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The extreme Arctic warm anomaly in November 2020

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ABSTRACT

In November 2020, the eastern Arctic experienced an extensive extreme warm anomaly (i.e., the second strongest case since 1979), which was followed by extreme cold conditions over East Asia in early winter. The observed Arctic warm anomaly in November 2020 was able to extend upwards to the upper troposphere, characterized as a deep Arctic warm anomaly. In autumn 2020, substantial Arctic sea-ice loss that exceeded the record held since 1979, accompanied by increased upward turbulent heat flux, was able to strongly warm the Arctic. Furthermore, there was abundant northward moisture transport into the Arctic from the North Atlantic, which was the strongest in the past four decades. This extreme moisture intrusion was able to enhance the downward longwave radiation and strongly contribute to the warm conditions in the Arctic. Further analysis indicated that the remote moisture intrusion into the Arctic was promoted by the large-scale atmospheric circulation patterns, such as the wave train propagating from the midlatitude North Atlantic to the Arctic. This process may have been linked to the warmer sea surface temperature in the midlatitude North Atlantic.

摘要

2020年11月北极东部显著偏暖, 表面气温暖异常为1979年以来第二强, 且北极表层偏暖可以延伸至对流层上层. 本文进一步研究了此次北极极端偏暖的可能原因. 2020年秋季北极海冰大幅减少, 11月从北大西洋向北极的水汽输送显著增加, 且二者的变化幅度均超过了1979年以来的最高纪录, 进而导致北极出现极端暖异常. 此外, 从中纬度向北极的Rossby波传播有利于向极水汽输送增加, 且此过程可能与北大西洋中纬度海温异常有关.

1. Introduction

The Arctic has been warming dramatically since the 1990s, at a rate of more than twice that of greenhouse gas–induced global warming (Huang et al., 2017). Arctic sea-ice decline and high-latitude snowcover retreat might play critical roles in causing polar surface warming, because they can change the surface albedo and increase cold-season heat transport from the ocean to the atmosphere (Cohen et al., 2014; Dai et al., 2019). Remote forcings such as poleward atmospheric energy transport (Graversen et al., 2008) and warm and moist air intrusion (Zhong et al., 2018) have also been proposed to cause Arctic warming. It is worth noting that the observed Arctic warming can extend from the surface to the upper troposphere (i.e., deep Arctic warming) (Ogawa et al., 2018; He et al., 2020). The large spread in the vertical distributions of Arctic warming trends between model simulations and observations or among various climate models implies the potential role of natural variability (Xu et al., 2019; Cohen et al., 2020). Xu et al. (2021) discussed the different mechanisms of Arctic surface warming and tropospheric warming using coordinated climate model experiments. It was concluded that Arctic surface warming is strongly coupled with sea-ice decline, and that poleward moisture transport from the Norwegian Sea and midlatitude North Atlantic to the Barents–Kara seas, but not sea-ice decline, is an important contributor to Arctic tropospheric warming (Xu et al., 2021). Despite intensive research on Arctic warming (Graversen et al., 2008; Perlwitz et al., 2015; Cohen et al., 2020; Wang et al., 2021), knowledge of the mechanism remains unclear.

The remote influence of Arctic warming has aroused considerable attention (Cohen et al., 2014; Screen, 2017; Mori et al., 2019). For example, Arctic warming has been proven to be associated with Eurasian cold winters (Mori et al., 2014; Kug et al., 2015), forming the warmer Arctic–colder Eurasia pattern (Overland et al., 2011). He et al. (2016) emphasized the importance of the unprecedented Arctic warming (Kim et al., 2017) on the record-breaking cold extremes over East Asia in January 2016. In the first half of winter 2020/21, extreme cold waves invaded East Asia (Peng et al., 2022; Yang and Fan, 2022), which is also believed to be linked with the warmer Arctic (Zheng et al., 2021). It is worth noting that an extraordinary increase in Arctic temperature was observed throughout the troposphere in November 2020 (Fig. 1). The

