Isentropic Potential Vorticity Analysis of a Sudden Spring Cold Wave and Record-breaking Blizzard Event in Ningxia: Postprint

Authors: Hu Liangfan, Hu Wendong 1,2,3, Siyu Gu1, Wang Lei[1,4], Wang Jinlan 5, Hu Wendong[1],[2],[3]

Date: 2019-03-07T00:00:00+00:00

Abstract

Using conventional observations, hourly data from ground-based dense stations, and 0.125°$×$0.125° 6-hourly reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), a diagnostic analysis of the sudden cold wave and extreme snowstorm event in Ningxia on April 2–3, 2016, was conducted using 315K isentropic potential vorticity from the perspectives of weather system evolution, cold air pathways, and disastrous weather forecasting indicators. The results indicate that: (1) This event belonged to the type of upper-level short-wave trough moving eastward and merging, with a splitting cold high pressure at the surface whose main body rapidly moved southward, accompanied by a frontal system, leading to strong cold air intrusion and post-frontal snowfall. (2) The circulation pattern was stable in the early stage, while the weather system underwent abrupt changes in the later stage, making it difficult to forecast using conventional meteorological data; the 315K isentropic potential vorticity chart can serve as an effective analysis and forecasting tool for short-term, localized spring cold wave snowfall processes. (3) Isentropic potential vorticity clearly traced the source and propagation pathways of the cold air: cold air from the tropopause over the Aral Sea region moved eastward and expanded southward, merging and intensifying with cold air from the mid-troposphere over the Tibetan Plateau, while cold air from the lower stratosphere over Novaya Zemlya, after slowly moving eastward in the early stage, accelerated southward from Lake Baikal to supplement it, triggering the cold wave. (4) Abnormally large values of isentropic potential vorticity can quantitatively and clearly depict the evolution of the key influencing system—the westerly belt short-wave trough—providing better indicative significance. (5) The temporal variation of high isentropic potential vorticity zones was consistent with the evolution of the cold wave, capable of indicating cold air activity 6 hours in advance; moreover, areas with isentropic potential vorticity greater than 1.0 PVU coincided with the cold wave and snowfall zones, while areas greater than 0.8 PVU coincided with strong cooling zones, which can serve as important indicators for refined quantitative forecasting.

Full Text

Preamble

DOI: 10.12118/j.issn.1000-6060.2019.02.06
Journal: Arid Land Geography (ChinaXiv Cooperative Journal)

Authors:
HU Liang-fan[1], HU Wen-dong[1],[2],[3], GU Si-yu[1], WANG Lei[1], , WANG Jin-lan

Affiliations:
[1] School of Atmospheric Science, Chengdu University of Information Technology, Chengdu 610225, Sichuan, China
[2] Sichuan Provincial Key Laboratory of Software Auto-developing and Intelligent Service, Chengdu 610225, Sichuan, China
[3] Sichuan Provincial Key Laboratory of Plateau Atmosphere and Environment, Chengdu 610225, Sichuan, China
Meteorology Service Center of Heilongjiang Province, Harbin 150030, Heilongjiang, China
Xinxiang Meteorological Bureau of Henan Province, Xinxiang 453000, Henan, China

Corresponding Author: HU Wen-dong, E-mail: huwendong@cuit.edu.cn

---

Introduction

In 1985, Hoskins et al. [1] introduced the isentropic potential vorticity (IPV) concept, which has since been widely applied in diagnosing atmospheric processes [2]. Subsequent research demonstrated IPV's utility in analyzing cold wave activities [3], with studies examining the 2008 southern China freezing rain and snow disaster [5] and other severe events [6-7]. The IPV tendency equation reveals that under adiabatic, frictionless conditions, IPV is conserved following air parcel motion, making it an effective tracer for cold air mass trajectories [8]. The 315K isentropic surface, located near 600 hPa, serves as a representative level for diagnosing mid-tropospheric systems.

This study investigates a record-breaking cold wave and snowstorm process that affected Ningxia from April 2-3, 2016, using conventional meteorological observations, automatic station hourly data, and ECMWF 6-hourly reanalysis data at 0.125°×0.125° resolution. The analysis focuses on the event's spatiotemporal characteristics, atmospheric circulation evolution, cold air sources and pathways, and the outbreak mechanism, with particular emphasis on IPV-based forecasting indicators.

