Decadal changes of wintertime poleward heat and moisture transport associated with the amplified Arctic warming

Xiaozhuo Sang

Nanjing University

Xiu-Qun Yang (✉ xqyang@nju.edu.cn)

Nanjing University <https://orcid.org/0000-0003-3716-9152>

Lingfeng Tao

Nanjing University

Jiabei Fang

Nanjing University

Xuguang Sun

Nanjing University

Research Article

Keywords: Arctic amplification, poleward heat transport, poleward moisture transport, stationary wave, transient eddy

Posted Date: June 7th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-264481/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Climate Dynamics on July 30th, 2021. See the published version at <https://doi.org/10.1007/s00382-021-05894-7>.

**Decadal changes of wintertime poleward heat and moisture transport
associated with the amplified Arctic warming**

Xiaozhuo Sang, Xiu-Qun Yang, Lingfeng Tao, Jiabei Fang, and Xuguang Sun

*CMA-NJU Joint Laboratory for Climate Prediction Studies, School of Atmospheric
Sciences, Nanjing University, Nanjing, China*

Corresponding author:

Dr. Xiu-Qun Yang,

School of Atmospheric Sciences,
Nanjing University, Nanjing 210023, China.

Email: xqyang@nju.edu.cn

Abstract

The Arctic warming, especially during winter, has been almost twice as large as the global average since the late 1990s, which is known as the Arctic amplification. Yet linkage between the amplified Arctic warming and the midlatitude change is still under debate. This study examines the decadal changes of wintertime poleward heat and moisture transports between two 18-yr epochs (1999-2016 and 1981-1998) with five atmospheric reanalyses. It is found that the wintertime Arctic warming induces an amplification of the high latitude stationary wave component of zonal wavenumber one but a weakening of the wavenumber two. These stationary wave changes enhance poleward heat and moisture transports, which are conducive to further Arctic warming and moistening, acting as a positive feedback onto the Arctic warming. Meanwhile, the Arctic warming reduces atmospheric baroclinicity and thus weakens synoptic eddy activities in the high latitudes. The decreased transient eddy activities reduce poleward heat and moisture transports, which decrease the Arctic temperature and moisture, acting as a negative feedback onto the Arctic warming. The total poleward heat transport contributes little to the Arctic warming, since the increased poleward heat transport by stationary waves is nearly canceled by the decreased transport by transient eddies. However, the total poleward moisture transport increases over most areas of the high latitudes that is dominated by the increased transport by stationary waves, which provides a significant net positive feedback onto the Arctic warming and moistening. Such a poleward moisture transport feedback may be particularly crucial to the amplified Arctic warming during winter when the ice-albedo feedback vanishes.

Keywords: Arctic amplification; poleward heat transport; poleward moisture transport; stationary wave; transient eddy

1. Introduction

The pronounced warming in the Arctic that is faster than the global average, known as the Arctic amplification (AA), has been observed during the past three decades (Graversen et al. 2008; Serreze et al. 2009; Cohen et al. 2014). Many studies suggested that sea ice decline is the primary cause of the observed AA due to the positive ice-albedo feedback (Screen and Simmonds 2010a; Dai et al. 2019). However, the greatest AA is found in the cold season when the solar radiation is low or even completely absent (Serreze and Francis 2006; Screen and Simmonds 2010b). Numerical experiments with atmospheric models showed that AA is still obvious with locked surface albedo (Alexeev et al. 2005; Graversen and Wang 2009), which suggest that surface albedo feedback is an important but not a dominating mechanism responsible for AA. The role of heat and moisture transports from outside the Arctic in AA was emphasized during winter when the shortwave radiation is negligible and the atmospheric boundary layer is stable (Zhang et al. 2013; Liu and Barnes 2015; Park et al. 2015b; Gong et al. 2017). It was found that, associated with anomalous large-scale circulations, poleward moisture fluxes into the Arctic lead to an increase in downward longwave radiation at the surface (Lee et al. 2011; Woods and Caballero 2016). Park et al. (2015a) showed that the positive trend of downward longwave radiation during winter accounts for as much as 50% of sea ice decline trend over the Arctic Atlantic sector.

Meanwhile, many observational and modeling studies suggested that the Northern Hemisphere (NH) midlatitude mean flow and waves can be affected by AA even if there

is a lot of controversies (Walsh 2014; Barnes and Screen 2015; Overland 2016; Vavrus 2018; Cohen et al. 2020). Cohen et al. (2014) proposed three potential dynamical pathways that may link the Arctic and the midlatitudes: jet stream, storm tracks, and planetary waves. Enhanced Arctic warming reduces the equator-to-pole temperature gradient at the surface, which causes the weakening of the midlatitude westerly winds (Coumou et al. 2015; Overland et al. 2015). A weak zonal jet could promote large amplitude and slowly-moving waves, which could create persistent weather conditions that may cause extreme weather events (Francis and Vavrus 2012; Liu et al. 2012; Screen and Simmonds 2014). Other studies questioned the validity of the above mechanisms, as they appear to be highly sensitive to the analysis metrics and datasets being used (Barnes 2013; Screen and Simmonds 2013). Generally, midlatitude atmospheric waves are characterized by transient eddies with zonal wavenumber typically larger than 5 and stationary waves with smaller wavenumbers as a response to diabatic and orographic forcing (Boer and Shepherd 1983; Petoukhov et al. 2013), the mechanisms of which are totally different. Previous studies did not distinguish the influence of AA on the stationary and transient waves in the midlatitudes. In this study, we will examine how the amplified Arctic warming can affect the stationary waves and transient eddies in the mid and high latitudes.

Stationary waves and transient eddies that may be affected by AA are the main agents for the atmospheric poleward transports of heat and moisture (Gimeno et al. 2015; Woods and Caballero 2016). Changes of these waves could cause changes in poleward transport, which may further have feedback onto AA. Previous studies

focused on one-way impact but paid little attention to the midlatitude feedback. Therefore, there is a need to understand how the changes of these waves can further affect AA via altering poleward heat and moisture transports. In this study, we will examine the poleward transport changes associated with AA, which would help understand the linkage between the Arctic and the midlatitudes.

