On the vertical extending of the explosive extratropical cyclone: A case study

Li-Zhi Jiang1,2 | Hai-Guo Yu3 | Li Dong4 | Shen-Ming Fu5 | Jian-Hua Sun1 | Fei Zheng5 | Kan Yi6 | Hui Ma7

1Key Laboratory of Cloud-Precipitation Physics and Severe Storms, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
2University of Chinese Academy of Sciences, Beijing, China
3Qinghai Green Energy Data Co., Ltd., Xining, China
4CGN New Energy Holdings Co., Ltd., Beijing, China
5International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China
6Institute of Science and Technology, China Three Gorges Corporation, Beijing, China
7Beijing GoldWind Smart Energy Technology Co., Ltd., Beijing, China

Abstract
Explosive extratropical cyclone (EEC) is the main disastrous weather system over the ocean and offshore areas in the cold season. As a type of vertically deep system, after decades of studies, key features of EECs' vertical extents still remain vague. Based on a reasonably simulated entire-troposphere-thick EEC, this study analyzes variation of the EEC's vertical extent and investigates governing mechanisms for its vertical extending. Main findings are as follows: (a) the EEC's vertical extent showed consistent variation features with its central sea level pressure and lower-level vorticity (correlation coefficients were ~0.9), whereas its relationship with EEC's maximum surface wind was not significant; (b) EEC's upward extending featured strong ascending motion and rapid cyclonic-vorticity enhancement at the top level of the cyclone and obvious inflow (convergence) in the lower troposphere. (c) vorticity budget at the EEC's top level shows that net import transport of cyclonic vorticity (by westerly and northwesterly winds) from the trough west of the cyclone dominated its upward extending, and upward transport of cyclonic vorticity from levels below the cyclone's top level acted as the second dominant factor. In contrast, divergence-related vertical shrinking around the EEC's top level was the most detrimental factor for the cyclone's upward extending.

KEYWORDS
cyclone's vertical extent, extratropical explosive cyclone, vorticity budget

INTRODUCTION
Explosive extratropical cyclones (EECs) are the major disastrous weather system for the ocean and offshore...
regions in the middle and high latitudes during cold seasons. They deepen rapidly with their central pressure decreasing by more than 24 hPa (relative to the equivalent latitude of 60°) in 24 hr (Sanders and Gyakum, 1980). EECs’ rapid development is often accompanied by a series of disastrous weather such as gale, cold wave and blizzard, which pose a great threat to coastal areas and maritime shipping (Bosart, 1981; Jia and Zhao, 1994; Wen and Huang, 2003; Fu et al., 2014; Koyama et al., 2017; Brâncuș et al., 2019). For this reason, the EECs are one of the key points in meteorology society across the globe in recent several decades (Schultz et al., 2018). A deep understanding of this kind of cyclone had been reached after a large number of studies were conducted. However, as a type of three-dimensional cyclone system (Pepler and Dowdy, 2020), thus far, there are few studies focus on its vertical extension.

Previous studies have found that the development of extratropical cyclones is often accompanied by a rapid vertical stretching. For example, Fu et al. (2015) analyzed an extratropical cyclone in the Yangtze River Basin and found that the top level (i.e., the uppermost level of a cyclone’s vertical range) of the cyclone extended from 750 hPa to 550 hPa within 12 hr. Li et al. (2019) investigated a cyclone that caused a catastrophic rainfall in Beijing and found that it took ~15 hr for the top level of this cyclone extended vertically from 500 hPa to 200 hPa. On average, the vertical stretching speed (VSS; which is calculated by the variation of a cyclone’s top level divided by corresponding time) was about −0.46 Pa·s⁻¹ for the former cyclone and around −0.56 Pa·s⁻¹ for the latter cyclone. The statistical analyses from Pepler and Dowdy (2020) also found the phenomenon that many EECs extended from bottom to top during their development. However, what key features can be found during EECs’ upward extending? Which mechanisms govern EECs’ upward extending? These two scientific questions remain to be answered.

