Numerical Simulation and Diagnostic Analysis of a Severe Convective Storm Process with Tornado[1]

Shou Shaowen, Zhang Lin, Shou Yixuan

（Jiangsu Meteorological Disasters Key Laboratory，Nanjing University Information Science & Technology, Nanjing,China, 210044）

1. Introduction

Severe convective weather is serious disastrous weather . It has such features as small spatial scale, short life span, abrupt occurrence and large destructive power. Due to the features, it is difficulty to predict strong convective weathers. Many scientists have investigated this issue. Along with the various improvements of meso-scale models and study of local strong convections, scientists have found some convection energy parameters with physical significance，such as CAPE, SRH etc. They can be used alone or combined together to affirm the likelihood of strong convection. Therefore, understanding the parameters of strong convections and their operating characteristics is doubtlessly very helpful to the analysis and forecast of strong convective weather. In particular, investigation on tornado is very rare in China up to now. The purpose of this article is to discuss the background condition of forming strong convective weather such as tornados via numerical simulation and diagnostic analysis of a tornado process occurred in China, thereby providing reliance and methods for predicting such severe weather.

2. Weather Scene and Synoptic Situation

The tornado process occurred at Nantong of Jiangsu Province ,China. Around 17:30, July 12th 2004. Zhizhong and Henan villages, Baochang town, Haimen city in Nantong region suffered raid of tornado and hail. The hailstones were as large as broad beans and the hailstorm lasted for 10 minutes or so. The storm moved from northwest to southeast and large area of farmlands suffered serious loss.

Before and after the occurrence of Nantong's tornado, it can be inferred from the CAPE value given by NCEP data that: at 14:00 of 12th, the early phase of strong convective weather occurred at Nantong, it was located in the center of CAPE magnitude, which was roughly 2800J / Kg and contained extremely large instability energy; At 20:00, the intensity of center CAPE magnitude diminished and moved slightly eastward to the region of Shanghai. This phenomena is also coincident with the strong convective weather occurred in Shanghai around 19:00.

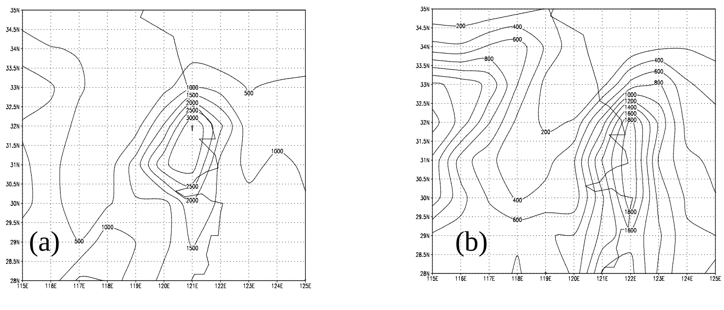

Fig1. Observed CAPE distributions at 1400 BST (a) and at 2000BST(b) ,12^{th} July (unit: J·Kg^{-1})

3. Numerical Simulation

This article has chosen the NCEP reanalysis data of horizontal resolution once every 6 hours between 02:00 July 12th and 08:00 July 13th of 2004 together with the routine sounding and ground data of the same period and performed numerical simulation with MM 5 V3.7 model to the process. The

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dual nested mesh with the regional center situated at 116°E, 33°N . The grid spacing of coarse mesh is 45km with 61×61 grid points while 15km with 61×61 grid points for fine mesh. The model roof pressure is 100 hPa and the integration step is 135s. The simulation results are exported once every hour.

Next, we perform diagnoses and analysis upon the simulation results. Starting from 15:00 of 12th, a center of gust wind exceeding 14m s^{-1} appeared at the place of 900 hPa over Nantong. The wind lasted until 19:00. It can be perceived from the figure that, the region of maximum wind speed distributed like a ribbon from NE-SW.The relative humidity over Nantong increased to about 85 % from 12:00.On one hand, the low-level gale brought about warm and wet air stream from southwest, on the other hand, it has provided condition for the occurrence of tornado.

The strong convective weather is the course of accumulation and liberation of instable energy. Nantong was laying in instable atmospheric stratification with dry and cold on upper layer and warm and wet on lower layer. In the stratification, the dry and cold air invasion and intense convergence of boundary layer warm and wet stream results in massive energy release and brought about the occurrence of tornado. The lower level strong warm advection encounters with the cold air on the rear of upper air vortex moving south-bound and form instable stratification. Starting from 14:00 of 12th, a bar-shaped region of negative extreme value of Showalter Index (SI) formed along the southeast shore. Nantong is just lying in the region of negative extreme value.

