

Analysis of the extremely cold and heavy snowfall in North America in January 2015

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ABSTRACT

With global warming and declining Arctic sea ice area in autumn observed by satellites since 1979, anomalous cold snaps in recent winters have affected large parts of North America, Europe, and East Asia. In January 2015, North America suffered extremely cold and heavy snowfall events. As revealed in this paper, the NCEP reanalysis data show that the temperature decreased significantly in January 2015 in North America, including the air temperature in the troposphere and the surface air temperature. Moreover, snow cover increased obviously in January 2015 in North America, while there was a significant negative anomaly of geopotential height. The wind formed the anomalous pattern, which favored cold currents blowing to the North American continent from the polar region, and bringing plenty of water vapor. Our results suggest that the anomalous north wind and decreasing westerly jet stream, which allowed cold and moist air to easily penetrate the North American continent from the Arctic, was one of the main reasons for the extremely cold and heavy-snow winter of 2015 in North America.

摘要

伴随全球变暖和有卫星观测记录以来北极秋季海冰面积的下降,近几年,北美、欧洲及东亚地区经历了异常的冷冬。2015年1月,北美地区也遭受了严重的冷冬和暴雪事件。文中用NCEP再分析数据显示2015年1月气温的下降主要在北美地区,且降雪覆盖明显增加。此时位势高度场负异常明显,形成了从北极地区吹向北美大陆地区的寒流,携带了大量水汽。本文结果显示异常强劲的北风和减弱的西风急流,导致了极地寒流和湿空气容易入侵北美大陆地区,是造成2015年1月北美大陆地区冷冬和暴雪事件的主要原因之一。

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1. Introduction

In January 2015, North America experienced anomalously cold conditions, along with heavy snowfall. The extremely cold weather in the past few winters over large parts of the Northern Hemisphere (NH) has caused problems in terms of personal safety, economic losses, disruption to transport, energy supply, and damage to agriculture (Cohen et al. 2010; Guirguis et al. 2011; Coumou and Rahmstorf 2012). Previous studies have shown that North Atlantic Oscillation (NAO), Arctic Oscillation (AO), the Pacific–North America pattern (PNA), Pacific Decadal Oscillation (PDO), and El Niño–Southern Oscillation (ENSO) have strong influences on extreme climate events in winter in North America or the NH (Griffiths and Bradley 2007; Cohen et al. 2012; Westby, Lee, and Black 2013; Loikith and Broccoli 2014; Ning and Bradley 2014a, 2014b; Cannon 2015). The Arctic sea-ice loss since 1979 has also caused severe winters (Wu, Huang, and Gao 1999; Liu et al. 2012; Wu et al.

2013) and contributed to the amplified warming in the Arctic (Screen and Simmonds 2010). Hartmann (2015) showed that a proximate cause of the cold winter in North America in 2013–14 was the pattern of sea surface temperature (SST) in the Pacific Ocean. Meanwhile, Lee, Hong, and Hsu (2015) indicated that the extratropical NH during the winter of 2013–2014 was constructively induced by anomalous SST in the tropical Pacific and extratropical North Pacific, as well as the low sea-ice concentration in the Arctic. In fact, as early as the 1990s, Chinese scholars proposed that the Barents–Kara Sea in winter is a key regional impacts on climate change, with the Arctic sea-ice changes in these regions bearing certain relationships with the winter wind. This conclusion was reached some 10 years or more earlier than similar results from outside of China (Wu, Huang, and Gao 1999). Recently, countries in East Asia have experienced frequent cold winters and extreme weather events. The recent cold winters in some

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East Asian countries have been directly connected to the recovery of the intensity of the Siberian high and its frequent positive anomalies since 2004 (Wu, Su, and Zhang 2011). Although some studies have investigated the predominant patterns of winter wind variability over East Asia and the Arctic (e.g. Wu, Overland, and D'Arrigo 2012; Wu et al. 2013), some important issues still remain unclear with respect to the North American continent.