From 13 to 17 November, 2018, an extremely strong explosive cyclone occurred in the North Atlantic region. During the lifecycle of the cyclone, its vertical range extended to the tropopause (its uppermost top level was 150 hPa), which means it was an entire-troposphere-thick EEC. This cyclone caused intense cold advection, heavy snow and strong winds in Eastern Canada. The maximum surface wind speed observed at Twillingate station reached up to ~40 m·s⁻¹ (https://climate.weather.gc.ca/). During the EEC’s rapid development, its top level extended upward swiftly (from 850 hPa to 200 hPa in 21 hr). The mean VSS was about −0.84 Pa·s⁻¹, which was much higher than that of conventional extratropical cyclones (Fu et al., 2015; Li et al., 2019). This EEC was used to answer the two scientific questions raised above.

The reminder of this paper is structured as follows. The data and methods are shown in Section 2, main results are presented in Sections 3–4, and a conclusion and discussion is provided in Section 5.

2 | DATA AND METHOD

2.1 | Data

The hourly 0.25° × 0.25° ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (C3S, 2017; Hersbach et al., 2020) were used to initialize the model and provide lateral boundary conditions. The GPM IMERG final precipitation L3 half hourly 0.1° × 0.1° V06 product (Huffman et al., 2019) was utilized to evaluate the performance of the simulation.

2.2 | Model configuration

The Advanced Research Weather Research and Forecasting (WRF-ARW) Model version 4.1.4 (Skamarock et al., 2019) was used in this study. Two domains of 15-km and 3-km resolution were utilized for simulation (Figure 1a), and they both had 50 vertical levels (model top was 50 hPa). The Kain–Fritsch cumulus parameterization scheme (Kain, 2004) was only used in the outer domain. The revised MM5 Monin-Obukhov surface layer scheme (Jiménez et al., 2012), Thompson V3.1 graupel scheme (Thompson et al., 2008), Yonsei University planetary boundary layer scheme (Hong et al., 2006), the unified Noah land surface model (Chen and Dudhia, 2001), the shortwave radiation scheme reported by Dudhia (1989), and the Rapid Radiative Transfer Model longwave radiation scheme (Mlawer et al., 1997) were used for both domains. The output from the inner domain was used for analyses and calculation.

2.3 | Cyclone parameters

An EEC’s deepening rate (Yoshida and Asuma, 2004) is defined as:

\[
\text{Deepening rate} = \left[\frac{p(t-6)-p(t+6)}{12}\right] \frac{\sin 60°}{\sin \frac{\phi(t-6)+\phi(t+6)}{2}},
\]

where \( t \) is time (units: hr), \( p \) is the cyclone’s central sea level pressure (units: hPa), and \( \phi \) is the cyclone’s central latitude.
An EEC is a type of three-dimensional cyclone system (every level of the cyclone must have a closed cyclone structure). The bottom level of an EEC is defined as the sea level, as an EEC is usually defined by the sea level pressure (Sanders and Gyakum, 1980). Above the sea level, geopotential height is used to identify EECs (Jiang et al., 2020). Therefore, in the pressure coordinate, within an EEC’s vertical extent, the level of minimum pressure is defined as the top level of the cyclone. In this study, features at the top level of an EEC is calculated by the vertical average from 50 hPa below the cyclone’s top level to 50 hPa above. According to the temporal average size of the EEC during the targeted period, we defined a circle with a radius of 700 km, which is centered in the EEC’s center (e.g., the orange circle in Figure 1a) as the central region of the cyclone. The cyclone-averaged features are calculated within this central region. As the vertical extending of an EEC is closely related to the cyclone-averaged vertical velocity around its top level, we defined a ratio of this vertical velocity to the cyclone’s VSS (RVV) to compare these two factors. This ratio indicates the contribution of the vertical velocity (at the top level of the cyclone) to the cyclone’s vertical stretching.

2.4 Vorticity budget

This study used the vorticity budget equation from (Kirk, 2003) as follow shows:

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V}_h \cdot \nabla \zeta - \omega \frac{\partial \zeta}{\partial p} + k \cdot \left( \frac{\partial \mathbf{V}_h}{\partial p} \times \nabla \omega \right) - \beta \zeta - (\zeta + f) \nabla_h \cdot \mathbf{V} + D(\zeta)$$

where $\zeta$ is the relative vorticity; $\mathbf{V}_h$ and $\omega$ are horizontal wind vector (subscript “h” means the horizontal
component) and vertical velocity in \( p \) coordinate (\( p \) is pressure), respectively; \( f \) is the Coriolis parameter and \( \beta = \frac{\partial f}{\partial y} \). Terms HAV and VAV are horizontal and vertical advection of vorticity, respectively; terms TIL, BT and STR show the effects of tilting, “\( \beta \) effect”, and stretching, respectively. Term RES is the residual term mainly due to friction and sub-grid processes. A total effect term TOT is defined as \( TOT = HAV + VAV + TIL + BT + STR \).