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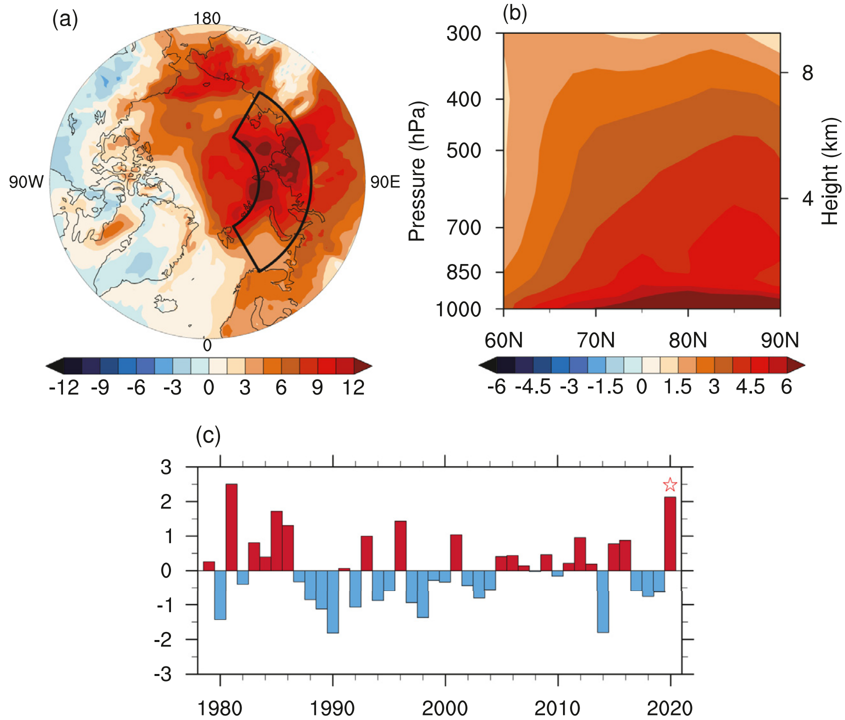

Fig. 1. Anomalies of (a) SAT and (b) vertical temperature averaged along 0°–180°E (units: °C) in November 2020, relative to the climatology of 1981–2010. (c) Normalized and detrended time series of November ARTI_2m during 1979–2020.

maximum surface air temperature (SAT) anomalies reached 12 °C over the Kara and Laptev seas (Fig. 1(a)), and the Arctic-averaged (0°–180°E) warm anomaly exceeded 3°C in the mid-troposphere (Fig. 1(b)). It has been revealed that winter SAT anomalies over the Barents–Kara seas were strongly negatively correlated with East Asian SAT anomalies in the later 30 days (Kug et al., 2015). Therefore, further investigation is needed into the cause of the extreme Arctic warm anomaly that followed by early-winter extreme cold temperatures over East Asia.

In this paper, we focus on the cause of the extreme Arctic warm anomaly in November 2020, which might provide some insights into understanding the mechanism of Arctic warming.

2. Data and methods

Monthly atmospheric data including SAT, surface sensible and latent heat fluxes, surface downward longwave radiation, 300-hPa geopotential height, air temperature, wind field, and specific humidity were obtained from the fifth major global reanalysis produced by ECMWF (ERA5) (Hersbach et al., 2020), with a horizontal resolution of 1.0° × 1.0°. Monthly sea-ice concentration and sea surface temperature (SST) data were obtained from the Met Office Hadley Center (Rayner et al., 2003). A 130-member ensemble of simulations from five atmosphere general circulation models (AGCMs: CAM4, WACCM, IFS, IAP4, and LMDZOR) prescribing daily varying sea ice and SST from the National Oceanic and Atmospheric Administration for the period 1982–2014 were also employed (Ogawa et al., 2018). Each ensemble member began with slightly different initial conditions.

An Arctic surface temperature index (ARTI_2m) is defined as the area-averaged SAT in the domain (70°–80°N, 30°–150°E) (black frame in Fig. 1(a)). An Arctic sea-ice index is defined as the area-averaged sea-ice concentration in the domain (75°–85°N, 30°–180°E) (red frame in Fig. 2(a)). A moisture index is defined as the area-averaged magnitude of water vapor transport anomalies integrated from 1000 hPa to 300 hPa in the domain (60°–75°N, 0°–90°E) (purple frame in Fig. 2(d)). High and low ARTI_2m years are defined when the normalized and detrended November ARTI_2m is above 0.5 and below −0.5, respectively.

The observed climate anomalies in 2020 are relative to the climatology of 1981–2010. We removed the linear trend from all data before carrying out the composite analysis.