Graversen et al. (2008) found greater warming aloft than at the surface based on ERA-40 and concluded that the atmospheric poleward energy transport is the main driver of AA. In contrast, Screen and Simmonds (2010a) showed that the Arctic warming is the strongest at the surface based on the ERA-Interim reanalysis and mainly caused by the diminishing sea ice. This disagreement indicates discrepancy among different atmospheric reanalyses in the observational studies of AA. Atmospheric reanalysis provides a dynamically consistent view of the past state of the atmosphere by optimally combining historical atmospheric observations with numerical weather forecast model, which has uncertainties resulting from the forecast model, data assimilation, and data sources used. The spatially sparse and short observations in the high latitudes make the reanalysis in these areas more reliant on the forecast model, satellite data, and data assimilation methods. Thus, there are much greater uncertainties in the capability of reanalysis to provide atmospheric variables over the polar regions compared to other regions of the globe (Bromwich et al. 2007; Lindsay et al. 2014). Besides, many previous studies demonstrated that the reanalysis with coarse resolution forecast model generally underestimates the midlatitude synoptic eddy activity and eddy forcing on mean flow (Blender and Schubert 2000; Hodges et al. 2011; Tilinina et

al. 2013). Thus, cautions are needed when analyzing the heat and moisture transports over mid and high latitudes related to transient eddies using reanalysis with coarse resolution forecast model.

The rest of the paper is organized as follows. Section 2 describes the atmospheric reanalysis datasets and the methods used. Section 3 presents the Arctic amplified warming and moistening, along with the decadal changes of poleward heat and moisture transports as the Arctic warms. The underlying mechanisms responsible for the influence of AA on the poleward transport changes are examined in section 4. Section 5 summarizes and discusses the possible feedback of mid and high latitude transport onto AA.

2. Data and methods

a. Atmospheric reanalysis datasets

In this study, daily variables are used which are taken from five atmospheric reanalyses (Table 1). One coarse-resolution reanalysis is NCEP–DOE R2 (NCEP2) (Kanamitsu et al. 2002). Four high-resolution reanalyses are ECMWF Interim Re-Analysis (ERA-Interim), 55-yr Japanese Reanalysis Project (JRA-55), NASA Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2), and NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al. 2010; Dee et al. 2011; Harada et al. 2016; Gelaro et al. 2017). One of the improvements of these reanalyses is the increasing spatial resolution of forecast models from T62 (~210km) in NCEP2 to T382 (~38km) in CFSR. MERRA-2 generates with a finite volume model, which uses a cubed-sphere horizontal discretization at an approximate resolution of $0.5^\circ \times 0.625^\circ$

(~55km). These reanalyses also apply improved model physics and data assimilation systems. Both ERA-Interim and JRA-55 implement four-dimensional variational data assimilation (4D-Var) to include the observed temporal distribution within the assimilation window. The advanced data assimilation, model physics, and increase of resolution help to reduce the bias in reanalyses.

The horizontal resolutions of the reanalysis products used are $2.5^\circ \times 2.5^\circ$ (longitude/latitude) for NCEP2, $1.5^\circ \times 1.5^\circ$ for ERA-Interim, $1.25^\circ \times 1.25^\circ$ for JRA-55, $0.5^\circ \times 0.625^\circ$ for MERRA-2, and $0.5^\circ \times 0.5^\circ$ for CFSR. The physical variables of reanalysis used in this study include the wind velocity, geopotential height, air temperature, and specific humidity from 1000 to 200 hPa, with a focus on the troposphere. Note that NCEP2 does not provide specific humidity data; thus, we compute it from the relative humidity. The time span is from January 1980 to December 2017, with the convention that wintertime of 1980 refers to December of 1980, January and February of 1981.

b. Decomposition of heat and moisture transports

The poleward heat and moisture transports can be decomposed, respectively, as,

$$[\overline{vT}] = [\bar{v}][\bar{T}] + [\bar{v}^* \bar{T}^*] + [\overline{v'T'}], \quad (1)$$

$$[\overline{vq}] = [\bar{v}][\bar{q}] + [\bar{v}^* \bar{q}^*] + [\overline{v'q'}], \quad (2)$$

where the brackets denote the zonal mean, the asterisks the departures from the zonal mean, the overbars the time mean, and the primes the departures from the time mean (Peixoto and Oort 1992). The term $[\bar{v}][\bar{T}]$ (or $[\bar{v}][\bar{q}]$) in Eq. (1) or (2) represents the heat (or moisture) transport by the mean meridional circulation, which dominates in the

tropics. The term $[\bar{v}^* \bar{T}^*]$ (or $[\bar{v}^* \bar{q}^*]$) represents the poleward heat (or moisture) transport by stationary waves, and the term $[\overline{v' T'}]$ (or $[\overline{v' q'}]$) the poleward heat (or moisture) transport by the transient eddies. In this study, since the focus is on the changes of waves, the changes of total transport over mid and high latitudes mentioned below only signify those by stationary and transient waves.

The time- and zonal-mean local temperature (moisture) tendency induced by heat (moisture) transports of stationary waves or transient eddies is proportional to their convergences which can be expressed as,

$$\frac{\partial[\bar{T}]}{\partial t} \propto -\frac{\partial[\bar{v}^* \bar{T}^*]}{\partial y} \text{ (or } -\frac{\partial[\overline{v' T'}]}{\partial y}), \quad (3)$$

$$\frac{\partial[\bar{q}]}{\partial t} \propto -\frac{\partial[\bar{v}^* \bar{q}^*]}{\partial y} \text{ (or } -\frac{\partial[\overline{v' q'}]}{\partial y}). \quad (4)$$

Moreover, the heat or moisture transports by a stationary wave component with zonal wavenumber k can be expressed as,

$$[\bar{v}^* \bar{T}^*]_k = [\bar{v}_k \bar{T}_k], \quad (5)$$

$$[\bar{v}^* \bar{q}^*]_k = [\bar{v}_k \bar{q}_k], \quad (6)$$

where $\bar{v}_k$ and $\bar{T}_k$ ($\bar{q}_k$) are the climatological meridional wind and temperature (moisture) disturbances, respectively, contributed only by stationary wave component with zonal wavenumber k , which are obtained by applying a Fourier transform.