3 | SIMULATION VERIFICATION AND OVERVIEW OF THE EVENT

3.1 | Simulation verification

As Figure 1a shows, the WRF-simulated EEC formed at 0900 UTC November 13, 2018, \( \sim 1 \) hr earlier than that of ERA5. The simulation had successfully reproduced the northeastward track of the EEC, with the mean distance (between WRF-simulated and ERA5-derived tracks) below 90 km (which is \( \sim 13\% \) of the average radius of the cyclone). The EEC’s central pressure showed consistent variation features in WRF simulation and ERA5 data (Figure 1b), and the maximum difference between them is \( \sim 10.7 \) hPa. Simulated EEC showed a larger maximum deepening rate (\( \sim 0.5 \) Bergeron bigger) than that of ERA5 data, which appeared \( \sim 3 \) hr earlier than that of ERA5 data (Figure 1b). Compared the accumulated precipitation during the EEC’s upward extending period (1500 UTC 13–1400 UTC 15, November), it can be found that although there are some obvious differences, the simulation had captured the main features of the GPM precipitation in terms of rainfall intensity, centers and horizontal distribution (Figures 1c–d). In summary, the simulation had reasonably reproduced the main characteristics of the EEC, and therefore can be used for further research.

3.2 | Overview of the event

The northeastward moving EEC formed at 0900 UTC November 13, 2018 (Figure 1a), reached its maximum

![Figure 2](image_url)
deepening rate of 3.2 Bergeron at 1000 UTC 14 November (Figure 1b), gained its lowest central pressure of 945.3 hPa at 0600 UTC 15 November, and extended upward to the uppermost top level of 150 hPa at 1400 UTC 15 November. Its associated maximum surface wind speed of 37.3 m s\(^{-1}\) appeared around 45.19°N, 38.40°W, at 0300 UTC 16 November (Figure 2b). Along with the cyclone’s development, the cyclone-averaged 900-hPa vorticity firstly increased rapidly, and then varied slowly after the cyclone’s top level reached 300 hPa (Figure 2c). The variation of cyclone-averaged 900-hPa vorticity was consistent with the variation of the cyclone’s top level with a correlation coefficient of −0.95. Before the EEC reached its uppermost top level of 150 hPa (1400 UTC 15 November), the cyclone-averaged 900-hPa divergence was mainly negative (Figure 2d), which means there was inflow in the lower levels of the cyclone. Then, after the EEC reached its maximum vertical extent, the cyclone-averaged 900-hPa divergence changed to positive, implying outflow dominated its lower levels. In summary, the cyclone’s vertical extent was closely related to the variation of its lower-level vorticity and central pressure (the correlation coefficients are −0.95 (exceeding the 99% confidence level) and 0.88 (exceeding the 99% confidence level), respectively). In contrast, the relationship between the EEC’s vertical extent and its maximum surface wind speed was not significant.

4 | KEY FEATURES AND GOVERNING MECHANISMS OF THE EEC’S UPWARD EXTENDING

4.1 | Key features

The explosive developing stage (≥1 Bergeron) of this EEC is from 1500 UTC 13 to 2100 UTC 14 November, 2018 (~30 hr), which is shorter than the EEC’s upward extending stage (1500 UTC 13–1400 UTC 15 November). According to the variation of VSS, the cyclone’s vertical extent was closely related to the variation of its lower-level vorticity and central pressure (the correlation coefficients are −0.95 (exceeding the 99% confidence level) and 0.88 (exceeding the 99% confidence level), respectively). In contrast, the relationship between the EEC’s vertical extent and its maximum surface wind speed was not significant.