3. Results

Fig. 1(a) shows the spatial pattern of Arctic surface temperature anomalies in November 2020. Extensive surface warm anomalies can be seen in the eastern Arctic, including the Barents–Kara seas, Laptev Sea, East Siberian Sea, and high-latitude Eurasia (Fig. 1(a)). The warm center (above 12 °C) was located over the Kara and Laptev seas and northern Siberia. It is noteworthy that the eastern Arctic experienced the second warmest November over the past four decades and the warmest November since 1982 (Fig. 1(c)). In the vertical direction, the pronounced warm signal extended from the surface to the upper troposphere, characterized as a deep Arctic warm anomaly (Fig. 1(b)). At 300 hPa, the Arctic-averaged (0°–180°E) temperature anomaly reached 1.5 °C. It is thus clear that a pronounced surface-amplified Arctic warm anomaly occurred throughout the troposphere in November 2020.

Arctic sea-ice decline has been revealed as a major cause of Arctic surface warming, through inducing increased upward turbulent heat flux to warm the atmosphere (Screen and Simmonds, 2010). Specifically, Arctic sea ice shows the most pronounced reduction in September throughout the year and the excess heat is transferred from the anomalously warm and ice-free ocean water to the atmosphere in autumn (Liu et al., 2012; Cohen et al., 2014), which substantially influences the atmosphere circulations. In autumn 2020, dramatic sea-ice reduction was observed from the Kara Sea eastwards to the East Siberian Sea (Fig. 2(a)), exceeding the record from 1979 (Fig. 2(c)). The area with reduced sea ice coincided greatly with the surface warmer area (Fig. 1(a) and Fig. 2(a)). We cannot yet attribute the surface warm conditions to sea-ice loss on this basis, because a warmer Arctic can also drive changes in sea ice (Sorokina et al., 2016; Blackport et al., 2019). Fig. 2(b) shows the corresponding anomalies of Arctic turbulent (sensible+latent) heat flux, which help to clarify the direction of the ice–atmosphere interaction. There was anomalous upward turbulent heat flux over the sea-ice

