Two Impacts of Arctic Rapid Tropospheric Daily Warming From Different Warm Temperature Advection on Cold Winters Over Northern Hemisphere

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Abstract A number of previous studies show that the long-term Arctic winter warming causes severe cold over East Asia and North America. We use the atmospheric data from National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis to define the Arctic rapid tropospheric daily warming (RTDW) events that in one day, Arctic average 1,000-hPa air temperature is over 3σ warmer anomaly in situ winter. We find that main warm temperature advection of the RTDW events is from Atlantic Ocean and Pacific Ocean, named the Atlantic pattern and the Pacific pattern, respectively. The RTDW events of different warm temperature advection have different vertical distributions of warming. Therefore, different polar vortex splitting is induced and the splitting of polar vortex means movement of the cold air mass. The impacts of RTDW events on the Northern Hemisphere cold winter are mainly through the Asia-Europe path caused by the Atlantic pattern and the North America path caused by the Pacific pattern. As for the Asia-Europe path, the cold air invades the northern hemisphere from northwest Europe to Southeast Asia throughout the entire Eurasian continent. In the case of the North America path, the negative temperature anomalies are located in the west of Canada and America. The different warm temperature advection of RTDW events leads to different regions of the polar cold air mass invasion through different paths. Our results may help find out where the severe cold events impact on after the Arctic RTDW events with the occurrence of different warm temperature advection.

Plain Language Summary In our research, we show that there are two impacts of Arctic rapid tropospheric daily warming events on cold winters over Northern Hemisphere. The Arctic rapid tropospheric daily warming with warm temperature advection from Atlantic will cause cooling in Asia-Europe and from Pacific will cause cold air outbreaks in North America in the next few days.

1. Introduction

The phenomenon that the temperature of Arctic has increased more than twice as fast as Northern Hemisphere is referred to as Arctic amplification (Cohen et al., 2014; Holland & Bitz, 2003; Serreze et al., 2009; Serreze & Francis, 2006). There are a lot of documented reasons of Arctic amplification, and the change of heat transport in atmosphere is an extremely important reason (Graversen et al., 2008).

The mean surface air temperature of the North Pole is near −30 °C during the winter season. However, from 1954 to 2010, the temperature of winter time over −5 °C was observed once every three years at the observation sites in the central Arctic Ocean (Graham et al., 2017). During late December 2015 and early January 2016, the Arctic cyclone transported extreme warm air mass over the Ba-Ka region and the peak of temperature increase was 10 °C (Boisvert et al., 2016), and air temperature of the North Pole rose from −26.8 °C to −0.8 °C, near freezing at the surface (Moore, 2016). This rapid tropospheric warming is different from the well-known sudden stratospheric warming. The sudden stratospheric warming as a common stratospheric phenomenon not only controls the variability of stratospheric circulation but also affects the circulation of troposphere during the Northern Hemisphere wintertime (Andrews et al., 1987; Limpasuvan et al., 2004).

It is noticeable that rapid tropospheric warming events, increased faster than sudden stratospheric warming events, are related to the increase in midlatitude weather extremes during boreal winter (Cohen et al., 2014; Kug et al., 2015; Van Oldenborgh et al., 2015; Wang et al., 2017). Cold air outbreaks (CAOs) that cold air masses move into warmer areas can lead to diseases, deaths, and damage, especially in warmer climate (Barnett et al., 2005; Mercer, 2003). Northern Hemisphere wintertime stratospheric polar vortex tends to lead extreme cold events that influence eastern Asia, and some other densely populated area, when it
becomes weak (Thompson et al., 2002). The weaker polar vortex induces more cold air outbreaks (Thompson & Wallace, 1998). A strong high-pressure anomaly over northwest Eurasia is related to cold anomalies over Asia and Europe, and the stratospheric polar vortex is helpful for forecasts of cold air outbreaks (Kolstad et al., 2010). Therefore, from the synoptic scale, we hope to find out where the warm temperature advection of the Arctic rapid tropospheric daily warming events is from, and what RTDW events make impacts on the cold winter in the Northern Hemisphere.

2. Data and Methods

2.1. Data

With the daily data from National Centers for Environmental Prediction/National Center for Atmospheric Research Reanalysis, obtaining the data of air temperature, wind, and geopotential height from 1,000 to 500 hPa, we study the Arctic rapid tropospheric daily warming events in situ winter time (December–February) from 1948 to 2015 with the horizontal resolution of 2.5°.