**FIGURE 3** The cyclone-averaged vertical speed (the green bars, units: Pa s\(^{-1}\)) (a), vorticity (blue bars, units: 10\(^{-5}\) s\(^{-1}\)) (b), divergence (brown bars, units: 10\(^{-5}\) s\(^{-1}\)) (c), and geopotential-height deviation (orange bars, units: gpm) (d) at the cyclone’s top level during its upward extending period, where the red line represents cyclone’s top level (units: hPa), and the number shows the correlation coefficient between the variable shown in the panel and cyclone’s top level during the cyclone’s vertical extending period. The black lines mark stages I–III.
extending period can be divided into three stages (Figure 3). In Stage I (1500 UTC 13–0500 UTC 14, November), it took ∼14 hr for the top level of the EEC ascended from 900 hPa to 850 hPa. The mean VSS for this stage was about −0.1 Pa·s⁻¹, which was much smaller than the mean ascending motions at the EEC's top level (−1.9 Pa·s⁻¹) (Figure 3a). The RVV in this stage was 19.6, implying that vertical advection was not a key factor contributing to EEC's upward extending. During this stage, the vorticity at the cyclone's top level gradually changed from negative to positive (Figure 3b), which indicates that the cyclonic wind field at the cyclone's top level got gradually strengthened; there kept strong convergence at the cyclone's top level (Figure 3c), which indicates that the whole layer of the EEC (the cyclone was shallow in this stage) featured uniform inflow. The geopotential-height deviation at the EEC's top level kept relatively small negative values (Figure 3d), indicating that the cyclone was weak in this stage.

During Stage II (0500 UTC 14–0200 UTC 15, November), the EEC entered its rapid upward-extending stage (Figure 3), during which the cyclone's top level ascended by 650 hPa in 21 hr (mean VSS was around −0.86 Pa·s⁻¹). Meanwhile, ascending motions at the cyclone's top level first increased rapidly, and then decreased slowly, which resulted in a mean value of about −2.4 Pa·s⁻¹ (Figure 3a). The RVV in this stage was 2.84, which is much smaller than that in stage I. The cyclone-averaged vorticity at the cyclone's top level (Figure 3b) showed consistent variation with the EEC's upward extending (correlation coefficient was −0.93). This is because there was a significant cyclonic wind field at the EEC's top level, which can effectively reflect the upward extending of the cyclone. During this stage, divergence at the EEC's top level changed rapidly from convergence to divergence (Figure 3c), which indicates that in the upper layer of the EEC, inflow changed to outflow as the cyclone became vertically deep. Negative geopotential-height deviation increased rapidly in absolute value (Figure 3d), consistent with the cyclone's quick development.

In Stage III (0200 UTC 15–1400 UTC 15, November) the EEC's top level reached 150 hPa slowly, with a mean VSS of −0.12 Pa·s⁻¹. Vertical motion at the cyclone's top level was weak (Figure 3a) and smaller than VSS, which showed a RVV of 0.19. This is significantly different from those in stages I-II, which implies that strong ascending motions were a favorable condition for cyclone's upward extending. In this stage, cyclonic vorticity, positive divergence and negative geopotential-height deviation at the EEC's top kept large values and changed slowly (Figure 3b–d), which indicates that the cyclone had entered its relatively stable maturity period.

### 4.2 Mechanisms governing the EEC’s upward extending

As discussed in Section 4.1, the vorticity at an EEC's top level can effectively reflect its upward extending. This section used the cyclone-averaged vorticity budget (Kirk, 2003) to investigate mechanisms governing the EEC's upward extending.

Before analysis, a check on the balance of the Equation (1) was conducted, and the result showed that, on average, the ratio of TOT to the local time derivative on the left hand side of Equation (1) was about 1.12. This means that the overall balance of the equation was good, and thus suitable for further analyses.

In the Stage I, the TOT term changed from negative to positive (mainly due to the sign change of HAV and enhancement of STR), which indicates that the cyclonic vorticity at the cyclone's top level changed from decreasing to increasing. After TOT turned positive, the cyclone's top level began to ascend upwardly from 900 hPa to 850 hPa (Figure 4a). For this stage, STR related to the convergence at the cyclone's top level (Figure 4d) and upward transport of cyclonic vorticity (VAV) (Figure 4b) dominated the EEC's upward extending. Horizontal advection was firstly detrimental and then conducive to the cyclone's upward extending (Figure 4a), which resulted in a total negative effect. Tiling mainly created negative vorticity, decelerating the upward extending (Figure 4c).