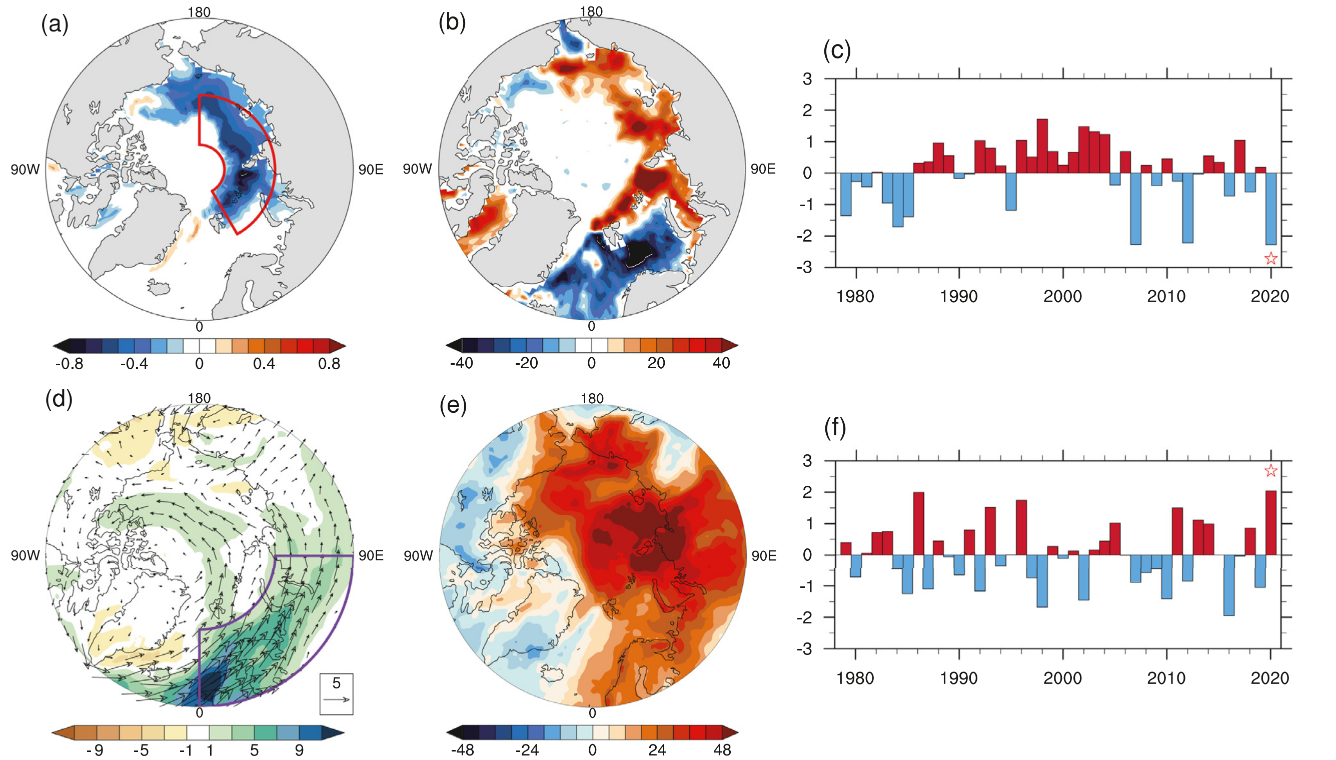

Fig. 2. Anomalies of (a) Arctic sea-ice concentration and (b) turbulent heat flux (upward positive; units: W m^{-2}) in autumn (September–November) 2020, relative to the climatology of 1981–2010. (c) Normalized and detrended time series of autumn Arctic sea-ice index during 1979–2020. (d, e) Anomalies of (d) water vapor transport vertically integrated from 1000 hPa to 300 hPa (vectors; units: 10^2 kg m^{-1} s^{-1}) and corresponding magnitude anomalies (shading; units: 10^2 kg m^{-1} s^{-1}) and (e) surface downward longwave radiation (units: W m^{-2}) in November 2020, relative to the climatology of 1981–2010. (f) Normalized and detrended time series of November moisture index during 1979–2020.

loss region (Fig. 2(b)). This means more heat was transferred from the ocean to the atmosphere and is indicative of the strong ice-driven surface warm conditions.

Conversely, the anomalous downward turbulent heat flux west of Novaya Zemlya (Fig. 2(b)) implies heat transfer from the atmosphere to the ocean, which is indicative of warm and moist air intrusion (Woods and Caballero, 2016). Previous studies suggest the influence of poleward moisture flux on Arctic warming (Park et al., 2015), particularly tropospheric warming (Xu et al., 2021), because moisture intrusion can enhance the downward longwave radiation over the Arctic (Park et al., 2015). In November 2020, there was abundant northward moisture transport from lower latitudes (e.g., the North Atlantic) to the Arctic (Fig. 2(d)), which strongly enhanced the downward longwave radiation (Fig. 2(e)) and thus contributed to the deep Arctic warm anomaly (Xu et al., 2021). It is noteworthy that the increase in poleward moisture transport was also the strongest in the past 40 years (Fig. 2(f)). That is, both the extreme low Arctic sea ice and strong moisture intrusion into the Arctic were important contributing factors to the extensive extreme Arctic warm anomaly in November 2020.

Relative to sea-ice reduction, the role of poleward heat and moisture transport from lower latitudes to the Arctic is just beginning to be understood (Cohen et al., 2020). To further investigate the contribution of moisture to the warmer Arctic, Fig. 3(a) presents the corresponding evaporation anomalies. A pronounced increase in evaporation anomalies occurred in the midlatitude North Atlantic (i.e., a major external moisture source) (Fig. 3(a)). However, another major external moisture source—the Norwegian Sea (Zhong et al., 2018; Xu et al., 2021)—did not show any positive evaporation anomalies (Fig. 3(a)). That is, the midlatitude North Atlantic could have been the main external moisture source for the Arctic warm anomaly. More evidence can be obtained from the large-scale atmospheric circulation anomalies (Fig. 3(b)). A well-organized wave train structure spanned from the midlatitude North Atlantic to the Arctic and central Eurasia through Greenland or western Europe (Fig. 3(b)), which corresponded to two (high-latitude and midlatitude) pathways (Zhong et al., 2018). Over the North Atlantic–Arctic sector, the wave train was composed of the positive phase of the North Atlantic Oscillation (NAO) and a strengthened Ural blocking (Fig. 3(b)), which is an optimal circulation pattern that steers the pathway of moisture from the North Atlantic to the Arctic (Luo et al., 2017).