c. Eady growth rate

According to linear baroclinic theories, the genesis of midlatitude transient eddies depends on the baroclinicity, which is proportional to the meridional temperature gradient divided by static stability (Eady 1949). The maximum Eady growth rate is calculated to measure the atmospheric baroclinicity, which is defined as

$$\sigma_{BI} = -0.31 \frac{g}{\theta N} \left| \frac{\partial \theta}{\partial y} \right|, \quad (7)$$

where N denotes the Brunt-Väisälä frequency, θ the potential temperature, and g the gravity acceleration (Lindzen and Farrell 1980; Hoskins and Valdes 1990).

d. Regression analysis

In this study, the decadal changes of wintertime poleward heat and moisture transports between two 18-yr epochs (1999-2016 and 1981-1998) associated with AA are firstly documented with five atmospheric reanalyses. To further confirm the impact of AA and its possible feedback, the relationship between the Arctic warming and the midlatitude poleward transport is then examined on interannual time scale. The components of more than 8 years for all variables are removed. An Arctic warming index is defined as wintertime mean surface air temperature (SAT) averaged over 75°~90°N and 0°~360°. The poleward heat and moisture transports are regressed on the normalized Arctic warming index to study the linkage between the Arctic SAT and the poleward transport on interannual time scale.

3. Changes in poleward heat and moisture transports

a. Observed Arctic warming and moistening

Near-surface in the Northern Hemisphere high latitudes is warming during recent two decades at a double rate of lower latitudes and the global average, which can be seen from SAT changes across five reanalyses (The colored solid lines in Fig. 1). This observed phenomenon is known as the Arctic amplification (AA). AA occurs in all seasons, with the strongest in autumn and winter (Figs. 1i,l). Although the warming trends are not identical among the reanalyses, as shown from the spread (the range

between minimum and maximum; shading in Fig. 1), the five reanalyses depict a consistent amplified warming trend since the late 1990s. All our analyses below are concentrated on the boreal winter (December, January, and February, DJF) when AA is the strongest and atmospheric poleward transport may play a vital role in AA due to the absent solar radiation in the Arctic (Park et al. 2015a). The amplified warming in high latitudes relative to the rest of the NH starts in the winter of 1998/99 (Figs. 1e,f). Therefore, we examine the epoch (decadal) differences of 18-yr mean SAT and any other variables between 1999/2000-2016/17 and 1981/82-1998/99 to represent atmospheric changes associated with AA. Note that the results can hold if the start year of AA is slightly changed.

Figure 2 demonstrates the decadal changes of SAT in five reanalyses. All reanalyses show an overall warming in the Arctic except over the Greenland-Labrador Sea in NCEP2 and MERRA-2. This warming is particularly pronounced over the Barents-Kara Sea. Furthermore, an additional warming can be seen over northeastern America and a cooling over Eurasian continents and North Pacific. Figure 3 shows the vertical structure of zonally averaged temperature and specific humidity changes. All the five reanalyses exhibit a significant Arctic warming throughout the troposphere, extending toward the midlatitude around 50°N, with maximum warming located in the lower troposphere (left panels of Fig. 3). NCPE2 and JRA-55 depict a slightly weaker warming in the mid-troposphere north of 60°N than the other reanalyses. Meanwhile, the Arctic warming is accompanied by the Arctic moistening, as shown from significantly increased specific humidity over the Arctic region (right panels of Fig. 3).

The Arctic moistening is confined in the lower troposphere below 700 hPa, with a slightly smaller magnitude in JRA-55 and a larger magnitude in NCEP2. Note that, due to lack of direct model output, the specific humidity in NCEP2 is derived from the relative humidity, which may yield bias.

b. Decadal changes in poleward heat and moisture transports

In this subsection, we examine the wintertime decadal changes in poleward heat and moisture transports associated with AA. The decadal changes in zonally averaged poleward heat transport in mid and high latitudes are shown in Fig. 4. Total heat transport changes (left panels of Fig. 4) from five reanalyses are contributed by stationary waves (middle panels of Fig. 4) and transient eddies (right panels of Fig. 4). Note that poleward transport change by the mean meridional circulation contributes little to the total heat transport changes in high latitudes. The climatological profiles of poleward heat and moisture transports by stationary waves and transient eddies are positive over the NH and peak in the midlatitudes, indicating that atmospheric waves transport heat and water vapor from the tropics to the Arctic (Peixoto and Oort 1992). As the Arctic warms, the poleward heat transport by stationary waves increases over most of regions north of 45°N except for the lower troposphere around 60°N (middle panels of Fig. 4), with the largest increase in the lower troposphere. The second maxima is located in the upper troposphere of the high latitudes and may be influenced by the stratosphere. On the other hand, the poleward heat transport by transient eddies significantly decreases in the mid-to-lower troposphere of the extratropics (right panels of Fig. 4). Thus, the increased poleward heat transport by stationary waves is mostly

offset by the decreased poleward heat transport by transient eddies. Consequently, the total poleward heat transport change in the mid and high latitudes below 600 hPa is minor (left panels of Fig. 4).

Similar to the heat transport, the zonally averaged poleward moisture transport by stationary waves also shows pronounced increases in the mid and high latitudes, especially at lower layers (middle panels of Fig. 5). NCEP2 shows a decrease of stationary moisture transport below 700 hPa between 50° and 65°N, which differs from the other four reanalyses and may be related to the bias in specific humidity calculation. The moisture transport by transient eddies decreases in the low levels except for the near-surface of the Arctic and increases in the upper levels (right panels of Fig. 5). The total poleward moisture transport increases in the high latitudes (left panels of Fig. 5), which is dominated by the increased moisture transport by stationary waves. The increased poleward heat and moisture transports by stationary waves are located in the lower troposphere over from the Barents Sea to western America with the largest increase over the Barents Sea, while the poleward heat and moisture transports by transient eddies show an overall decrease in high latitudes.

c. Local tendencies induced by poleward heat and moisture transport changes

To get a better understanding of the contribution of the poleward heat and moisture transport changes to the Arctic warming and moistening, heat and moisture transport flux convergences by stationary waves and transient eddies are further diagnosed according to Eqs. (3) and (4), respectively. As shown in the middle panels of Fig. 6, the stationary heat flux convergence enhances over the region north of 75°N, which

corresponds to the maximum poleward stationary heat transport around 75°N (middle panels of Fig. 4). On the other hand, the transient eddy heat flux convergence shows an overall decrease north of 75°N, which tends to induce a decrease in temperature in high latitudes (right panels of Fig. 6). The total heat flux convergence generally shows a cancellation between the stationary and transient heat flux convergences, which reveals little contribution of the total poleward heat transport to the Arctic warming.