In Stage II, term TOT maintained a strong positive value (Figure 4a), which indicates that the cyclonic vorticity at the top level of the EEC increased rapidly. This resulted in rapid upward extending of the cyclone. As Figure 4a shows, for this stage, the horizontal vorticity advection (HAV) played a dominant role (contribution was ∼164%), implying that net import transport of cyclonic vorticity from outside was of great importance. From Figure 4e–f, it can be seen that, the positive vorticity transported into the EEC range mainly came from the central region of a shortwave trough west of the cyclone. The transport by westerly and northwesterly winds through the western boundary of the EEC made the largest contribution. Upward transport of positive vorticity (VAV) accounted for 11% of TOT (Figure 4b), which was the second favorable factor for the cyclone's upward extending. In contrast, negative STR due to the strong divergence at the cyclone's top level (Figure 3c) was the most detrimental factor (contribution was −51%) for the EEC's upward extending through inducing vertical shrinking. The effect of tilting first produced negative vorticity and then generated cyclonic vorticity (Figure 4c), which resulted in a net negative effect (−4%).

In stage III, TOT at the EEC's top level decreased rapidly and changed from positive to negative (Figure 4a). This indicates that the favorable conditions for EEC's upward
extending disappeared, and thus no obvious changes were found in the cyclone’s top level. In this stage, terms HAV and TIL were conducive to maintaining cyclonic vorticity at the EEC’s top level, whereas negative STR due to divergence was the most detrimental factor for the above process. Since the vertical velocity at the EEC’s top level was
close to 0 (Figure 3a), VAV was approximately 0, which applied a nearly neutral effect on cyclonic-vorticity maintenance.

5 | CONCLUSION AND DISCUSSION

The EECs are a type of three-dimensional cyclone system. After years of studies, key features during their upward extending and the associated mechanisms still remain unclear. This study attempts to fill in this research gap by conducting analysis to a reasonably simulated entire-troposphere-thick EEC. It is found that the EEC’s vertical extent showed consistent variation features with its central sea level pressure and lower-level vorticity. The cyclone’s upward extending was characterized by strong ascending motion and rapid cyclonic-vorticity enhancement at its top level and obvious inflow in its lower levels. Cyclonic vorticity at the EEC’s top level can effectively reflect its upward extending. Vorticity budget shows that net import transport of cyclonic vorticity (by westerly and northwesterly winds) from the trough west of the EEC dominated its upward extending, and upward transport of cyclonic vorticity acted as the second dominant factor. Based on a case study, we have proposed a general method to analyze the EECs’ vertical extending. However, due to the limitation of case study, general features of EECs’ vertical extending can only be obtained by investigating more cases in the future.

ACKNOWLEDGMENTS

The authors thank the ECMWF, NASA, and JAXA for providing the data. This research was supported by the Key Research Program of Frontier Sciences, CAS (Grant No. ZDBS-LY-DQC010) and the National Natural Science Foundation of China (grant nos. 41775046 and 42075002).

ORCID

Li-Zhi Jiang @ https://orcid.org/0000-0003-1273-9788
Shen-Ming Fu @ https://orcid.org/0000-0001-9670-0607

REFERENCES

Bosart, L.F. (1981) The Presidents’ day snowstorm of 18-19 February 1979: a subsynoptic-scale event. *Monthly Weather Review*, 109, 1542–1566.
Brâncuş, M., Schultz, D.M., Antonescu, B., Dearden, C. and Ştefan, S. (2019) Origin of strong winds in an explosive Mediterranean Extratropical cyclone. *Monthly Weather Review*, 147, 3649–3671.
Chen, F. and Dudhia, J. (2001) Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part I: model implementation and sensitivity. *Monthly Weather Review*, 129, 569–585.

Copernicus Climate Change Service (C3S). (2017) ERAS: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS) [Accessed: 31st May 2020]. Retrieved from https://cds.climate.copernicus.eu/cdsapp#!/home.

Dudhia, J. (1989) Numerical study of convection observed during the winter monsoon experiment using a mesoscale two-dimensional model. *Journal of the Atmospheric Sciences*, 46, 3077–3107.

Fu, S., Sun, J. and Sun, J. (2014) Accelerating two-stage explosive development of an extratropical cyclone over the northwestern Pacific Ocean: a piecewise potential vorticity diagnosis. *Tellus A: Dynamic Meteorology and Oceanography*, 66, 23210.

Fu, S.M., Li, W.L. and Ling, J. (2015) On the evolution of a long-lived mesoscale vortex over the Yangtze River basin: geometric features and interactions among systems of different scales. *Journal of Geophysical Research - Atmospheres*, 120, 11889–11917.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R.J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S. and Thépaut, J.N. (2020) The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049.

