the reaches of the Yangtze and Huaihe River during 12–16 June 1991. *Acta Meteorologica Sinica*, **52**(2), 187–193.