Dry intrusion played an important role during the occurrence and growth of the strong convective weather. Dry intrusion is characterized by high potential vorticity (PV) and low humidity air sinking from the higher level of troposphere. This article has represented dry and cold and warm and moist air with simulated dry PV and pseudo-equivalent potential temperature. The analysis is carried out on the cross-section diagram along 32˚N. As a result we found that, when the tornado occurred in Nantong, there was apparent dry intrusion in the upper air. At 16:00 of 12th, the high PV column at higher level of troposphere descended eastward with large value, whereas the value over Nantong was 351K. As the dry and cold air moved eastward and superimposed over the lower level warm -wet airflow with high θ_{se} .

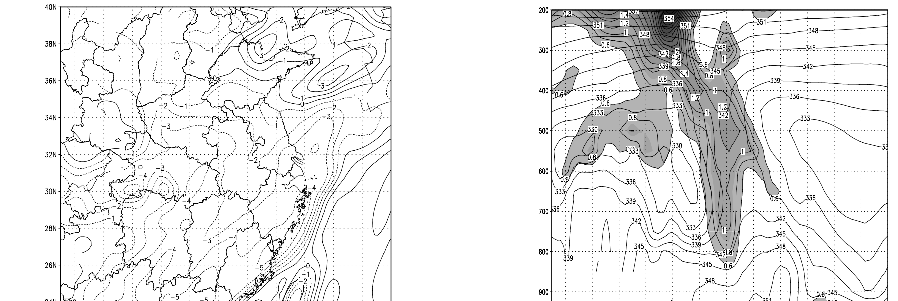

Fig2. (a) Simulated SI index distribution at 1700 BST 12th July (unit: °C) and (b) Simulated longitude-height section of dry PV (shadow, unit: PVU) and potential pseudo-equivalent temperature (solid line, unit: K) along 32°N

4. The Atmospheric Convective Energy Parameters

(1) Best Convective Available Potential Energy（BCAPE）: Since there is the issue of deciding starting altitude within the calculation of CAPE, Cook et al of the Hydrology and Weather Predicting Center of US (HPC) and Desautels et al of Canada have all attempted to apply optimal CAPE to routine business. The computing method selected by this article is from Desautels and Verret [1].

(2) Convection Inhibiting Energy（CIN）: Colby (1984) put forward the concept of Convection Inhibition Energy. $CIN = g\int_{Z_i}^{Z_{LFC}} \frac{T_e - T_p}{T_B} dz$, where T_e and T_p represent environment and air parcel temperature respectively. T_B is the mean temperature of stable layer while Z_i and Z_{LFC} are the starting level and free convection level respectively. CIN also represents the negative work of LFC when average air parcels of atmospheric boundary layer reach the level of free convection via the stable layer.

(3) Normalized Convective Available Potential Energy（NCAPE）: NCAPE=CAPE/△H_{LFC} , NCAPE indicates the magnitude of average acceleration or average buoyancy.

(4) Computing the Convective Available Potential Energy with Density Temperature: If the ascending process is assumed to be reversible saturated moist adiabatic process, we can substitute the virtual temperature with density temperature. The definition of density temperature is: $T_\rho = T(1 + r/\varepsilon)/(1 + r_T)$, where, $r_T = r + r_l + r_i$ is the total mixing ratio of water substances. r_l and r_i represent the mixing ratio of liquid water and ice respectively. ε is the ratio of dry air gas constant and water vapor specific gas constant. And r is the mixing ratio.

(5) Energy－Helicity Index (EHI) : $EHI = CAPE \cdot SRH / 1.6 \times 10^5$, When EHI is larger, the probability of supercell and tornado is larger. It effectively combines the buoyancy energy and kinetic parameter. Davies [2] indicated that, the majority of tornados occur as EHI >1.