The moisture flux convergence by stationary waves is similar to that of heat and is characterized by increases in the high latitudes, which tends to moisten the polar region (middle panels of Fig. 7). The moisture flux convergence by transient eddies decreases below 600 hPa in mid and high latitudes and slightly increases above it, which is prone to play a negative feedback in the Arctic moistening (right panels of Fig. 7). The total moisture flux converges over the polar region, which is dominated by the transport of stationary eddies and tends to amplify the Arctic moistening.

d. Poleward transports associated with interannual Arctic warming

In order to confirm the impact of AA on the high latitude poleward heat and moisture transports and their possible feedbacks onto the Arctic warming, which are investigated with decadal changes above, the interannual relationship between the Arctic warming and the midlatitude poleward transport is examined below. The components of more than 8 years for all variables are removed. The interannual anomalies of the poleward heat and moisture transports and their convergences are regressed upon a normalized the Arctic warming index as described in Section 2d. The regression analysis is based on the CFSR dataset, since the new high-resolution

reanalysis has made big improvements in resolving transient eddies (Hodges et al. 2011; Jung et al. 2012). On the interannual time scales, when winter Arctic SAT anomalies are positive, significant positive poleward heat and moisture transport anomalies by stationary waves are observed in the lower troposphere of the high latitudes, with the maximum located at 75° N (Figs. 8b,e), which induce increases in the tendency of Arctic temperature and moisture, respectively (Figs. 9b,e). Meanwhile, negative poleward heat and moisture transport anomalies by transient eddies occupy the lower-troposphere of the high latitudes (Figs. 8c,f) and cause the decrease in the tendency of Arctic temperature and moisture (Figs. 9c,f) except for the moisture over the Arctic near-surface. The results of increased transport by stationary waves and decreased transport by transient eddies are quite consistent with those from decadal differences (center and left panels of Figs. 4,5). The total poleward heat transport shows a weak and insignificant positive anomaly north of 75° N that is basically offset by stationary waves and transient eddies (Fig. 8a), which induces weak and insignificant temperature tendencies north of 80° N (Fig. 9a). The total moisture transport exhibits positive anomalies in the high latitudes with maxima located in the lower troposphere, which is dominated by the stationary component (Fig. 8d). The total moisture transport converges north of 75° N, showing positive moisture tendencies in the Arctic (Fig. 9d). Therefore, on the interannual time scales, the total poleward heat transport shows cancellation between stationary and transient components, while the total poleward moisture transport increases as Arctic warms. This confirms the impact of AA on the high latitude poleward heat and moisture transports and their feedbacks onto the Arctic

warming on the decadal time scales.

4. Mechanisms for the poleward heat and moisture transport changes

a. Mechanisms for stationary heat and moisture transport changes

Figures 10a-e show the decadal changes of 18-yr mean 500 hPa geopotential height among five reanalyses. An increased geopotential height is centered in the Novaya Zemlya where the tropospheric warming is the most amplified and the sea ice loss is the most. The rise of 500 hPa height over Novaya Zemlya weakens the trough over the northwestern Russia, as shown in black contours in the left panels of Fig. 10. Another increased geopotential height is found over the North Atlantic, with the center located in the southern Greenland. The increased geopotential height extends to the Arctic and tends to link up with that over the Novaya Zemlya. The decreased geopotential height extends from the Bering Strait to the Beaufort Sea, which weakens the climatological ridge. These changes are consistent among five reanalyses, with the maximum magnitude in NCEP2 and minimum in ERA-Interim. Both the increased height over Novaya Zemlya and Greenland and the decreased height over Chukchi Sea contribute to the transition of dominant stationary wave component from zonal wavenumber 2 before 1999/2000 to wavenumber 1 after 1999/2000, which are shown in contours in the left panels of Fig. 10.

To further identify the changes in stationary waves with different spatial scales, we decompose the 500 hPa geopotential height into zonal wavenumber space. The results of the changes in amplitude of zonal wavenumber 1-6 are shown in the right panels of Fig. 10. The increase in the amplitude of wavenumber 1 and decrease in the

amplitude of wavenumber 2 north of 55°N are found in all reanalyses. The amplitude
 changes of stationary waves with zonal wavenumber larger than 2 are much smaller,
 with a slight decrease of wavenumber 3 and a slight increase of wavenumber 4 in the
 mid and high latitudes. For the extratropical stationary waves forced by diabatic heating
 or orography, the heating is balanced by meridional temperature advection from a dry
 dynamical perspective (Hoskins and Karoly 1981; Held et al. 2002). Therefore, an
 enhanced stationary wave meridional wind v^* is required for balance with reduced
 equator-to-pole temperature gradient under the background of AA, which leads to an
 increase in the amplitude of stationary wave (Wills et al. 2019). However, our results
 show an increase in zonal wavenumber 1 but a decrease in zonal wavenumber 2 in high
 latitudes, due to the increased geopotential height over Novaya Zemlya and
 Greenland. Our results suggest little evidence for an overall increase in stationary wave
 amplitude as the Arctic warms.

In terms of Eq. (5), the stationary heat transport is further decomposed into
 components with zonal wavenumbers $k = 1\sim 3$, which are shown in Fig. 11. The
 poleward heat transport by zonal wavenumber 1 exhibits an overall increase in the high
 latitudes, which peaks in the lower troposphere north of 70°N (left panels of Fig. 11).
 The poleward heat transport by wavenumber 2 decreases north of 75°N throughout the
 troposphere and slightly increases south of 75°N (middle panels of Fig. 11). The coarse
 resolution reanalysis, NCEP2, shows large differences from other reanalyses, with
 decrease in the upper troposphere of midlatitude (Fig. 11f). The poleward heat transport
 by wavenumber 3 increases north of 75°N and decreases south of that latitude with

small amplitude.