Because of their considerable impact upon society, climate extremes have attracted increasing attention in recent climate studies (Easterling et al. 2000; Meehl and Tebaldi 2004). Some explanations have been offered for the recent severe winter of 2009–10 from the perspective of dominant modes of climate variability (Cohen et al. 2010; Seager et al. 2010; Ratnam et al. 2011). The major teleconnection patterns of the NH, ENSO, and AO were of moderate to strong amplitude, potentially making both key players during the extreme cold and snowy winter of 2009–2010 in the NH (Cohen et al. 2010). The notion of changes in atmospheric circulation being linked with recent extreme weather events in winter has also been suggested, including an association with the declining Arctic sea ice in autumn (Porter, Cassano, and Serreze 2012; Ogi and Rigor 2013; Tang et al. 2013). Liu et al. (2012) demonstrated that the decrease in autumn Arctic sea-ice area is linked to changes in the winter NH atmospheric circulation that bears some resemblance to the negative phase of winter AO. Griffiths and Bradley (2007) indicated that AO is a good predictor of winter warm nights, while ENSO is a good predictor of consecutive dry days in northeastern America. Westby, Lee, and Black (2013) evaluated the low-frequency modulation from NAO, the PNA, ENSO, and PDO on anomalous temperature regimes, i.e. cold air outbreaks and heat waves, during boreal winter over the continental United States, as simulated by GCMs from CMIP5. Loikith and Broccoli (2014) found that the PNA and the North Annular Mode (NAM) play important roles in the occurrence of extreme temperature days in regions in the vicinity of the characteristic atmospheric circulation anomalies associated with these modes of variability. It has been suggested that the weakening poleward temperature gradient due to Arctic amplification is contributing to a slower progression of Rossby waves in upper-level flows, which in turn leads to more persistent weather conditions that favor extreme events in North America and the North Atlantic (Francis and Vavrus 2012). Some studies have demonstrated that the recent decline in autumn Arctic sea ice may play a critical role in the cold and snowy winters in northern continents (Francis et al. 2009; Overland and Wang 2010; Blüthgen, Gerdes, and Werner 2012). Wu et al. (2013) researched the dominant patterns of 850 hPa daily wind field variability over northern Eurasia during the winter season, which benefited by improving the

prediction ability for extreme weather events. However, the unexpected extremely cold and heavy-snow winter in January 2015 in North America still draws much attention.

In this paper, through data analysis (NCEP–NCAR reanalysis data), we examine the anomalously cold winter in North America in January 2015. The data are introduced in Section 2, the results are presented in Section 3, and conclusions and discussion are presented in Section 4.

2. Data

Monthly mean fields of 1000–300 hPa air temperature and surface air temperature were obtained from the NCEP–NCAR reanalysis data-set (Kistler et al. 2001). Monthly mean fields of 1000–300 hPa geopotential height and winds were obtained from the NCEP–NCAR reanalysis data-set and ERA-Interim. Daily mean fields of snowfall were obtained from the ERA-Interim data-set. Daily mean fields of 1000–300 hPa specific humidity were obtained from the NCEP–NCAR reanalysis data-set. All data have a resolution of $2.5^\circ \times 2.5^\circ$ and cover the period from 1979 to 2015 in the NH (30°N to the North Pole). The reference period for anomalies is 1979–2012.

3. Results

In January 2015, North America suffered extremely cold events. The minimum air temperature anomaly reached -4.3°C , which was the lowest temperature from 2010 to 2015 in North America (Figure 1a). The distributions of 500 hPa air temperature and geopotential height anomalies in the NH in January 2015 are shown in Figure 1b. There was a clear negative anomaly of 500 hPa air temperature in North America (Figure 1b), while it was significantly positive over East Asia, western America, and the North Pacific and Atlantic oceans. The 500 hPa isobaric line in North America is significantly consistent with the negative anomaly of air temperature, which illustrates the barotropic atmosphere (Figure 1b). The center of the lower temperature was over northeastern America, and this lower air temperature phenomenon sustained throughout the whole troposphere over North America, averaged from 30°N to the North Pole (Figure 1c). Meanwhile, in East Asia, western America, and the North Pacific and Atlantic oceans, the air temperature was significantly positive throughout the whole troposphere. To investigate this phenomenon, the surface air temperature anomaly was analyzed (Figure 2). The surface air temperature, with its pattern the same as the air temperature throughout the whole troposphere but with larger amplitude, also decreased significantly in January 2015 over North America (Figure 2).

