Research Article

The Role of Rossby-Wave Propagation in a North American Extreme Cold Event

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The Eliassen–Palm flux and Plumb wave activity flux are calculated using the European Centre for Medium-Range Weather Forecasts interim reanalysis daily dataset to determine the propagation of Rossby waves before a North American cold wave in January 2014. The results show that the upward wave activity fluxes mainly come from planetary waves 1 and 2, which provide a stable circulation background for the influence of the subplanetary-scale waves 3 and 4. The Rossby-wave propagation anomalies between the troposphere and the stratosphere are due to the modulating effects of waves 3 and 4 on waves 1 and 2. During 9–14 January 2014, the modulating effects helped strengthen upward and eastward wave activity fluxes over the Atlantic region and enhance the Pacific high in the stratosphere in its early stage. Later in 19–24 January, the downward wave activity fluxes over the east Pacific due to the modulating effects were beneficial to downward development of the stratospheric high over the Pacific and the formation of a blocking high over the west coast of North America in the troposphere accompanied by a strong adjacent cold low on the east side. These circulations benefit the southward invasion of polar cold air reaching the lower latitudes of east North America, leading to the cold wave outbreak.

1. Introduction

The Arctic polar vortex is one of the most important atmospheric circulations in the Northern Hemisphere (NH) winter and is also an important feature of the winter stratosphere. Cold wave outbreaks in the high latitudes of the NH winter are always associated with changes in the polar vortex [1–3]. It is easier for polar cold air to intrude farther south when the polar vortex is weak. Xiong et al. [4] suggested that Asian cold weather is mainly caused by polar vortex variation. During the extremely weak polar vortex of stratospheric sudden warming, the East Asian trough is strengthened and East Asia experiences cold events [5, 6].

To some extent, there are always interactions between the stratospheric polar vortex and wave activity of different scales [7]. Planetary wave activity can affect the intensity of the stratospheric polar vortex, and the anomalous stratospheric polar vortex can also have effects on the planetary

waves (PWs). The interaction between the PWs and the stratospheric polar vortex anomaly can affect the short-term climate in the troposphere via a top-down mechanism [8]. When the polar vortex is weak, more stratospheric wave activities propagate polewards [9] and extreme cold events in the mid- and high latitudes occur more frequently [10].

Although most previous studies have suggested that variation of the polar vortex is mainly affected by PWs 1 and 2, some studies [e.g., [11]] have shown that the activities of transient waves are probably the main factor affecting the evolution of the stratospheric polar vortex. Transient waves are more active in the troposphere, but in some cases they can enter the lower stratosphere, where they interact with the PWs and have an implication to stratospheric anomalies [12]. Song and Robinson [13] pointed out that the response of the troposphere to the stratosphere is mainly caused by wave 3. Chshyolkova et al. [14] indicated that polar vortex disturbance in the stratosphere is the result of

FIGURE 1: Composited 2-m surface temperature anomalies (shading; K) in January 2014 relative to the 30-year climatology: (a) composition for 1–15 January; (b) composition for 21–29 January. The 30-year climatology refers to the 30-year average of January in 1981–2010.

the interaction of PWs and transient waves. The blocking highs that usually accompany cold waves are more likely to resonate with subplanetary-scale waves. The effects of transient waves and PWs on atmospheric circulations are not separable, as these two types of waves modulate each other [15].

The polar vortex index [16–18], which is used for medium- and long-term weather forecasts, or the stratospheric northern annular mode index [19], which is used for short-term climate predictions [20], could be exploited to predict cold waves in weather forecasting, but attempts have not been very successful. One reason maybe of the underlying interaction between transient waves and planetary waves remains unclear. A North American cold wave in late January 2014 is used as an example in this paper. We focus on the modulating effects of the subplanetary-scale waves represented by waves 3 and 4 on the circulation evolution throughout the stratosphere–troposphere and explore the causes and precursor signals of extreme low-temperature events.