(6) Severe Weather Threatening Index (SWEAT): The SWEAT index can be written as: $SWEAT = 12D + 20(TT - 49) + 2f_8 + f_5 + 125(S + 0.2)$,where, f_8 is wind speed of 850hPa; f_5 is wind speed of 500 hPa; $S = \sin D$ (D is the wind direction difference of 500 and 850hPa); $TT = T_{850} + T_{d850} - 2T_{500}$. The index reflected the synthetic action of instability energy, wind vertical shear upon the storm intensity. In U.S, the critical value of SWEAT for tornados is 400.

5. Application of the Convective Energy Parameters

The above indexes all have certain significance upon strong convective weathers, yet among them, EHI and SWEAT etc. are not frequently applied on severe weather analysis in China. Below we performed some comparison and discussion to the advantage and disadvantage of these parameters as well as their indication significance in this case of tornado of Nantong.

(1) BCAPE: BCAPE has better decided the starting level of air parcels. Through out this article, we calculated the BCAPE space and time distribution adopting the uplifting procedure of reversible saturated wet adiabatic which is relatively coincident with the actual atmosphere. The result indicates that, around 18:00, Nantong is located in the central section of the region with maximal simulated BCAPE; some parts attained 2600J/Kg, which is close to actual values. During the simulation, large value regions appeared along Jiangsu starting from 15:00. Later the center moved slightly eastward, which corresponds to the severe weather occurred in Shanghai around 20:00. Large value of BCAPE corresponds to the massive convection energy over Nantong. There was a zone of convergence with intense convections caused by dry and cold air moving south-bound and warm and wet air moving northward. It moved eastward slowly and released energy. Severe weathers occurred along the way. It can be seen that, the BCAPE value over Nantong increased with large gradient between 17:00 and 18:00. It dropped slightly afterwards. This coincides well with actual weather situation. But with regard to some other problems, the consideration of BCAPE is not thoughtful enough. One of the existing problem is : BCAPE has only taken into account the condition of vaporous water, which is quite different with actual atmosphere. We calculated BCAPE with density temperature instead of virtual temperature and took into account the impact of liquid and solid state water when considering buoyancy and convective available energy. As a result, we effectively skipped some deceitful values when calculating BCAPE, which reflected the actual conditions of atmosphere more faithfully. It can be inferred from Fig. 3b and Fig. 4a that, the spatial distribution and time-variation of convection available potential energy calculated with density temperature is very identical with BCAPE, except that the central value is smaller than revealed by BCAPE. On the time-variation diagram of BCAPE over Nantong calculated with density temperature, it trend of variation is almost coincident with BCAPE, except that the value is smaller. This is closer to the actual condition. In addition, the vertical distribution of CAPE, especially the CAPE of lower level played important role during the development and evolution of convective storms. Regarding to the thickness of free convection layer and the average buoyancy within this thickness, NCAPE has also reduced some computational error. Johns and Doswell [3] have mentioned that: for most super monomers, their CAPE might be less than 1500J/Kg, yet they might happen in the environment with small total CAPE but larger lower level CAPE. Calculations of NCAPE in this article still regard BCAPE as the computation factor and follow above statements. The thickness from 500 hPa to the uplift altitude of air parcel is chosen to compute NCAPE. From Fig. 3c, the NCAPE of lower atmosphere over Nantong laid within the large value region of from 16:00.This has emphasized that the occurrence of severe weather over Nantong depend on the accumulation and releasing of instability energy on its lower level air.

BCAPE carries out discussion mainly regarding to the upward current. Similarly, the growth condition of convections can be perceived from the ascending air stream. CIN is the restraining factor for the occurrence and development of convective energy. Its physical significance is the critical value which must be exceeded by the convective potentiality obtained by air parcels. If the CIN value is relatively large, it implies that the action of local lower level convergence upon the severe weather. This means that the storm tends to convert into convective systems with large scale, which is disadvantageous of forming tornados. On Fig. 3b, the value of CIN descended to the lowest point before severe weather occurred. This indicates favorable factors for generating tornados. Colby et al[4] indicated that: the convection started from the overlay region of fairly large convective potentiality index and smallest convection suppression energy. Nevertheless, the convection potentiality index has the value of opposite sign against the SI indexing with respect to the expression. We can interpret it as: the convection happens at the overlap of negative value region of fairly bigger SI and region of small CIN value. Starting from 14:00, the upper air of Nantong laid in the small value region of CIN extending from northeast to south-west, which is the converging zone of two strands of airflows. This means it was very likely for small scale severe weather to happen at that moment.