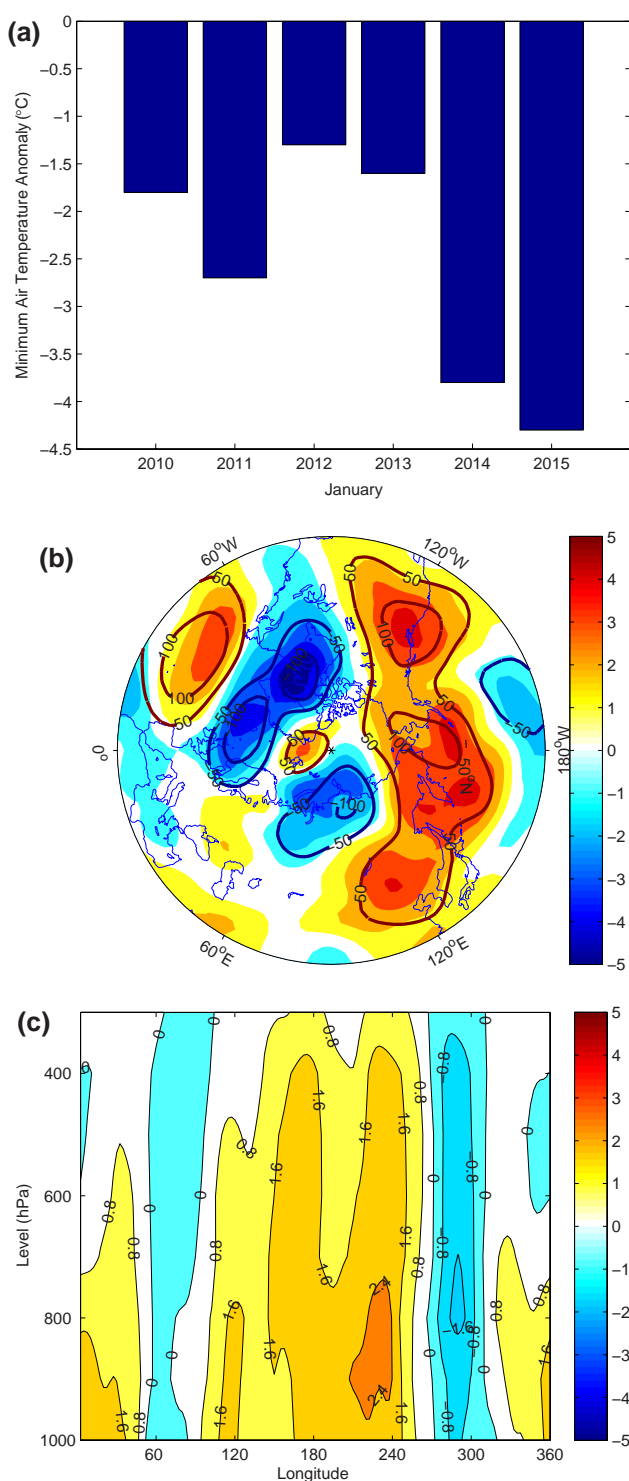


Figure 1. (a) Minimum air temperature anomaly in North America (40–65°N, 240–300°E) in January from 2010 to 2015, (b) 500 hPa air temperature anomalies (color scale; °C) and geopotential height anomalies (contours; m) in January 2015, and (c) meridional mean air temperature anomalies (averaged from 30°N to the North Pole) from NCEP data. The corresponding climatological variables are from 1979 to 2012.