3. IPV Analysis on the 315K Isentropic Surface

3.1 315K IPV Field Characteristics

On April 2, 2016 at 08:00 UTC (Figure 4), the IPV field on the 315K isentropic surface exhibited a high-value zone along 35°-45°N, corresponding to the cold air mass behind the trough. This configuration indicated that the IPV effectively captured the spatial distribution of the cold air mass. The 315K isentropic surface intersected the 600 hPa pressure level in the northern region and the 400 hPa level in the southern region, while the 250 hPa level marked the upper boundary of the analysis domain. The IPV high-value zone between 45-50°N, $C1, C2$, represented the main cold air reservoir, with L2 denoting the primary low-pressure system. The L2a system, embedded within the larger circulation, represented a mesoscale feature associated with the cold air outbreak.

3.3 IPV Diagnostic Analysis

The diagnostic analysis reveals three key features: (1) The L3 system moved southeastward along the high-value IPV zone, with the cold air activity center showing clear propagation; (2) The interaction between stratospheric and tropospheric air masses occurred over the 60°-80°E region, where the upper-level trough intensified through merging processes; (3) The IPV values exceeded 1.5 PVU in the L3a sector, indicating strong dynamic forcing for the cold wave development.

3.4 IPV Tendency Equation

The IPV tendency equation can be expressed as the sum of local change and advection terms. For forecasting applications, the advection term dominates the evolution of IPV features [8]. The analysis shows that positive IPV advection correlates with cold air movement, while negative advection indicates decaying systems. The 6-hourly evolution of IPV patterns provides predictive capability for cold air activity timing and intensity.

4. IPV-Based Forecasting Applications

4.1 IPV Threshold Values for Operational Forecasting

On April 14 at 08:00 UTC (Figure 4), the 315K IPV analysis showed that regions with IPV values exceeding 1.0 PVU corresponded well with precipitation zones (>0.1 mm). The 0.8 PVU contour effectively delineated the boundary of significant temperature drops, with values above this threshold indicating areas experiencing cooling greater than 8°C. The spatial distribution of IPV anomalies quantitatively tracked the small trough evolution, offering superior temporal resolution compared to conventional observations.

The relationship between IPV values and surface impacts shows:

- IPV > 1.0 PVU: Heavy precipitation zones

- IPV $>$ 0.8 PVU: Significant temperature drop zones ($\Delta T > 8$°C)
- IPV $>$ 0.6 PVU: Moderate cooling zones ($\Delta T > 6$°C)

These thresholds remained consistent throughout the event, with the 315K isentropic surface providing a stable reference frame for tracking the cold air mass. The 6-hourly IPV evolution allowed for 6-12 hour lead time in predicting the cold wave's initiation and intensity.

4.2 Dynamic Diagnosis

The dynamic diagnosis indicates that the IPV framework successfully captured the coupling between upper-level trough evolution and surface cyclone development. The L2 and L3 systems interacted through vorticity advection, with the 700 hPa and 500 hPa levels showing consistent patterns of height falls and temperature advection. The rapid southward movement of the surface anticyclone, as indicated by the IPV analysis, preceded the frontal passage by 6-12 hours, providing crucial forecast lead time.

Conclusion

This study demonstrates that the 315K isentropic potential vorticity serves as an effective tool for analyzing and predicting sudden cold wave and extreme snowstorm processes in spring. The IPV analysis clearly traced the cold air sources from the Aral Sea region and Lake Baikal, showing their merger and enhancement over the Qinghai-Tibet Plateau. The temporal evolution of IPV coincided with the cold wave's initiation, outbreak, recession, and ending stages, providing predictive capability 6 hours ahead. Spatially, the zones of heavy snowfall and severe temperature drops corresponded to IPV values exceeding 1.0 PVU and 0.8 PVU, respectively. The method offers better spatiotemporal resolution than conventional observations and can serve as a key quantitative forecasting indicator for Ningxia region.

References

[1] HOSKINS B J, MCINTYRE M E, ROBERTSON A W, et al. On the use and significance of isentropic potential vorticity maps[J]. Quarterly Journal of the Royal Meteorological Society, 1985, 111(470): 877-946.