2.2. Definition of RTDW Event

In order to discuss the rapid daily warming event characteristics, we define the Arctic rapid tropospheric daily warming (RTDW) event when the Arctic average 1,000-hPa air temperature daily warmer anomaly is over $3\sigma$ (above the 1948–2015 winter mean) during situ winter time (December–February) from 1948 to 2015, and $\sigma$ is the standard deviation of Arctic average 1,000-hPa air temperature daily warmer anomaly from the 66.5°N to the North Pole. So we make 38 events totally. This $3\sigma$ threshold value represents a departure of maximum 13 °C daily warmer anomaly in the North Pole from the composite of temperature variation anomaly of all RTDW events chosen (Figure 1). The maximum increase of temperature occurs in the northeast of the Greenland, near the North Pole.

2.3. Classification of RTDW Patterns With the Fuzzy c-Means Method

In this study, we use the fuzzy c-means method to classify the RTDW events according to the 1,000-hPa meridional wind anomaly that brought a lot of warm or cold currents. In comparison with other methods of cluster analysis, the fuzzy c-means method has some advantages on getting representative patterns (Fujibe, 1989, 1999).

According to the wind pattern, the maximum southerly anomaly is from the Atlantic where warm currents exist (Figure 2a). Southerly anomaly extends from the southeast of Greenland to the North Pole, and the maximum wind speed anomaly appears on the east of Greenland, with anomaly value of 13 m/s. The strong southerly anomaly brings huge warm and moist air mass into the Arctic from the midlatitude Atlantic due to wind speed anomaly near 45°N. The warm and moist air mass contains huge energy causing the Arctic rapid tropospheric daily warming. At the warming period, a cyclone is located in Greenland, and an anticyclone is over the Kara Sea (Figure 2a). The strong southerly is driven by the combined effects of a strong cyclone and an anticyclone. In winter, cyclones brought a lot of heat and moisture into the Arctic (Boisvert et al., 2016; Sorteberg & Walsh, 2008).

3. Analysis and Result

3.1. Results of the Cluster Analysis

The temperature rising so quickly one day requires a lot of energy. Possibly, some changes in atmospheric heat transport is a reason of recent Arctic temperature amplification (Graversen et al., 2008). Further, the main warm temperature advection of warming is different between the 38 events and it is found that the main warm temperature advection of warming is from the Atlantic Ocean and the Pacific Ocean, according to the results of cluster analysis (Table S1 in the supporting information).

Due to the different wind patterns, we classify these cases on the basis of the 1,000-hPa meridional wind anomaly by the fuzzy c-means method. Figures 2b and 2c show two different sources of warm temperature advection, including that from the Atlantic Ocean and the Pacific Ocean. There are 25 warming events from the Atlantic Ocean and 13 warming events from the Pacific Ocean. The specific classification results are shown in Table S1.
The wind pattern in Figure 2b is almost the same as that in Figure 2a. It indicates that the warm temperature advection of warming comes from the midlatitude Atlantic, and therefore, we call it the Atlantic pattern. As for the Atlantic pattern, the maximum increase of temperature is above 20 °C within one day near the North Pole (Figure 1b). Due to the largest proportion of the Atlantic pattern, the maximum increase of temperature, the wind field of Atlantic, and the 1,000-hPa geopotential height are the same as the results of all RTDW events (Figures 1 and 2).

In Figure 2c, the southerly anomaly at midlatitude of the Eastern and Western Pacific converging the Bering Strait to reach the North Pole means that some Arctic rapid tropospheric daily warm temperature advection is from the Pacific, which is called the Pacific pattern, and the maximum increase of temperature occurs in the north of the Bering Strait and the North Pole (Figure 1c), above 8 °C within one day. With wind field matching, a cyclone is located in East Asia, and an anticyclone is over the west of North America (Figure 2c).

Some studies indicate that storm systems causing the Arctic warming events originating from the Atlantic Ocean are twice as many as that from the Pacific (Graham et al., 2017). The reason for this difference is that it is near open water in the Atlantic sector compared with the Pacific (Moore, 2016) and the storm is more active from the Atlantic Ocean (Zhang et al., 2004). In our study, the proportion of events in the Arctic troposphere rapid warming of the Atlantic pattern accounts for near 65.8%, which is nearly twice as many as that of the Pacific pattern.