We further discuss the possible drivers of the planetary waves propagating from the North Atlantic to the Arctic. In November 2020, widespread warmer SST dominated the midlatitude North Atlantic from 20°N to 45°N, with a warm center (above 1.6°C) near the Gulf Stream (Fig. 3(c)). Matching the warmer SST, anomalous divergent wind appeared in the upper troposphere (Fig. 3(d)). In other words, the warmer SST over the midlatitude North Atlantic could possibly have induced the upper-level divergent wind anomalies and thus driven the atmospheric Rossby wave propagation. This result is also consistent with Sato et al. (2014).

To verify the above hypothesis about the remote impact on the Arctic warm anomaly in November 2020, Fig. 4(a–e) presents the composite November climate anomalies between high and low ARTI_2m years during 1979–2020 in ERA5. The significant surface warm anomalies over the eastern Arctic are largely consistent with the warm conditions in 2020 (Fig. 4(a)). Moreover, the significant warm signal was able to extend upwards to the upper troposphere (Fig. 4(b)). Associated with the deep Arctic warm anomaly, there was significantly increased moisture transport into the Arctic from the North Atlantic (Fig. 4(c)) via the atmospheric circulation patterns (Fig. 4(d)). This further supports the contribution of remote moisture to the deep Arctic warm anomaly in November 2020. The large-scale atmospheric wave train spanning from the midlatitude North Atlantic to the Arctic (Fig. 4(d)) may have been