During the past few winters, North America, Europe, and Central Asia have experienced anomalously cold conditions, along with heavy snowfall (WMO, 2009, 2010,

2011). In January 2015, in North America, with the anomalously low temperature (Figure 1), the snow cover anomaly values were high (Figure 3a). It should be noted that the snow cover anomaly signal was strongest over the Tibetan Plateau (Figure 3a). Due to the heaviest snowfall mainly occurred on 27 January 2015 in North America, this paper focuses on the tropospheric specific humidity anomalies during 20–28 January 2015, combined with the wind anomalies (Figure 3b). As shown in Figure 3b, the highest water vapor content occurred over the center of northwestern America. Meanwhile, the wind anomalies blew to northeastern America from the high water content region, which provided plenty of water vapor for the heavy snowfall (Figure 3). The occurrence of low temperatures and heavy snowfall in January 2015 in North America was connected with the anomalous patterns of geopotential height and zonal and meridional winds in the NH.

Similar to temperature, the tropospheric geopotential height was also lower in North America and higher in East Asia, western America, the North Pacific and Atlantic oceans, and the polar region in January 2015 (Figure 4). The lower geopotential height sustained throughout the whole troposphere in North America. The anomaly of geopotential height affected the atmospheric circulation over North America in January 2015, which formed the northerly wind anomaly. This anomaly allowed the colder polar air to penetrate into North America.

To further study this phenomenon, the meridional and zonal winds were investigated (Figure 5). There was a significant negative anomaly of meridional wind over North America in January 2015, and the negative anomaly existed throughout the whole troposphere above the American continent, with the vertical distribution averaged from 30°N to the North Pole (Figures 5a and 5b). However, there were positive anomalies in East Asia and the North Pacific and Atlantic oceans (Figure 5a). The 500 hPa zonal wind was not significantly weaker over North America, but was over the North Pacific Ocean (Figure 5c). This obviously negative anomaly existed throughout the whole troposphere averaged over the North Pacific Ocean (120–180°W) (Figure 5d). The weakened westerly jet stream was significantly weak over western North America, which reduced the resistance to a southward invasion of cold polar air (Figures 5c and 5d). So, these anomalies directly led to cold polar air blowing over the North American continent, and were responsible for the cold events in this area.

To confirm whether these cold events in North America in January 2015 were caused or partly caused by the cold air invasion from the Arctic, the anomalous patterns of geopotential height and zonal and meridional winds over the NH are shown in Figure 6 using ERA-Interim data. The results are compatible with the NCEP results in Figures 4 and 5.

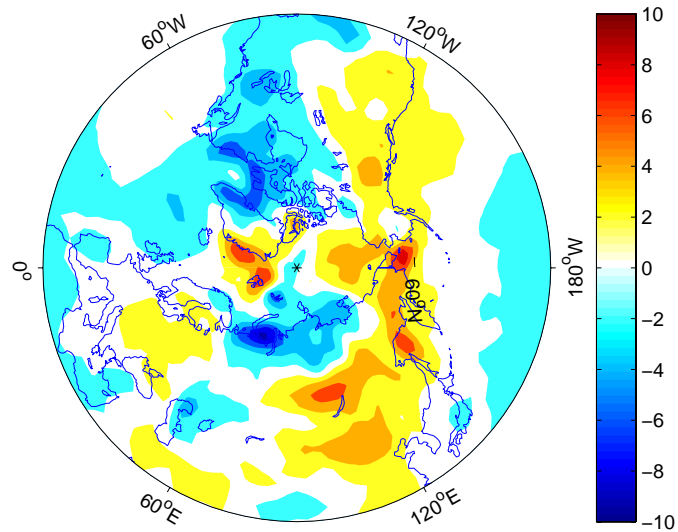


Figure 2. Surface air temperature anomalies ($^{\circ}\text{C}$) in January 2015 from NCEP data. The corresponding climatological variable is from 1979 to 2012.