In terms of Eq. (6), results from the decomposition of the stationary poleward moisture transport are similar to that of heat transport (Fig. 12). The poleward moisture transport by zonal wavenumber 1 shows a widespread increase in the high latitudes, with the largest increase in the lower troposphere, which is associated with the enhanced amplitude of zonal wavenumber 1 (left panels of Fig. 12). Meanwhile, corresponding to the reduced amplitude of zonal wavenumber 2, the moisture transport by wavenumber 2 decreases in high latitudes, which is opposite to the changes in moisture transport by zonal wavenumber 3. Thus, the key process responsible for the increase of poleward heat and moisture transports by stationary waves is the amplified stationary wave component of zonal wavenumber 1.

b. Mechanisms for transient heat and moisture transport changes

Under the influence of AA, meridional temperature gradient is expected to decrease and tend to weaken baroclinicity (Wang et al. 2017). To verify this hypothesis, the vertical structures of the changes in Eady growth rate which is calculated in terms of Eq. (7), meridional potential temperature gradient and Brunt-Väisälä frequency from five reanalyses are displayed in left, central and right panels of Fig. 13, respectively. All the reanalyses demonstrate the decreased baroclinicity in the mid and high latitudes as the Arctic is warming, except for the low-level Arctic (left panels of Fig. 13). A significant decrease in baroclinicity is found along 50°-65°N from the surface to 400 hPa. Another decrease in baroclinicity located in the lower- and mid-troposphere over polar region (around 80°N) is evident in ERA-Interim, MERRA-2,

and CFSR. The changes in baroclinicity follow those in meridional temperature gradient that are characterized by significant decrease in mid and high latitudes, except for the low-level Arctic (central panels of Fig. 13). The reduced static stability contributes to the enhancement of atmospheric baroclinicity over the polar region (right panels of Fig. 13).

To assess the changes of transient eddy activities associated with the reduced atmospheric baroclinicity, we calculate the decadal changes of eddy kinetic energy (EKE), which is defined as $EKE = \overline{(u'^2 + v'^2)}/2$. To distinguish the relative contributions from low- and high-frequency components, a 121-point lanczos filter is applied to decompose the transient eddy into its high- (2~10 days) and low-frequency (10~90 days) components. The high-frequency eddies are also known as synoptic eddies, which represent weather patterns such as midlatitude storms. The low-frequency eddies are associated with more persistent weather patterns like blocking. Then the corresponding high- and low-frequency components of EKE are obtained as $EKE_h = \overline{(u_h'^2 + v_h'^2)}/2$ and $EKE_l = \overline{(u_l'^2 + v_l'^2)}/2$, respectively, where the overbar indicates climatology, and subscripts h and l represent high-frequency and low-frequency components, respectively. The results of decomposition of EKE are shown in Fig. 14. On the whole, the transient EKE decreases above 900 hPa and increases below. MERRA-2 shows the largest decrease among five reanalyses with the center of maximum located in the upper troposphere (left panels of Fig. 14). The EKE changes in NCEP-2 and ERA-Interim are smaller than those in other three reanalyses and statistically insignificant. By comparing the relative contributions from high- and low-

frequency components, it is found that the high-frequency synoptic EKE changes (middle panels of Fig. 14) are comparable to the total transient EKE changes. The low-frequency EKE increases between 50° and 70°N and north of 85°N and decreases between 70°N and 85°N with statistical insignificance (right panels of Fig. 14). Hence, the total transient EKE changes are dominated by the synoptic EKE changes, although the latter are partially canceled by the low-frequency EKE changes. These results support the hypothesis that the decreased baroclinicity caused by the weakened meridional temperature gradient is an important contributor to the attenuation of transient eddy activity.

To estimate the role of different wave components in the changes of poleward transport, we apply the same decomposition method as in EKE for poleward heat and moisture transports in all five reanalyses, as shown in Figs. 15 and 16. The left panels of Fig. 15 show the transient poleward heat transport, and the second and third columns are the heat transports by high- and low-frequency eddies, respectively. The changes in transport by transient eddies are not exactly equal to the sum of those by high- and low-frequency. Because the transient eddies defined here include the eddies with time scale longer than 90 days, which are known as very-low frequency. The changes in poleward transport by very-low frequency are small and can be ignored. It is illustrated that the poleward heat transport by transient eddies decreases over most of the mid and high latitudes except for the upper-level over polar region, which is a common feature of all reanalyses (left panels of Fig. 15). The decreased transient poleward heat transport peaks in the lower troposphere north of 60°N . The heat transports by both high- and

low-frequency eddies decrease in the lower troposphere (below 600 hPa), each contributing half to the transient transport decrease. In the middle- and upper-troposphere, the opposite changes are found for the transport by synoptic and low-frequency eddies, with the combined changes that decrease south of 70°N and slightly increase north of 70°N.

Similar to Fig. 15, the changes in poleward moisture transport by transient eddies and its components with different time scales are shown in Fig. 16. The poleward transient moisture transport decreases in the lower troposphere except for polar region and increases in the middle- and upper-troposphere (left panels of Fig. 16). The gross features are similar to the synoptic moisture transport, which is characterized by an overall decrease in the middle- and lower-troposphere in the mid and high latitudes and a slight increase in the upper troposphere and near-surface of the Arctic (central panels of Fig. 16). For low-frequency transport, an overall increase is found in the mid and high latitudes with the maximum located at 60°N and extending to 500 hPa, which is partially offset by the synoptic transport (right panels of Fig. 16). Note that the low-frequency transport also slightly contributes to the decreased transient transport at low levels of 75°N. Thus, corresponding to the weakened synoptic eddy activities, the poleward heat and moisture transports by synoptic eddies decrease throughout the troposphere in the high latitudes, which play dominant roles in the total transient transport.

5. Conclusions and discussion

This study investigates the influence of the Arctic amplification on the midlatitude

atmospheric waves and their contributions to the poleward heat and moisture transports. Five atmospheric reanalyses (NCEP2, ERA-Interim, JRA-55, MERRA-2 and CFSR) are used to study wintertime poleward heat and moisture transport changes in the mid and high latitudes associated with the Arctic amplification which is the strongest during the boreal winter for recent two decades. Major conclusions are illustrated in a schematic diagram, as shown in Fig. 17.