Hong, S.-Y., Noh, Y. and Dudhia, J. (2006) A new vertical diffusion package with an explicit treatment of entrainment processes. *Monthly Weather Review*, 134, 2318–2341.

Huffman, G.J., Stocker, E.F., Bolvin, D.T., Nelkin, E.J., Tan, J. (2019). GPM IMERG Final Precipitation L3 Half Hourly 0.1 degree × 0.1 degree V06, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC) [Accessed: 31st May 2020]. https://doi.org/10.5067/GPM/IMERG/3B-HH/06

Jia, Y. and Zhao, S. (1994) A diagnostic study of explosive development of extratropical cyclone over East Asia and West Pacific Ocean. *Advances in Atmospheric Sciences*, 11, 251–270.

Jiang, L., Fu, S. and Sun, J. (2020) New method for detecting extratropical cyclones: the eight-section slope detecting method. *Atmospheric and Oceanic Science Letters*, 13, 436–442.

Jiménez, P.A., Dudhia, J., González-Rouco, J.F., Navarro, J., Montávez, J.P. and García-Bustamante, E. (2012) A revised scheme for the WRF surface layer formulation. *Monthly Weather Review*, 140, 898–918.

Kain, J.S. (2004) The Kain-Fritsch convective parameterization: an update. *Journal of Applied Meteorology*, 43, 170–181.

Kirk, J.R. (2003) Comparing the dynamical development of two mesoscale convective vortices. *Monthly Weather Review*, 131, 862–890.

Koyama, T., Stroeve, J.C., Cassano, J.J. and Crawford, A.D. (2017) Sea ice loss and Arctic cyclone activity from 1979 to 2014. *Journal of Climate*, 30, 4735–4754.

Li, W., Xia, R., Sun, J., Fu, S., Jiang, L., Chen, B. and Tian, F. (2019) Layer-wise formation mechanisms of an entire-troposphere-thick extratropical cyclone that induces a record-breaking catastrophic rainstorm in Beijing. *Journal of Geophysical Research*, 124, 10567–10591.
Mlawer, E.J., Taubman, S.J., Brown, P.D., Iacono, M.J. and Clough, S.A. (1997) Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave. *Journal of Geophysical Research-Atmospheres*, 102, 16663–16682.

Pepler, A.S. and Dowdy, A.J. (2020) A three-dimensional perspective on extratropical cyclone impacts. *Journal of Climate*, 33, 5635–5649.

Sanders, F. and Gyakum, J.R. (1980) Synoptic-dynamic climatology of the “bomb”. *Monthly Weather Review*, 108, 1589–1606.

Schultz, D.M., Bosart, L.F., Colle, B.A., Davies, H.C., Dearden, C., Keyser, D., Martius, O., Roebber, P.J., Steenburgh, W.J. and Volkert, H. (2018) Extratropical cyclones: a century of research on Meteorology’s centerpiece. *Meteorological Monographs*, 59, 16.1–16.56.

Skamarock, W.C., Klemp, J.B., Dudhia, J., Gill, D.O., Liu, Z., Berner, J., Wang, W., Powers, J.G., Duda, M.G., Barker, D.M. and Huang, X.-Y. (2019) A Description of the Advanced Research WRF Version 4. NCAR Tech. Note NCAR/TN-556 +STR, pp. 145. https://doi.org/10.5065/1dfh-6p97.

Thompson, G., Field, P.R., Rasmussen, R.M. and Hall, W.D. (2008) Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: implementation of a new snow parameterization. *Monthly Weather Review*, 136, 5095–5115.

Wen, Y.Q. and Huang, L.W. (2003) Diagnosis analysis of explosive cyclone influencing navigation safety. *Navigation of China (in Chinese)*, 55, 55–60.

Yoshida, A. and Asuma, Y. (2004) Structures and environment of explosively developing extratropical cyclones in the northwestern Pacific region. *Monthly Weather Review*, 132, 1121–1142.

How to cite this article: Jiang L-Z, Yu H-G, Dong L, et al. On the vertical extending of the explosive extratropical cyclone: A case study. *Atmos Sci Lett*. 2021;22:e1028. https://doi.org/10.1002/asl.1028