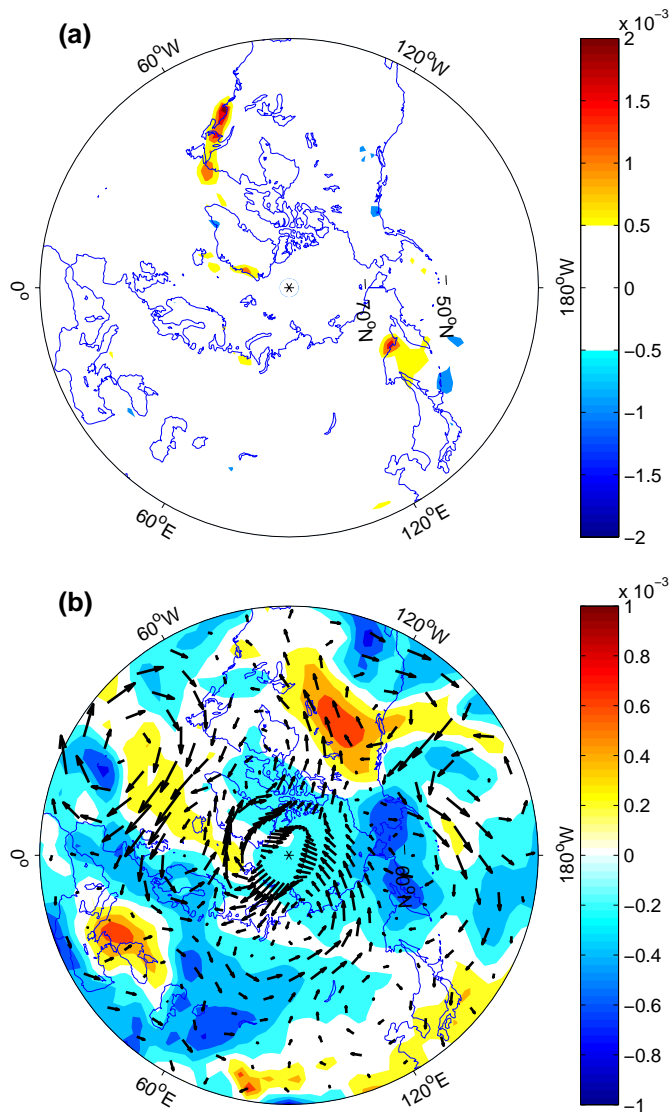


Figure 3. (a) Spatial distributions of snowfall anomalies (m of water equivalent per six hours) during 25–28 January 2015 from ERA-Interim data. (b) 1000–300 hPa averaged specific humidity anomalies (color scale; kg kg^{-1}) during 20–28 January 2015 and wind anomalies (vectors; m s^{-1}) in January 2015 from NCEP data. The climatological variables are from 1979 to 2012.

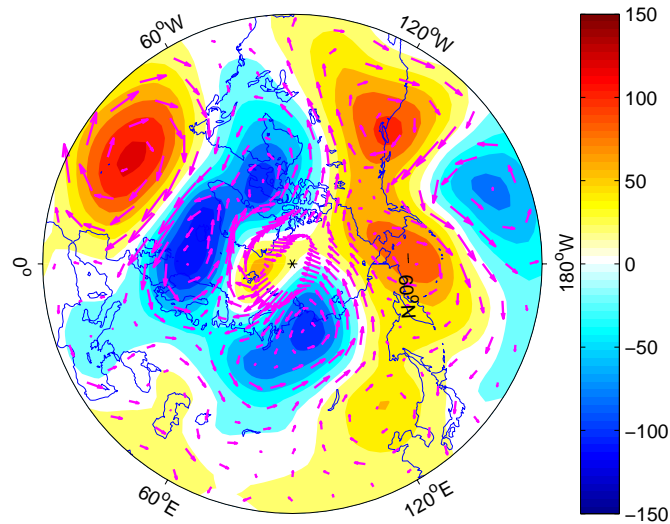


Figure 4. 1000–300 hPa averaged geopotential height anomalies (color scale; m) and wind anomalies (vectors; m s^{-1}) in January 2015 from NCEP data. The corresponding climatological variables are from 1979 to 2012.