2. Data and Methodology

The European Centre for Medium-Range Weather Forecasts interim reanalysis global daily dataset is used in this study [21]. The Eliassen–Palm flux (EPF) [22] and the Plumb wave activity flux (WAF) [23] are calculated to determine the propagation of PW packets in two- or three-dimensional space, as mentioned by Shi et al. [24].

3. Circulation Characteristics during the Cold Wave

The 2-m surface temperature anomaly shows two different patterns in January 2014 (Figure 1). In the first half of January (Figure 1(a)), the temperature anomaly in the NH is

relatively weak and is mainly located north of 50°N latitude, with the cold anomaly located in Siberia. In late January (Figure 1(b)), the temperature anomaly is stronger. In the high latitudes north of 50°N, the cold anomaly is mainly located in the eastern hemisphere and the warm anomaly in the western hemisphere. In the mid-latitudes south of 50°N, a new temperature anomaly center appears, with a cold center of −10 K located in east North America, while Eurasia has a warm anomaly. In winter, the effects of cold waves at the same intensity are much stronger in the mid-latitudes than in the high latitudes. Therefore, it is worth studying this continuous extreme cold event in east North America in late January 2014.

Based on the daily variation of the 500-hPa geopotential height and its departure from the climatology (Figure 2), the formation of the Alaskan blocking high and deepening of the North American trough (Figure 2(d)) are the most important factors contributing to the continuous intrusion of cold air into east North America. During 9–14 January (Figures 2(a) and 2(b)), the Alaskan ridge develops, the North American trough deepens, and the Atlantic ridge moves westwards and is strengthened. On 19 January (Figure 2(c)), both the Alaskan and Atlantic ridges are weakened, the North American trough moves eastwards, and the polar low in the trough extends to the lower latitudes. On 24 January (Figure 2(d)), the Alaskan high ridge and the Atlantic high ridge anomalously strengthen to form two blocking highs, which divide the polar vortex over east North America, corresponding to the extreme cold in east North America around 24 January. On 29 January (Figure 2(e)), the westward Atlantic high ridge retreats to the east coast of North America, and the polar vortex shrinks and remains in east North America, maintaining the extreme cold.

The evolution of the polar vortex and the anticyclone in the middle stratosphere (Figure 3) indicate that the stratospheric circulation is related to the tropospheric circulation.

FIGURE 2: Daily geopotential height (contours; gpm) and its anomalies (shading; gpm) at 500 hPa in January 2014 relative to the 30-year climatology. The 30-year climatology refers to the 30-year average of January in 1981–2010. Contour interval: 100 gpm.

FIGURE 3: Daily geopotential height (contours; gpm) and its anomaly (shading; gpm) at 10 hPa in January 2014 relative to the 30-year climatology. The 30-year climatology refers to the 30-year average of January in 1981–2010. Contour interval: 240 gpm.

FIGURE 4: Time series of the vertical component of the EPF for waves 1–4 (curves; $10^5 \text{ m}^2 \text{ s}^{-2}$) over $45^\circ\text{--}75^\circ\text{N}$ at 100 hPa from December 2013 to February 2014.

During 9–14 January (Figures 3(a) and 3(b)), the polar vortex splitting is responsible for the PW 2 pattern, and the Atlantic high is stronger than the Pacific high at 10 hPa. From 19 January (Figure 3(c)), the polar vortex shrinks, the Atlantic high gradually weakens, and the Pacific high increases. On 24 January (Figure 3(d)), the stratospheric circulation converts to a vortex displacement pattern (i.e., PW 1 pattern). On 29 January (Figure 3(e)), the Pacific high enhances and moves eastwards, and the polar vortex significantly extends to east North America and invades the lower latitude region of 30°N .

The evolution of the stratospheric polar vortex and its adjacent high (Figure 2) and the variation of tropospheric circulation (Figure 3) are cooperative, especially in the early stage of the positive anomaly of the stratospheric Atlantic ridge and then in the enhancement of the stratospheric Pacific high and the formation of tropospheric Alaskan blocking high. The relationship between the above systems and its impact on the North American cold wave are discussed in Section 4.