The four kinds of energy parameters mentioned above are only related with thermodynamic factors of atmosphere. As is well known, the atmospheric motion is a sophisticated process. Its dynamic factor is also a non-negligible aspect. The following two parameters have effectively taken this issue into account.

(2) EHI: EHI is a very useful parameter. It has synthetically considered the dynamic and thermodynamic factors of air parcel movements. The possibility of apparent tornados augments as EHI enlarges. EHI is a very good factor of recognition. The value of EHI has a certain degree of correlation with the intensity of tornados. The EHI of 90% non -supercell thunderstorms are <0.77; the EHI of less than 1/3 of supercells representing evident tornados are less than 0.77. Whereas for over 50% of evident tornados, EHI are larger than 1.5. The calculating factor of EHI is composed by integrating BCAPE and SRH. On Fig. 3e, the EHI value of simulated, EHI center over Nantong has attained over 1.6. The large value region also presented the trend of NE-SW and kept moving eastward slowly .The tornado weather of Nantong and severe weather of Shanghai demonstrated the indication significance of EHI .Besides, the forecast time-effectiveness of EHI is also very good. On the EHI time-variation chart over Nantong, it increased most quickly between 17:00 and 18:00. This is evidently correspondent to the severe weather occurred later on.

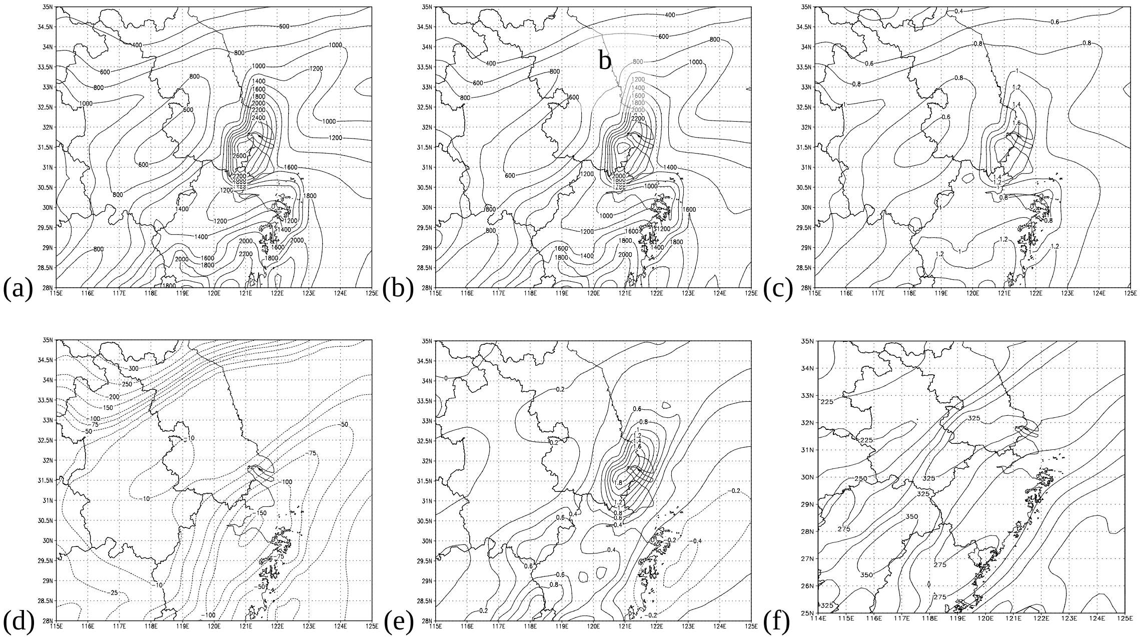

Fig 3. The spatial distribution diagram of different simulated energy parameters at 18:00 of 12th July.
(a). BCAPE (unit: J·Kg^{-1}) ; (b). BCAPE calculated by density temperature (unit: J·Kg^{-1}); (c) . NCAPE (unit: J·Kg^{-1});
(d). CIN (unit: J·Kg^{-1}); (e). EHI (unit: J·Kg^{-1}·m^{2}s^{-2}); (f). SWEAT