In association with the Arctic amplification, the zonal mean wintertime poleward heat and moisture transports by stationary waves increase in the high latitudes, which tend to induce increases in the temperature and moisture over the Arctic, thus acting as a positive feedback onto the Arctic warming. The increases in stationary poleward heat (moisture) transport are primarily due to the increase in stationary wave meridional wind, while the increase in stationary temperature (moisture) contributes little (not shown). The enhanced stationary transports are mainly contributed from the increased transport by stationary wave component with zonal wavenumber 1. Our result shows an increase in the amplitude of stationary wave component with zonal wavenumber 1 but a decrease in that with zonal wavenumber 2. This result is different from what is expected by the dry dynamical mechanism based on the reduced equator-to-pole temperature gradient (Hoskins and Karoly 1981; Wills et al. 2019) and is a step forward from previous studies that suggested increased stationary wave amplitude (Francis and Vavrus 2012; Liu et al. 2012).

On the other hand, the amplified Arctic warming decreases the transient eddy activities by reducing the low-level equator-to-pole temperature gradient and

baroclinicity in the high latitudes, which results in the decreases of both poleward heat and moisture transports by transient eddies. The weakened eddy heat flux in the NH associated with a decrease in meridional temperature gradient that arises from AA has also been well captured by observational studies and climate models (Chemke and Polvani 2020). The reductions in the poleward transport by transient eddies tend to check the Arctic warming and moistening, thus generating a negative feedback. In total, the increased poleward heat transport by stationary waves is nearly cancelled by the decreased poleward heat transport by transient eddies. Thus, the total poleward heat transport shows minor changes, contributing little to the Arctic warming. However, the total poleward moisture transport increases over most areas of the high latitudes where the role of stationary waves is dominant. These changes by epoch differences are significantly consistent with the interannual anomalies in transport and flux convergence as regressed upon the Arctic warming index. Therefore, the poleward moisture transport increase by stationary waves which acts as a positive feedback plays a crucial role in the Arctic amplification during winter when the ice-albedo feedback vanishes.

The results are compared well among four high-resolution reanalyses, while NCEP2 is often in disagreement with other four reanalyses. The relatively coarse model resolution (T62, ~210km) used in NCEP2 which may underestimate transient eddy activities is likely the reason for the differences (Hodges et al. 2011). Moreover, retrieves of satellite data employed may also cause difference (as shown in Table 1), especially over the polar region. It implies that it is better to use the high-resolution

reanalyses (ERA-Interim, JRA-55, MERRA-2 and CFSR) in the study of eddy-related issues in the mid and high latitudes.

In this study, we examine the impact of the Arctic amplification on the mid and high latitude stationary waves and transient eddies and their relative contributions and potential feedbacks onto the amplified Arctic warming, in a manner of two-way interactions on decadal timescale. We find the importance and positive feedback role of poleward moisture transport in amplifying the Arctic warming. This finding agrees with those presented by other recent studies showing an increase of poleward moisture flux and its positive effect on the Arctic SAT (Graversen and Burtu 2016; Woods and Caballero 2016; Lee et al. 2017a). However, for moisture transport, we only consider the contribution of moisture transport to the Arctic moistening through moisture budget analysis. To examine the feedback more comprehensively, the longwave radiation effect of the Arctic moistening needs to be further identified in the future study, which is suggested to be an important contributor to the Arctic warming and sea ice decline especially during winter when the ice-albedo feedback vanishes (Park et al. 2015a; Lee et al. 2017b).

Although our current study provides a new insight into the amplified Arctic warming and midlatitude linkage, the results are limited to a relatively short period (1980-2016) which may affect the statistical confidence, given the large internal variabilities in the mid and high latitudes. A major caveat of observational studies is that correlation alone cannot provide any unambiguous support for causality. Cause and effect can be established through sensitivity or perturbation studies using dedicated

501 model simulations, but models are subject to several deficiencies. Model experiments
502 forced with the Arctic sea-ice loss produce significantly different circulation responses
503 (Peings and Magnusdottir 2014; Screen et al. 2014), which are mainly caused by the
504 sensitivity to the magnitude (Chen et al. 2016) and geographic patterns of sea-ice loss
505 (Pedersen et al. 2016; Screen 2017) and the highly nonlinear interactions among model
506 processes. Meanwhile, it is inaccurate to characterize the Arctic amplification only with
507 sea ice loss, because other processes, such as poleward transport from outside the Arctic,
508 are also critical to the Arctic warming (Screen et al. 2012; Ding et al. 2014; Park et al.
509 2015b; Gong et al. 2017). To make further progress, adequate description of the
510 underlying physical processes behind the Arctic warming and coordinated experiments
511 with as many different models as possible are needed (Screen et al. 2018).

Acknowledgments

This study is supported by the National Natural Science Foundation of China (Grant Nos. 41621005 and 41875086) and the National Key Basic Research and Development Program of China (Grant No. 2018YFC1505902). We are also grateful for support from the Jiangsu Collaborative Innovation Center for Climate Change. NCEP2 was provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, and was obtained from the website at <https://www.esrl.noaa.gov/psd/>. The ERA-Interim data was produced by ECMWF and was obtained from <https://apps.ecmwf.int/datasets/>. The JRA-55 data was developed by the Japan Meteorological Agency (JMA) and is available at https://jra.kishou.go.jp/JRA-55/index_en.html. MERRA-2 is available at https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/. The CFSR data was provided by Research Data Archive at the National Center for Atmospheric Research and is available at <http://dx.doi.org/10.5065/D69K487J>.

References

- Alexeev VA, Langen PL, Bates JR (2005) Polar amplification of surface warming on an aquaplanet in “ghost forcing” experiments without sea ice feedbacks *Climate Dynamics* 24:655-666. <https://doi.org/10.1007/s00382-005-0018-3>
- Barnes EA (2013) Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes *Geophysical Research Letters* 40:4734-4739. <https://doi.org/10.1002/grl.50880>
- Barnes EA, Screen JA (2015) The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change* 6:277-286. <https://doi.org/10.1002/wcc.337>
- Blender R, Schubert M (2000) Cyclone Tracking in Different Spatial and Temporal Resolutions *Monthly Weather Review* 128:377-384. [https://doi.org/10.1175/1520-0493\(2000\)128<0377:CTIDSA>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0377:CTIDSA>2.0.CO;2)
- Boer GJ, Shepherd TG (1983) Large-Scale Two-Dimensional Turbulence in the Atmosphere *Journal of Atmospheric Sciences* 40:164-184. [https://doi.org/10.1175/1520-0469\(1983\)040<0164:LSTDTI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1983)040<0164:LSTDTI>2.0.CO;2)
- Bromwich DH, Fogt RL, Hodges KI, Walsh JE (2007) A tropospheric assessment of the ERA-40, NCEP, and JRA-25 global reanalyses in the polar regions *Journal of Geophysical Research: Atmospheres* 112. <https://doi.org/10.1029/2006JD007859>
- Chemke R, Polvani LM (2020) Linking midlatitudes eddy heat flux trends and polar amplification *npj Climate and Atmospheric Science* 3:8. <https://doi.org/10.1038/s41612-020-0111-7>
- Chen HW, Zhang F, Alley RB (2016) The Robustness of Midlatitude Weather Pattern Changes due to Arctic Sea Ice Loss *Journal of Climate* 29:7831-7849. <https://doi.org/10.1175/jcli-d-16-0167.1>
- Cohen J et al. (2014) Recent Arctic amplification and extreme mid-latitude weather *Nature Geoscience* 7:627-637. <https://doi.org/10.1038/ngeo2234>
- Cohen J et al. (2020) Divergent consensus on Arctic amplification influence on