4. Rossby-Wave Propagation and Circulation Anomaly

Usually, stratospheric polar vortex disturbance and Rossby-wave activity are related. In January 2014, the intensity and trend of the vertical WAF for waves 1–3 and waves 1–4 are roughly the same as the evolution of PW 2 (Figure 4). In early January, the WAFs of wave 1, wave 3, and wave 4 remain near the zero line. After 12 January, the upward WAF of PW 1 is increased, while the downward flux of wave 3 is increased. Around 22 January, the downward WAF of wave 3 is at its strongest, the upward flux of PW 2 is weakened, the upward flux of PW 1 is more than PW 2, and the total WAFs for waves 1–3 reach a minimum. After the cold wave outbreak on 24 January, the increase in PW 2 activity takes the total flux up to a maximum value. The pattern of wave activity for

PWs 1 and 2 is consistent with the circulation mode shown in Figure 3.

In general, the stratospheric circulation anomalies are related to the activity of PWs 1 and 2 (Figure 3), but the subplanetary-scale waves represented by wave 3 (in Figure 4) have an important influence on the vertical propagation of wave activity. Therefore, the relationship between the wave activity anomaly and the transformation of the circulation structure is worth studying. For instance, how do the stratospheric high anomalies transfer from the Atlantic to the Pacific (in Figure 3)? How is the North American blocking high established (in Figure 2(d))?

The three-dimensional WAF describes the local characteristics of wave propagation. Figures 5 and 6 show the longitude-pressure cross-sections of the daily $50^\circ\text{--}70^\circ\text{N}$ WAF and its vertical component (WAFz) for different wave numbers. For the composited WAF of PWs 1 and 2 (Figures 5(a1)–5(a5)), upward wave activities are mainly located in the Pacific and the continents on both sides, which helps maintain the Pacific high in the stratosphere. Although the wave activities of waves 1–3 (Figures 6(a1)–6(a5)) and 1–4 (Figures 6(b1)–6(b5)) are similar, the significant difference in WAF between waves 1–4 and waves 1 and 2 (Figures 5(a1)–5(a5)) suggests that waves 3 and 4 have important modulating effects on PWs 1 and 2.

The modulating effects of waves 3 and 4 help strengthen the upward WAFs over the Atlantic region and enhance the stratospheric Pacific high in its early stage (Figures 6(b1) and 6(b2)). Later in 19–24 January, the downward WAFs over the east Pacific, due to the modulating effects, are beneficial for downward development of the stratospheric high over the Pacific and the formation of a blocking high over the west coast of North America in the troposphere (Figures 6(b3), 6(b4), and 2). Based on the temperature and geopotential height anomalies (Figures 5(b1)–5(b5)), the stratospheric Atlantic high, which is in its strongest stage (Figure 3(a)), has a deep vertical structure on 9 January. In the same period, the upward WAFs originate from the lower part of the high (red shading and vectors in Figures 6(a1) and 6(b1)). On 14 January, the Atlantic high is weakened, and the upward and eastward WAFs located in East Asia strengthen the Pacific high in the middle stratosphere (Figures 6(a2) and 6(b2)). On 19 January, the Atlantic high is further weakened, the stratospheric Pacific high is at its strongest, a large downward WAF occurs on the east side of the Pacific high, and both the high and adjacent low on the east side develop downward (Figures 6(a3) and 6(b3)). On 24 January, due to the downward WAF, the high near the surface reaches its maximum strength (Figure 6(b4)), the blocking is maturing on the west coast of North America, and the adjacent surface low in east North America is also strong (Figure 2(d)). The northerly winds between the blocking and the low are beneficial for guiding the southward intrusion of Arctic cold air, corresponding to the outbreak of a cold wave in east North America. On 29 January, the downward WAF anomaly tends

FIGURE 5: Continued.