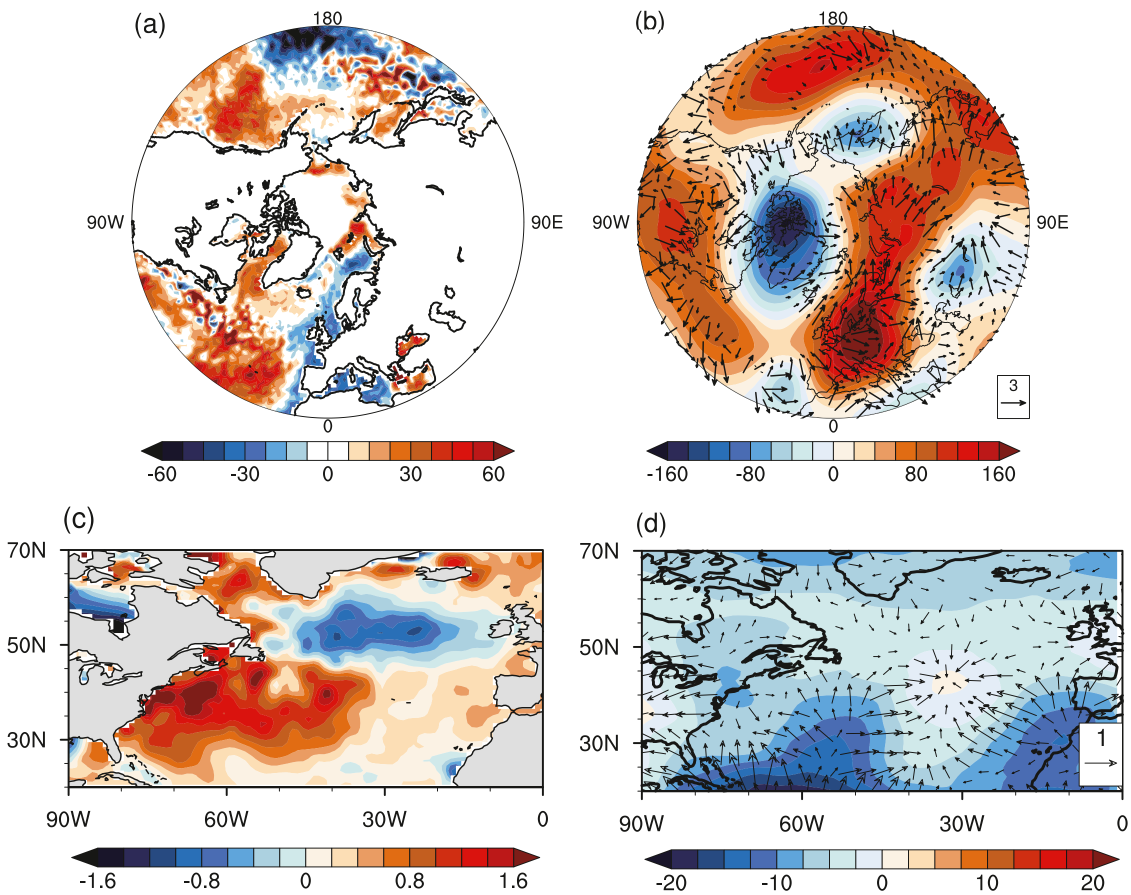

Fig. 3. Anomalies of (a) evaporation multiplied by 28.5 (1 mm d^{-1} = 28.5 W m^{-2}), (b) 300-hPa geopotential height (shading; units: m) and wave activity flux (vectors; units: 10^{11} m^2 s^{-2}; computed according to Takaya and Nakamura (2001)), (c) SST (units: °C), and (d) 300-hPa velocity potential (shading; units: 10^5 m^2 s^{-1}) and divergent wind (vectors; units: m s^{-1}) in November 2020, relative to the climatology of 1981–2010.

linked to the significant SST forcing near the Gulf Stream (Fig. 4(e)). This hypothesis can be further verified using the results from the ensemble mean of the five AGCMs, which displays a significant wave train pattern from the North Atlantic to the Arctic and warmer SST near the Gulf Stream, associated with the warmer Arctic (Fig. 4(f, g)). The composite results based on ERA5 and model simulations are highly consistent with the climate anomalies in November 2020, providing evidence that the poleward moisture transport from the midlatitude North Atlantic via the atmospheric circulation patterns related to SST forcing was an important contributing factor to this deep Arctic warm anomaly.

4. Conclusions and further discussion

In this study, we analyzed the extreme Arctic warm anomaly in November 2020 (i.e., the second strongest case since 1979) and investigated the possible causes. The results showed that amplified surface warm conditions were observed over the eastern Arctic in November 2020, with the largest warm anomalies over the Kara and Laptev seas and northern Siberia. This warm signal was able to extend upwards to the upper troposphere, characterized as a deep Arctic warm anomaly.

There was dramatic Arctic sea-ice loss and increased upward turbulent heat flux in autumn 2020, which meant a direct response of surface warm anomalies to sea-ice variability. In addition, abundant northward moisture advection from the midlatitude North Atlantic to the Arctic in November was able to enhance the downward longwave radiation and thus warm the Arctic. Both the reduction in autumn sea ice over the region (75°–85°N, 30°–180°E) and the increase in poleward moisture intrusion over the region (60°–75°N, 0°–90°E) exceeded the record held since 1979, which greatly contributed to the extreme Arctic warm anomaly in November 2020. Atmospheric circulation anomalies in the North Atlantic–Arctic sector were characterized by the positive phase of the NAO and an intensified Ural blocking. The planetary wave train spanning from the midlatitude North Atlantic to the Arctic through Greenland or western Europe was able to determine the transport of remote moisture to the Arctic. It has also been further discussed that the planetary wave propagation may have been related to warm SST forcing near the Gulf Stream.

The above hypothesis regarding the remote impact on the Arctic warm anomaly in November 2020 was further verified by composite analysis based on ERA5 and model simulations. The high consistency between the climate anomalies in November 2020 and the composite climate anomalies (i.e., high ARTI_2m minus low ARTI_2m years) supports the role of moisture intrusion into the Arctic from lower latitudes, which may have been related to the warmer SST near the Gulf Stream, in the deep Arctic warm anomaly. We therefore suggest a joint influence from the extremely low Arctic sea ice and strong moisture intrusion on the extreme Arctic warm anomaly in November 2020. Note that we have not yet determined the relative contributions of Arctic sea-ice loss and moisture intrusion; the influence of midlatitude SST forcing needs to be further investigated in future work.