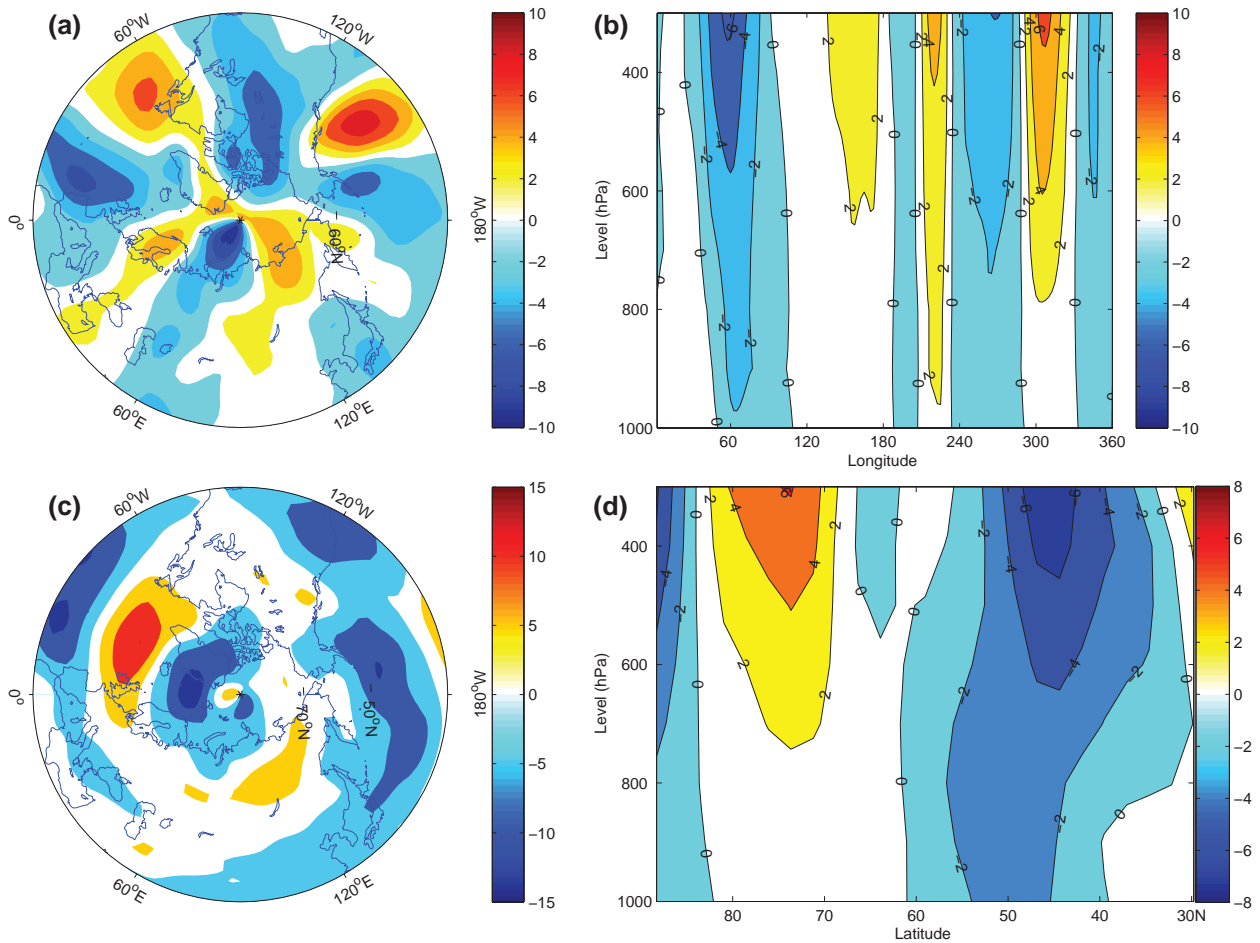


Figure 5. (a) 1000–300 hPa averaged meridional wind anomalies (color scale; m s^{-1}), and (b) their meridional mean anomalies (color scale; averaged from 30°N to the North Pole) in January 2015 from NCEP data. (c) 500 hPa zonal wind anomalies (color scale; m s^{-1}), and (d) 1000–300 hPa zonal mean wind anomalies in the North Pacific (120°W – 180°W) in January 2015 from NCEP data. The corresponding climatological variables are from 1979 to 2012.