FIGURE 5: Longitude-pressure cross-sections of the daily 50° – 70° N mean zonal anomaly of geopotential height (contours; gpm), WAF (vectors: $>60 \text{ m}^2 \text{ s}^{-2}$ only), and WAFz (shading; $\text{m}^2 \text{ s}^{-2}$) of PWs 1 and 2 in January 2014 ((a1)–(a5)). ((b1)–(b5)) As in ((a1)–(a5)), respectively, but for the geopotential height anomaly (contours; m) and temperature (shading; K). WAF components are scaled by $\sqrt{1000 \text{ hPa}/p}$ horizontally and by $100 \times \sqrt{1000 \text{ hPa}/p}$ vertically.

to end, and the surface high begins to weaken (Figure 6(b5)). It appears that Figure 6(a1) is significantly different from Figure 6(b1) in Atlantic area, suggesting that wave 4 may more favor the strengthening of upward wave flux over the Atlantic area. Also note that the effect of wave 4 on the tropospheric blocking over the west coast of North America cannot be negligible when comparing Figures 6(a3) and 6(b3).

The horizontal WAF of PWs 1 and 2 generally shows a poleward propagation in the high latitudes near the tropopause (Figures 7(a1)–7(a5)), which is the main channel for PWs entering the stratosphere (Figures 5(a1)–5(a5)). However, the pattern of horizontal WAF involving waves 3 and 4 is significantly different (Figures 7(b1)–7(b5)). During 19–29 January (Figures 7(b3)–7(b5)), the WAF of PWs 1–4 is along the Pacific–North America teleconnection (PNA) wave path, which contributes to the maintenance of the large amplitude disturbance of Rossby waves in North America. By comparing Figures 7(a1)–7(a5) and Figures 7(b1)–7(b5), it is found that wave paths in the Pacific–North America region are mainly modulated by waves 3 and 4. The stable strong disturbance of Rossby waves caused by the PNA wave path is helpful for the continuous invasion of cold air. Although the subplanetary-scale waves, such as PWs wave 3 and wave 4, cannot propagate directly into the stratosphere, they can significantly affect the wave activity into the stratosphere and change the stratospheric circulation (Figure 6) by modulating PWs 1–2 through wave–wave interactions.

5. Conclusions

By diagnosing the evolution of wave activity, the present study finds that the subplanetary-scale waves have an important influence on the occurrence of the cold wave in east

North America in late January 2014. The positive anomaly of the stratospheric Atlantic high is the early background for the North American cold wave, and then the wave activity anomalies of subplanetary-scale waves represented by waves 3 and 4 contribute to the large-scale migration of wave energy through troposphere–stratosphere interactions, which is followed by the establishment of a local tropospheric circulation structure that is favorable to a cold wave.

The planetary-scale waves PWs 1 and 2 provide subplanetary-scale waves 3 and 4 with a stable circulation background. The continuous upward WAFs of PWs 1 and 2 in the East Asia–Pacific region maintain the Pacific high in the stratosphere. The propagation anomalies of Rossby waves between the troposphere and the stratosphere are due to the modulating effects of waves 3 and 4 on PWs 1 and 2. At the extended range scale, the modulating effects help strengthen the upward and eastward WAFs over the Atlantic region, enhancing the Pacific high in the stratosphere in its early stage. About ten days later, the downward WAFs over the east Pacific due to the modulating effects are beneficial to downward development of the stratospheric high over the Pacific and formation of the tropospheric blocking high over west coast of North America accompanied by a strong adjacent cold low on the east side.

This cold wave is an important aspect of troposphere–stratosphere interaction. The energy redistribution through the troposphere–stratosphere–troposphere is conducive to the maintenance of the PNA wave path, which contributes to the WAF over North America that causes the southward invasion of polar cold air into lower latitudes in east North America. Therefore, the wave activity anomaly of

FIGURE 6: As in Figure 5 ((a1)–(a5)), but for waves 1–3 ((a1)–(a5)) and waves 1–4 ((b1)–(b5)).

FIGURE 7: Daily geopotential height (contours; m) and WAFs (vectors: $>12 \text{ m}^2 \text{ s}^{-2}$ only) of PWs 1 and 2 ((a1)–(a5)) and waves 1–4 ((b1)–(b5)) at 250 hPa in January 2014. Contour interval: 120 gpm.

subplanetary-scale waves represented by waves 3 and 4 is the most important factor contributing to this cold wave.

Conflicts of Interest

The authors declare no conflicts of interest.

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