In addition, if we synthetically considered the wind speed term, wind direction shearing and thermodynamic factors, they will have good indicating significance. SWEAT index has such function. We have discussed the SWEAT index with actual data during severe convective weather of Jiangsu Province in recent 10 years. Statistics show that, when tornado occurs, the SWEAT are largely around 300.The simulation result of this case, Fig. 3c has also verified this statement. During this case of severe weather, the SWEAT indexes over Nantong were almost over 325. From the result of this simulation, we also found that, the SWEAT value over Nantong increased faster between 17:00 and 18:00 than previous hours. Through this case of weather phenomena, we found that its time-effectiveness is higher than other parameters. It has synthetically considered the thermodynamic term, shearing term and wind speed term. Although the wind speed term and thermodynamic term played major role regarding the value, there is abnormal sudden changes with respect to the wind direction shearing term over Nantong around 17:00 on the time-variation diagram of wind direction shearing term. This fits well with the severe weather around 17:00. It has non-negligible guidance significance over, entire SWEAT index and, the, occurrence of severe weathers.

From above simulation results, we found that, if BCAPE is calculated with density temperature, the result will be better than that calculated with virtual temperature. The central position and intensity correspondence of SWEAT and EHI indexes are both good, while we have considered more factors with them. They also have a certain degree of resolution and period of validity upon the types of severe weathers. Meanwhile, we found that, on the upper air of mono - stations, the time-varying rates of intensity for the above three parameters were the largest. The increasing rate of these energy parameters can effectively indicate the variation of weathers. Besides, the spatial distribution and positions of CIN and NCAPE also have fairly good indicating significance for severe weathers.

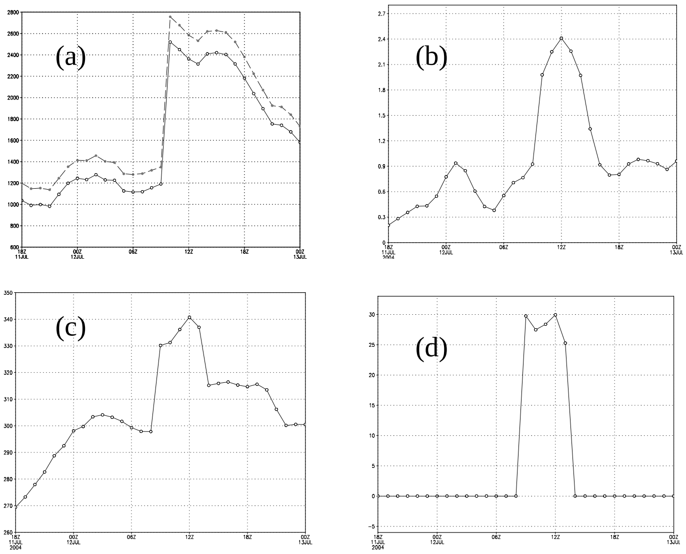

Fig4. The simulated temporal variation of energy parameters over Nantong

(a). BCAPE (dashed line, unit: J·Kg^{-1}) and BCAPE calculated by density temperature (solid line , unit: J·Kg^{-1}) ; (b). EHI (unit: J·Kg^{-1}·m^{2}s^{-2}) ; (c). SWEAT index ; (d). Wind direction shearing tern of SWEAT index

6. Conclusion

(1) It can be concluded from the observation analysis and simulation results that: the invasion of dry and cold air in upper layer and the intense convergence of warm and humid air at lower level brought about instable stratification. This provided energy condition for the generation of the tornado of Nantong on July 12th, 2004.

(2) All above parameters have good correspondence upon the severe weather process. The effect will be better if the virtual temperature is replaced by density temperature. Concerning the vertical distribution of BCAPE, especially the lower level distribution, it is more reasonable to compute NCAPE than referring to the total value of BCAPE alone. EHI has synthetically considered SRH and BCAPE, which is favorable to distinguish the types of severe weathers. The time derivative of BCAPE, density temperature BCAPE, EHI and SWEAT indexes have distinct indicating significances upon severe weathers. Through utilizing numerical simulation and combining various convection parameters from every aspect, it is possible to capture the process of development of severe convective weather.

(3) Calculating SWEAT index with simulation. This case has reconfirmed the statistical results of severe weathers of Jiangsu Province in the recent decade. The SWEAT index also has distinct indicating significance upon strong convective weathers of China. Here, although the wind direction shearing term of SWEAT index does not account for a large proportion on the total magnitude, it has non - negligible indicating significance during its time-variation process. This indicates that the shearing of wind direction and speed have distinct effect on forming tornados.

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