555 midlatitude severe winter weather Nature Climate Change 10:20-29.
 556 <https://doi.org/10.1038/s41558-019-0662-y>

557 Coumou D, Lehmann J, Beckmann J (2015) The weakening summer circulation in the
 558 Northern Hemisphere mid-latitudes Science 348:324-327.
 559 <https://doi.org/10.1126/science.1261768>

560 Dai A, Luo D, Song M, Liu J (2019) Arctic amplification is caused by sea-ice loss under
 561 increasing CO2 Nature Communications 10:121.
 562 <https://doi.org/10.1038/s41467-018-07954-9>

563 Dee DP et al. (2011) The ERA-Interim reanalysis: configuration and performance of
 564 the data assimilation system Quarterly Journal of the Royal Meteorological
 565 Society 137:553-597. <https://doi.org/10.1002/qj.828>

566 Ding Q, Wallace JM, Battisti DS, Steig EJ, Gallant AJE, Kim H-J, Geng L (2014)
 567 Tropical forcing of the recent rapid Arctic warming in northeastern Canada and
 568 Greenland Nature 509:209-212. <https://doi.org/10.1038/nature13260>

569 Eady ET (1949) Long Waves and Cyclone Waves Tellus 1:33-52.
 570 <https://doi.org/10.3402/tellusa.v1i3.8507>

571 Francis JA, Vavrus SJ (2012) Evidence linking Arctic amplification to extreme weather
 572 in mid-latitudes Geophysical Research Letters 39:L06801.
 573 <https://doi.org/10.1029/2012GL051000>

574 Gelaro R et al. (2017) The Modern-Era Retrospective Analysis for Research and
 575 Applications, Version 2 (MERRA-2) Journal of Climate 30:5419-5454.
 576 <https://doi.org/10.1175/jcli-d-16-0758.1>

577 Gimeno L, Vázquez M, Nieto R, Trigo RM (2015) Atmospheric moisture transport: the
 578 bridge between ocean evaporation and Arctic ice melting Earth System
 579 Dynamics 6:583. <https://doi.org/10.5194/esd-6-583-2015>

580 Gong T, Feldstein S, Lee S (2017) The Role of Downward Infrared Radiation in the
 581 Recent Arctic Winter Warming Trend Journal of Climate 30:4937-4949.
 582 <https://doi.org/10.1175/jcli-d-16-0180.1>

583 Graverson RG, Burtu M (2016) Arctic amplification enhanced by latent energy

584 transport of atmospheric planetary waves Quarterly Journal of the Royal
 585 Meteorological Society 142:2046-2054. <https://doi.org/10.1002/qj.2802>
 586 Graversen RG, Mauritsen T, Tjernström M, Källén E, Svensson G (2008) Vertical
 587 structure of recent Arctic warming Nature 451:53-56.
 588 <https://doi.org/10.1038/nature06502>
 589 Graversen RG, Wang M (2009) Polar amplification in a coupled climate model with
 590 locked albedo Climate Dynamics 33:629-643. [https://doi.org/10.1007/s00382-](https://doi.org/10.1007/s00382-009-0535-6)
 591 [009-0535-6](https://doi.org/10.1007/s00382-009-0535-6)
 592 Harada Y et al. (2016) The JRA-55 Reanalysis: Representation of Atmospheric
 593 Circulation and Climate Variability Journal of the Meteorological Society of
 594 Japan Ser II 94:269-302. <https://doi.org/10.2151/jmsj.2016-015>
 595 Held IM, Ting M, Wang H (2002) Northern Winter Stationary Waves: Theory and
 596 Modeling Journal of Climate 15:2125-2144. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0442(2002)015<2125:Nwshta>2.0.Co;2)
 597 [0442\(2002\)015<2125:Nwshta>2.0.Co;2](https://doi.org/10.1175/1520-0442(2002)015<2125:Nwshta>2.0.Co;2)
 598 Hodges KI, Lee RW, Bengtsson L (2011) A Comparison of Extratropical Cyclones in
 599 Recent Reanalyses ERA-Interim, NASA MERRA, NCEP CFSR, and JRA-25
 600 Journal of Climate 24:4888-4906. <https://doi.org/10.1175/2011jcli4097.1>
 601 Hoskins BJ, Karoly DJ (1981) The Steady Linear Response of a Spherical Atmosphere
 602 to Thermal and Orographic Forcing Journal of Atmospheric Sciences 38:1179-
 603 1196. [https://doi.org/10.1175/1520-0469\(1981\)038<1179:Tslroa>2.0.Co;2](https://doi.org/10.1175/1520-0469(1981)038<1179:Tslroa>2.0.Co;2)
 604 Hoskins BJ, Valdes PJ (1990) On the Existence of Storm-Tracks Journal of the
 605 Atmospheric Sciences 47:1854-1864. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1990)047<1854:OTEOST>2.0.CO;2)
 606 [0469\(1990\)047<1854:OTEOST>2.0.CO;2](https://doi.org/10.1175/1520-0469(1990)047<1854:OTEOST>2.0.CO;2)
 607 Jung T et al. (2012) High-Resolution Global Climate Simulations with the ECMWF
 608 Model in Project Athena: Experimental Design, Model Climate, and Seasonal
 609 Forecast Skill Journal of Climate 25:3155-3172. [https://doi.org/10.1175/jcli-d-](https://doi.org/10.1175/jcli-d-11-00265.1)
 610 [11-00265.1](https://doi.org/10.1175/jcli-d-11-00265.1)
 611 Kanamitsu M, Ebisuzaki W, Woollen J, Yang S-K, Hnilo JJ, Fiorino M, Potter GL (2002)
 612 NCEP–DOE AMIP-II Reanalysis (R-2) Bulletin of the American