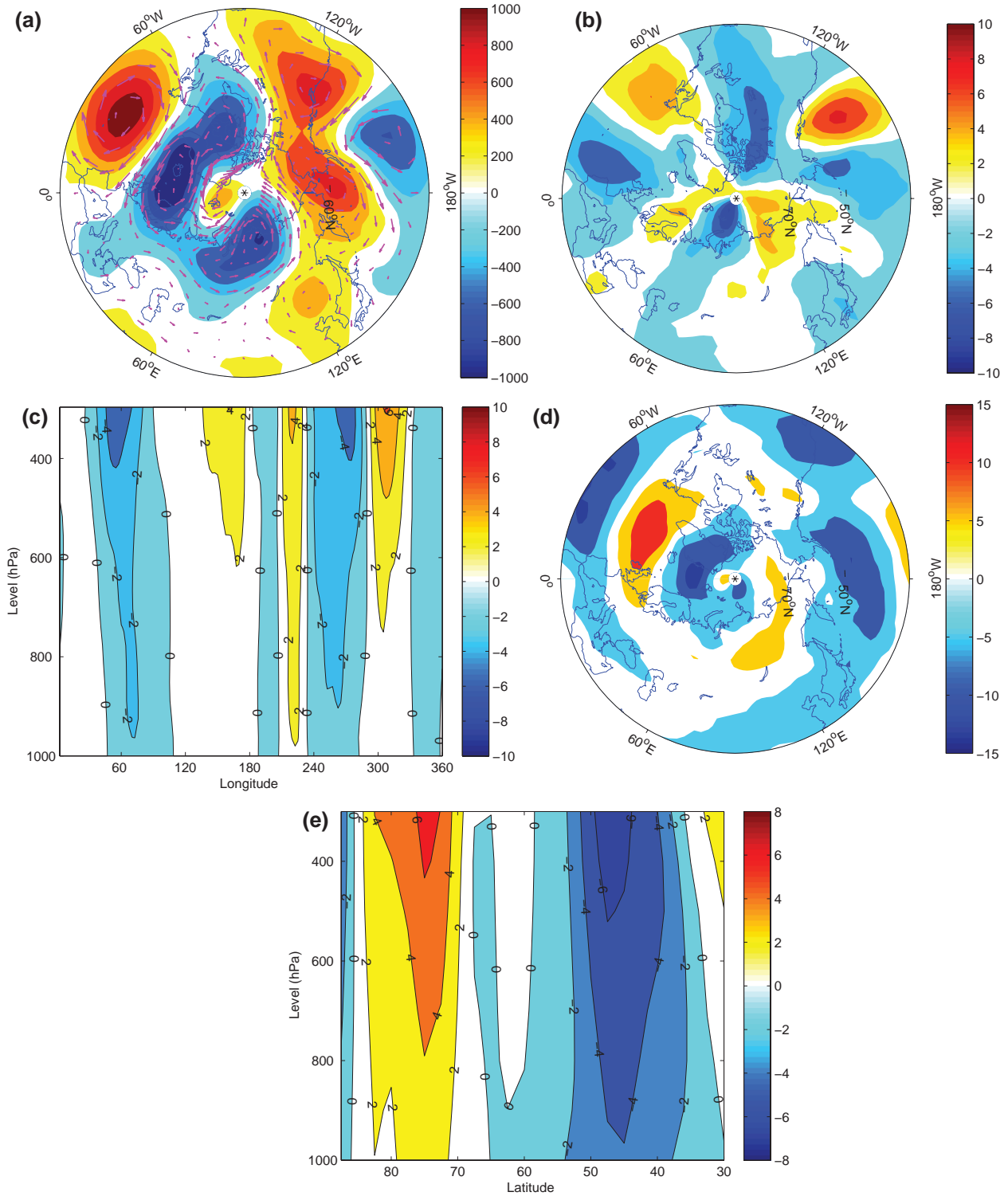


Figure 6. (a) 1000–300 hPa averaged geopotential height anomalies (color scale; $\text{m}^2 \text{s}^{-2}$) and (b) wind anomalies (vectors; m s^{-1}), meridional wind anomalies (m s^{-1}), and (c) their meridional mean anomalies (averaged from 30°N to the North Pole) in January 2015 from ERA-Interim data. (d) 500 hPa zonal wind anomalies (m s^{-1}), and (e) 1000–300 hPa zonal mean wind anomalies in the North Pacific ($120\text{--}180^\circ\text{W}$) in January 2015 from ERA-Interim data. The corresponding climatological variables are from 1979 to 2012.

4. Conclusion and discussion

In January 2015, North America experienced extreme cold temperatures and heavy snowfall. In this study, we investigated these phenomena using NCEP–NCAR and ERA-Interim data. The results suggest that these extreme weather events in North America were connected with stronger than normal northerly wind and a weaker than usual westerly jet stream. The anomalous conditions of atmospheric circulation in the NH favored the intrusion of cold polar air into North America in January 2015. When the southward-moving cold polar air encountered warm and humid air, it created conditions conducive to the formation of a cold winter and heavy snow in North America. The geopotential height decreased anomalously and water vapor increased in January 2015 in North America. The geopotential height anomaly produced a pressure difference and, subsequently, atmospheric circulation pattern changes. The northerly wind became stronger over North America and the westerly jet stream became weaker over western North America, which was conducive to blowing the cold and moist polar air over North America. Therefore, extremely cold temperatures and heavy snowfall occurred in January 2015 in North America.