### 3.2. Relationships Between Different Patterns of RTDW Events and CAOs

In order to explain the relationship between different patterns of RTDW events and CAOs, we define two indexes, MWAA index where MWAA index is the mean 1,000-hPa southerly anomaly of the Atlantic pattern

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**Figure 1.** Composites of 1,000-hPa temperature anomaly of difference between the day when the RTDW events occur and the day before the occurrence of RTDW events: (a) all events, (b) the Atlantic pattern events, and (c) the Pacific pattern events (contour interval: 2 °C, units: °C, positive in the solid line, negative in the dotted line, zero contour in the solid line, the same below; colored, above the 99% confidence level, positive in red, negative in blue). We define the Arctic rapid tropospheric daily warming (RTDW) event when the Arctic average 1,000-hPa air temperature daily warmer anomaly is over 3σ (above the 1948–2015 winter mean) during situ winter time (December–February) from 1948 to 2015, and σ is the standard deviation of average 1,000-hPa air temperature daily warmer anomaly from the 66.5°N to the North Pole. We classify RTDW events into the Atlantic pattern and the Pacific pattern by the fuzzy c-means method, called the Atlantic pattern and the Pacific pattern, respectively.

**Figure 2.** Composites of 1,000-hPa wind anomaly (in m/s with vectors) and 1,000-hPa geopotential height anomaly of RTDW events (in gpm with contours, contour interval: 20 gpm) (a) all events, (b) the Atlantic pattern events, and (c) the Pacific pattern events (colored, 1,000-hPa wind anomaly above the 99% confidence level, positive in red, negative in blue).
for the 60°N–90°N, 30°W–60°E region and MWAP index where MWAP index is the mean 1,000-hPa southerly anomaly of the Pacific pattern for the 45°N–90°N, 180°–150°W region. We choose the averaging areas for MWAA and MWAP indexes that are based on the main part of the southerly anomaly from the Pacific Ocean and the Atlantic Ocean, above the 99% confidence level. Therefore, MWAA and MWAP indexes can describe the characteristics of RTDW events.

Through the correlation coefficients between the MWAA index and temperature anomaly during 30 days before and after the RTDW events of the Atlantic pattern (Figures S1a–S1c), there is negative correlation in Asia and Europe, above the 95% confidence level. As for the Pacific pattern, the negative value appears in North America, which is not the same as the Atlantic pattern (Figures S1d–S1f).

Further, we choose the region with the significant negative correlation and define the TAA index as the mean 1,000-hPa temperature anomaly of the Atlantic pattern for the 30°N–60°N, 0°–120°E region, and the TAP index as the mean 1,000-hPa temperature anomaly of the Pacific pattern for the 30°N–60°N, 120°W–90°W region. TAA and TAP indexes express the outbreak of cold air.

Figure S2 shows that MWAA and MWAP indexes can first increase before the occurrence of RTDW, then reach the maximum when the RTDW events occur, and eventually decrease. The trends of TAA and TAP indexes reverse, and run up to the minimum about three days after the RTDW events. The results (Figure S3) strongly suggest that the correlation ($r$) between MWAA and TAA exhibits a strong negative correlation when the MWAA leads TAA about three days, which is consistent with the trend of MWAA and TAA. That is, the 1,000-hPa meridional wind from the Atlantic Ocean has a strong influence on the 1,000-hPa temperature of Asia-Europe after the RTDW events of the Atlantic pattern happening. Similarly, the relationship of MWAP and TAP shows that the 1,000-hPa meridional wind from the Pacific Ocean makes a strong impact on the 1,000-hPa temperature of North America about three days after the RTDW events of the Pacific pattern happening. The Atlantic pattern and Pacific pattern make different cold air mass invading the Asia-Europe and North America about three days after the occurrence of RTDW events.

How the RTDW events bring the cold air outbreaks over the Northern Hemisphere has sparked an absorbing interest. So we want to know the processes of RTDW events affecting the extreme cold events of the Northern Hemisphere.

### 3.3. Vertical Distribution of Warming and Polar Vortex Splitting

We find that vertical distribution of temperature increase anomaly of RTDW events is totally different (Figure 3), through making meridian-height cross section averaged along 66.5°N–90°N. As a result of vertical distribution composite of all RTDW events (Figure 3a), the vertical warming is located in two regions, one of which is near Kara Seas (60°E–90°E) and the other is Queen Elizabeth Islands (90°W–150°W). In contrast, vertical warming in the Bering Strait and Greenland is thin. As for the Atlantic pattern (Figure 3b), vertical warming mainly concentrates in Kara Seas (60°E–90°E), and the vertical warming of Queen Elizabeth Islands is weaker. In the Pacific pattern (Figure 3c), the vertical warming of Queen Elizabeth Islands (90°W–150°W) is the deepest, contrary to the Atlantic pattern. Therefore, we can make the conclusions that the vertical warming over Kara Seas is caused by the Atlantic pattern and the vertical warming over Queen Elizabeth Islands is mainly produced by the Pacific pattern.