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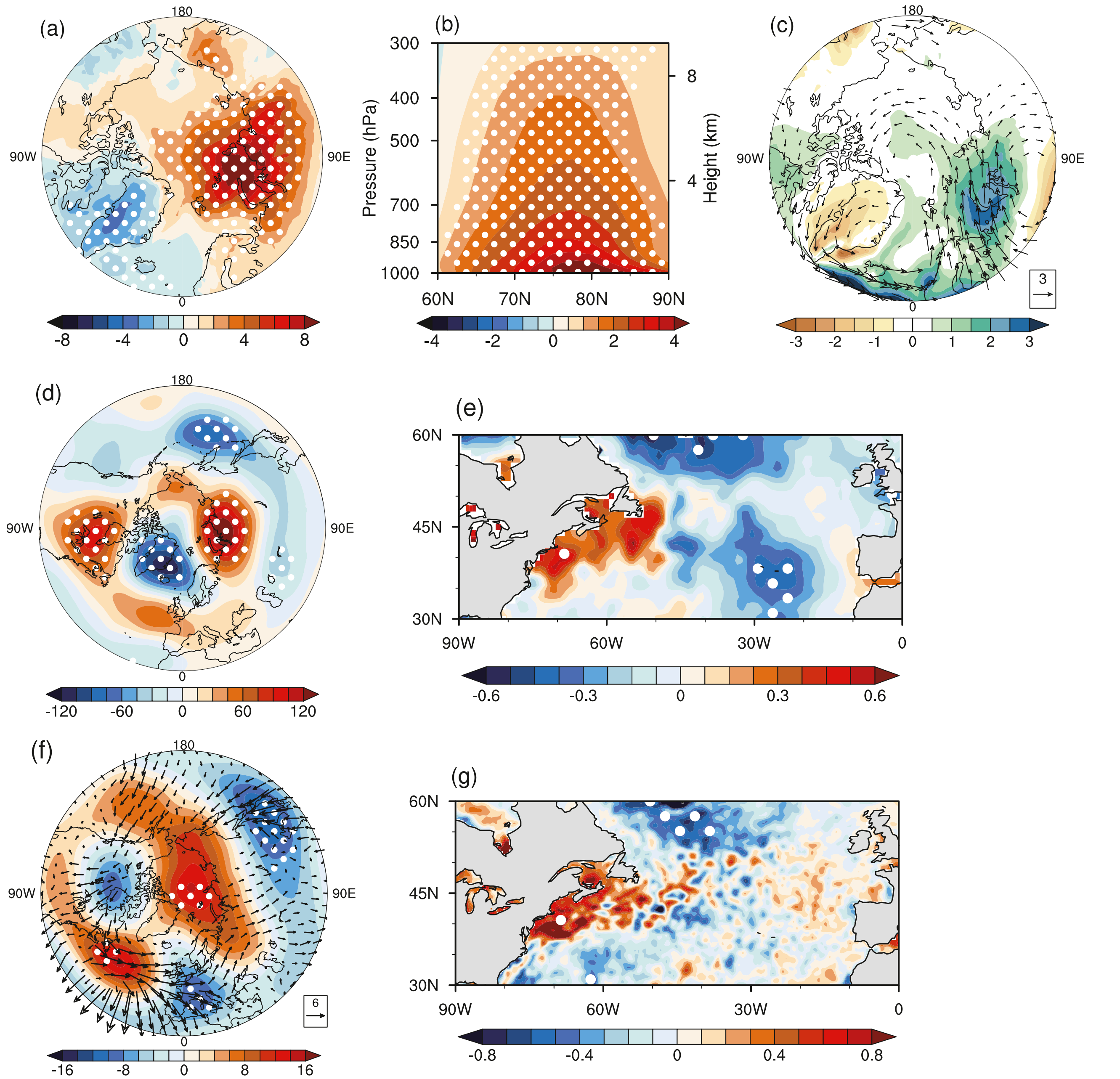

Fig. 4. Composites of November (a) SAT, (b) vertical temperature averaged along 0°–180°E, (c) water vapor transport vertically integrated from 1000 hPa to 300 hPa (vectors; units: 10^2 kg m^{-1} s^{-1}) and corresponding magnitude anomalies (shading; units: 10^2 kg m^{-1} s^{-1}), (d) 300-hPa geopotential height (units: m), and (e) SST (units: °C) between the high and low ARTI_2m years during 1979–2020 from ERA5. (f, g) Composites of November (f) 300-hPa geopotential height (shading; units: m) and wave activity flux (vectors; units: 10^{-2} m^2 s^{-2}) and (g) SST (units: °C) between the high and low ARTI_2m years during 1982–2014 from the ensemble mean of five AGCMs. Dotted values exceed the 90% confidence level.

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