To better understand the reasons behind extreme winter weather in the NH, other dominant modes of climate variability and natural chaotic variability of general circulation need to be investigated. The NAO index usually has a significantly positive (negative) relationship with warm (cold) temperature extremes over most of the region. This is because, during high-NAO winters, the Bermuda/Azores high extends to northeastern America, meaning this positive pressure anomaly blocks the polar jet stream from entering the region and the east-to-west pressure gradient induces southerly wind anomalies, leading to positive temperature anomalies (Ning and Bradley 2014b). The PNA and NAM play important roles in the occurrence of extreme temperature days in America in the opposite way in wintertime (Loikith and Broccoli 2014). The association between ENSO and extended winter precipitation extremes in North America was examined by stationary, linear nonstationary, and nonlinear nonstationary fitting (Cannon 2015). In boreal winter, the declining Arctic sea ice in autumn plays an important role in the following winter's atmospheric circulation system, which causes cold events and snowfall (Liu et al. 2012; Vihma 2014; Gao et al. 2015). Natural variability plays a major role in inducing anomalously warm SST and low Arctic sea-ice concentration in the Bering Sea, which contributes to the intensity of extreme weather in the extratropical NH during winter. If anthropogenic warming has a significant impact on causing the synchronization of the aforementioned anomalies in SST and sea-ice concentration, and this trend

continues, severe winters similar to that in 2013–2014 may occur more frequently in the future (Lee, Hong, and Hsu 2015). Thus, comprehensive research is still needed for fully understanding the cold winter in North America in January 2015.

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