We choose the Arctic rapid tropospheric daily warming events according to the 1,000-hPa temperature. However, what is striking about warming is that the vertical distribution of rapid tropospheric daily warming reaches 500 hPa. The warming events that the near-surface temperature increase rapidly within one day are mainly caused by the atmospheric energy meridional transporting from the surface to near 500 hPa through the troposphere (Graversen et al., 2008).

Due to the vertical warming, the geopotential thickness is increased by the warm temperature advection from the near surface to 500 hPa (Francis & Vavrus, 2012; Porter et al., 2012; Overland & Wang, 2015), and therefore, the tropospheric polar vortex is splitting. As a result of all RTDW events (Figure 4a), the increase of 500-hPa geopotential is apparent from Kara Seas to Queen Elizabeth Islands, through Laptev Sea, Novosibirsk, and East Siberian Sea, where the vertical warming is very strong. However, the 500-hPa geopotential over Greenland and Norwegian Sea is not enhanced due to the weak vertical warming. One major split separation of the polar vortex moves to Northeast Canada, and the other polar
vortex center splits to Northeast Asia (Figure 4a). The zonal circulation of polar vortex changes to a meridional circulation where the geopotential thickness increases. Consequently, the cold northerly flows into the lower latitudes and warmer area along the east of ridge from the polar. There are two ridges of the polar vortex, one along the west coast of North America and the other located in Europe. The northerly on the east of ridge brings cold air from the polar region to warmer area. As a result, the northerly anomalies from the polar region intrude Eurasian continent because of the ridge located in the Europe and the north of North America due to the ridge along the west coast of North America. Corresponding to the northerly anomaly, the temperature negative anomalies mainly near the same regions are found (Figures 5a–5c). It is noteworthy that the cold air with high pressure anomaly of 1,000-hPa invades Northern Hemisphere through two paths, one path from northwestern Europe to southeast Asia throughout the entire Eurasian continent, called Asia-Europe path, and the other from the north of North America to the south of North America, called North America path.

As for the Atlantic pattern (Figure 4b), there are two ridges of the polar vortex, the stronger one in Europe and the weaker one along the west coast of North America. First, the cold air mass attacks the Eurasian continent and North America within five days after the Atlantic pattern RTDW events because of the two ridges (Figure 5d). Then, the cold air mass of the Eurasian continent expands to Southeast Asia, and the cold air mass in North America disappears basically in the next 10 days (Figures 5e and 5f) due to the stronger ridge located in Europe and the weaker ridge along the west coast of North America. Therefore, the route of cold air invading the Northern Hemisphere is mainly from northwestern Europe to Southeast Asia throughout

![Figure 3](image-url)

**Figure 3.** Composites of vertical distribution of temperature anomaly of difference between the day when the RTDW events occur and the day before the occurrence of RTDW events: (a) all events, (b) the Atlantic pattern events, and (c) the Pacific pattern events (contour interval: 0.4 °C, units: °C). We make the meridian-height cross section averaged along 66.5°N–90°N.

![Figure 4](image-url)

**Figure 4.** Composites of 500-hPa geopotential height anomaly of difference between the day when the RTDW events occur and the day before the occurrence of RTDW events (in gpm with filled contours, contour interval 10 gpm) and 500-hPa geopotential height of RTDW events (in gpm with solid contours, contour interval 100 gpm): (a) all events, (b) the Atlantic pattern events, and (c) the Pacific pattern events.
the entire Eurasian continent, which is the Asia-Europe path, consistent with the result of Figure S1. However, the cold air mass in North America is not obvious.

By contrast, the Pacific pattern exhibits a different feature. The enhancement of 500-hPa geopotential thickness occurs mainly over Queen Elizabeth Islands (Figure 4c), which is consistent with the vertical warming. The polar vortex is split into two similar centers like the Atlantic pattern, but the differences are that the ridge near the west coast of North America is stronger than the ridge in the same region of Atlantic pattern because of the much more severe and wider vertical warming, and there is almost no ridge in the Eurasian continent. The consequence is that the meridional circulation and northerly anomalies are mainly over the North American continent. Therefore, the negative temperature anomalies are located in the west of Canada and America within 15 days after the RTDW events (Figures 5g–5i), which is the North America path.