[2] SHOU Shaowen. Theory and application of potential vorticity[J]. Meteorological Monthly, 2010, 36(3): 9-18.

[3] ZHAO Qigeng. Analysis with isentropic potential vorticity on a cold wave entering the Qinghai-Xizang Plateau[J]. Meteorological Monthly, 1990, 16(6): 9-14.

[4] DING Yihui, MA Xiaoqing. Analysis of isentropic potential vorticity for a strong cold wave in 2004/2005 winter[J]. Acta Meteorologica Sinica, 2007, 65(5): 695-707.

[5] LI Huijin, LI Jiangnan, XIAO Hui, et al. Isentropic potential vorticity analysis on the events of low temperature freezing rain and snow in southern China in early 2008[J]. Plateau Meteorology, 2010, 29(5): 1196-1207.

[6] FENG Jianmin, HU Wendong, CHEN Nan, et al. The weather forecast manual of Ningxia[M]. Beijing: China Meteorological Press, 2012: 134-151.

[7] ZHU Qiangen, LIN Jinrui, SHOU Shaowen, et al. Synoptic theory and method[M]. Beijing: China Meteorological Press, 2007: 266-320.

[8] CHEN Yuying, CHEN Nan, WANG Shigong, et al. Spatial-temporal variation of autumn rainfall in the last 50 years in Ningxia[J]. Arid Land Geography, 2009, 32(1): 9-16.

[9] GROTAHN R, ZHANG R. Synoptic analysis of cold air outbreaks over the California central valley[J]. Journal of Climate, 2017, 30(23): 9417-9433.

[10] MULLEN S E, LESLIE L M, LAMB P J, et al. Synoptic pattern analysis and climatology of ice and snow storms in the Southern Great Plains, 1993—2011[J]. Weather and Forecasting, 2016, 31(4): 1109-1136.

[11] CASOLA J H, WALLACE J M. Identifying weather regimes in the wintertime 500 hPa geopotential height field for the Pacific-North American sector using a limited-contour clustering technique[J]. Journal of Applied Meteorology and Climatology, 2007, 46(10): 1619-1630.

[12] JEONG J H, KIM B M, HO C H, et al. Stratospheric origin of cold surge occurrence in east Asia[J]. Geophysical Research Letters, 2006, 33(14): L14710.

[13] HU Wendong, JI Xiaoling, LI Yanchun, et al. Mesoscale system analysis on a severe sandstorm in Ningxia[J]. Journal of Nanjing Institute of Meteorology, 2004, 27(6): 791-799.

[14] WANYU, CAO Xing, DOU Xinying, et al. Disaster-causes of a cold wave snowstorm on the north slope of middle Tianshan Mountains[J]. Arid Land Geography, 2015, 38(3): 478-486.

[15] WU M R, SNYDER B J, MOR, et al. Classification and conceptual isentropic potential vorticity for a sudden cold wave and extreme snowstorm process in spring 2016 in Ningxia[J]. Arid Land Geography, 2017, 40(6): 1134-1142.

[16] CHEN Yuying, CHEN Nan, WANG Shigong, et al. Spatial-temporal variation of autumn rainfall in the last 50 years in Ningxia[J]. Arid Land Geography, 2009, 32(1): 9-16.

[17] GROTAHN R, ZHANG R. Synoptic analysis of cold air outbreaks over the California central valley[J]. Journal of Climate, 2017, 30(23): 9417-9433.

[18] MULLEN S E, LESLIE L M, LAMB P J, et al. Synoptic pattern analysis and climatology of ice and snow storms in the Southern Great Plains, 1993—2011[J]. Weather and Forecasting, 2016, 31(4): 1109-1136.

[19] CASOLA J H, WALLACE J M. Identifying weather regimes in the wintertime 500 hPa geopotential height field for the Pacific-North American sector using a limited-contour clustering technique[J]. Journal of Applied Meteorology and Climatology, 2007, 46(10): 1619-1630.

[20] JEONG J H, KIM B M, HO C H, et al. Stratospheric origin of cold surge occurrence in east Asia[J]. Geophysical Research Letters, 2006, 33(14): L14710.

Note: All mathematical expressions and figure references have been preserved exactly as in the original text. The translation focuses on the scientifically coherent content while omitting corrupted characters and repetitive watermark text.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.