Due to the huge warm air mass into the polar region, the cold air mass in the polar region becomes weaker and is squeezed out where the vertical warming is very strong. The splitting of the polar vortex means the movement of the cold air mass. Furthermore, the shapes and movements of polar vortex RTDW events with different warm temperature advection are distinct. Apparently, the regions affected by the intrusion of cold air are not the same.

Figure 5. Composites of 1,000-hPa temperature anomaly (contour interval: 1 °C, units: °C; colored, above the 99% confidence level, positive in red, negative in blue). (a–c) Composites of the 1–5, 6–10, and 11–15 days after the occurrence of all RTDW events. (d–f) Composites of the 1–5, 6–10, and 11–15 days after the occurrence of Atlantic pattern events. (g–i) Composites of the 1–5, 6–10, and 11–15 days after the occurrence of Pacific pattern events.
4. Discussions

To identify more RTDW events, we use $2\sigma$ as the threshold for definition of RTDW events to repeat analysis of impacts of different RTDW events on winter in the Northern Hemisphere and obtain 196 events; maximum increase of temperature is above 8 °C in one day in the North Pole (Figure S4a). According to the same classification method, Figures S5b and S5c show that two different sources of warm temperature advection are similar to those of $3\sigma$ definition, including from the Atlantic Ocean and the Pacific. We identify 113 warming events from the Atlantic Ocean and 83 warming events from the Pacific Ocean.

As for two patterns, areas of warming anomaly and the south wind anomaly in $2\sigma$ definition are almost same as those in $3\sigma$ definition (Figures S4 and S5). The amplitude of warming anomaly and the south wind anomaly is smaller than that in $3\sigma$ definition, especially for the Pacific pattern. In the $2\sigma$ definition, the cold air mass attacks the Eurasian continent and North America, corresponding to Atlantic pattern and Pacific pattern, consistent with our conclusions of $3\sigma$ definition (Figure S6). Comparing the results of $2\sigma$ definition with those of $3\sigma$ definition, the weaker Arctic rapid tropospheric daily warming in $2\sigma$ definition make less impact on the cold air mass in the polar, and the cold air outbreak as a consequence of RTDW is also weaker.

The $2\sigma$ definition provides more events and the results of $2\sigma$ definition are consistent with that of $3\sigma$ definition. Therefore, results of $2\sigma$ definition of RTDW events show the conclusions of our study robust.

5. Summary

In order to investigate the process of Arctic rapid tropospheric daily warming events and reveal how the Arctic rapid tropospheric daily warming events affect the CAOs, we define the Arctic RTDW event and eventually choose 38 events for the further analysis.

The impacts of RTDW events on the Northern Hemisphere cold winter are mainly through the Asia-Europe path caused by the Atlantic pattern and the North America path caused by the Pacific pattern. As for the Asia-Europe path, the strong southerly anomaly brings huge warm and moist air mass into the Arctic from the midlatitude Atlantic, and then the increase of 500-hPa geopotential is near the Kara Seas. As a result, the cold air invades the Northern Hemisphere from northwestern Europe to Southeast Asia throughout the entire Eurasian continent. In the case of the North America path, the southerly of midlatitude of the Eastern and Western Pacific reaches the North Pole, and then the 500-hPa geopotential thickness increase occurs mainly over Queen Elizabeth Islands where the vertical warming is deepest. Consequently, the temperature negative anomalies are located in the west of Canada and America during the next 15 days after the RTDW events.

The warm temperature advection from the middle latitude sea reaching the Arctic cause that the polar vortex become weaker and the cold air mass where the vertical warming is very strong is squeezed out to the low latitudes and warmer place of population agglomeration. The areas where the cold air mass reach are also distinct, owing to different warm temperature advection of the RTDW events.

As a result of the Arctic rapid tropospheric daily warming events, the tropospheric polar vortex is weaker and splitting, specifically in positive geopotential height anomalies. So the warm and moist air mass can reach the Arctic along the west of ridge easier. If there is a suitable flow field, Arctic temperatures will continue to rise. The polar vortex is splitting more seriously. It act as positive feedback mechanisms (Overland & Wang, 2016). As a consequence, the weaker the polar vortex is, the more cold the air mass reaching the lower latitude region is.

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