613 Meteorological Society 83:1631-1644. <https://doi.org/10.1175/bams-83-11->
614 [1631](https://doi.org/10.1175/bams-83-11-1631)

615 Lee HJ et al. (2017a) Impact of Poleward Moisture Transport from the North Pacific on
616 the Acceleration of Sea Ice Loss in the Arctic since 2002 Journal of Climate
617 30:6757-6769. <https://doi.org/10.1175/jcli-d-16-0461.1>

618 Lee S, Gong T, Feldstein SB, Screen JA, Simmonds I (2017b) Revisiting the Cause of
619 the 1989–2009 Arctic Surface Warming Using the Surface Energy Budget:
620 Downward Infrared Radiation Dominates the Surface Fluxes Geophysical
621 Research Letters 44:10,654-610,661. <https://doi.org/10.1002/2017GL075375>

622 Lee S, Gong T, Johnson N, Feldstein SB, Pollard D (2011) On the Possible Link
623 between Tropical Convection and the Northern Hemisphere Arctic Surface Air
624 Temperature Change between 1958 and 2001 Journal of Climate 24:4350-4367.
625 <https://doi.org/10.1175/2011jcli4003.1>

626 Lindsay R, Wensnahan M, Schweiger A, Zhang J (2014) Evaluation of Seven Different
627 Atmospheric Reanalysis Products in the Arctic Journal of Climate 27:2588-
628 2606. <https://doi.org/10.1175/jcli-d-13-00014.1>

629 Lindzen RS, Farrell B (1980) A Simple Approximate Result for the Maximum Growth
630 Rate of Baroclinic Instabilities Journal of Atmospheric Sciences 37:1648-1654.
631 [https://doi.org/10.1175/1520-0469\(1980\)037<1648:Asarft>2.0.Co;2](https://doi.org/10.1175/1520-0469(1980)037<1648:Asarft>2.0.Co;2)

632 Liu C, Barnes EA (2015) Extreme moisture transport into the Arctic linked to Rossby
633 wave breaking Journal of Geophysical Research: Atmospheres 120:3774-3788.
634 <https://doi.org/10.1002/2014JD022796>

635 Liu J, Curry JA, Wang H, Song M, Horton RM (2012) Impact of declining Arctic sea
636 ice on winter snowfall Proceedings of the National Academy of Sciences
637 109:4074-4079. <https://doi.org/10.1073/pnas.1114910109>

638 Overland J, Francis JA, Hall R, Hanna E, Kim S-J, Vihma T (2015) The Melting Arctic
639 and Midlatitude Weather Patterns: Are They Connected?* Journal of Climate
640 28:7917-7932. <https://doi.org/10.1175/JCLI-D-14-00822.1>

641 Overland JE (2016) A difficult Arctic science issue: Midlatitude weather linkages Polar

642 Science 10:210-216. <https://doi.org/10.1016/j.polar.2016.04.011>

643 Park D-SR, Lee S, Feldstein SB (2015a) Attribution of the Recent Winter Sea Ice
 644 Decline over the Atlantic Sector of the Arctic Ocean Journal of Climate
 645 28:4027-4033. <https://doi.org/10.1175/jcli-d-15-0042.1>

646 Park HS, Lee S, Son S-W, Feldstein SB, Kosaka Y (2015b) The Impact of Poleward
 647 Moisture and Sensible Heat Flux on Arctic Winter Sea Ice Variability Journal of
 648 Climate 28:5030-5040. <https://doi.org/10.1175/jcli-d-15-0074.1>

649 Pedersen RA, Cvijanovic I, Langen PL, Vinther BM (2016) The Impact of Regional
 650 Arctic Sea Ice Loss on Atmospheric Circulation and the NAO Journal of
 651 Climate 29:889-902. <https://doi.org/10.1175/jcli-d-15-0315.1>

652 Peings Y, Magnusdottir G (2014) Response of the Wintertime Northern Hemisphere
 653 Atmospheric Circulation to Current and Projected Arctic Sea Ice Decline: A
 654 Numerical Study with CAM5 Journal of Climate 27:244-264.
 655 <https://doi.org/10.1175/jcli-d-13-00272.1>

656 Peixoto JP, Oort AH (1992) Physics of Climate. American Institute of Physics, New
 657 York,

658 Petoukhov V, Rahmstorf S, Petri S, Schellnhuber HJ (2013) Quasiresonant
 659 amplification of planetary waves and recent Northern Hemisphere weather
 660 extremes Proceedings of the National Academy of Sciences 110:5336-5341.
 661 <https://doi.org/10.1073/pnas.1222000110>

662 Saha S et al. (2010) The NCEP Climate Forecast System Reanalysis Bulletin of the
 663 American Meteorological Society 91:1015-1058.
 664 <https://doi.org/10.1175/2010bams3001.1>

665 Screen JA (2017) Simulated Atmospheric Response to Regional and Pan-Arctic Sea Ice
 666 Loss Journal of Climate 30:3945-3962. <https://doi.org/10.1175/jcli-d-16-0197.1>

667 Screen JA, Deser C, Simmonds I (2012) Local and remote controls on observed Arctic
 668 warming Geophysical Research Letters 39.
 669 <https://doi.org/10.1029/2012GL051598>

670 Screen JA, Deser C, Simmonds I, Tomas R (2014) Atmospheric impacts of Arctic sea-

ice loss, 1979–2009: separating forced change from atmospheric internal
 variability *Climate Dynamics* 43:333–344. <https://doi.org/10.1007/s00382-013-1830-9>

Screen JA et al. (2018) Consistency and discrepancy in the atmospheric response to
 Arctic sea-ice loss across climate models *Nature Geoscience* 11:155–163.
<https://doi.org/10.1038/s41561-018-0059-y>

Screen JA, Simmonds I (2010a) The central role of diminishing sea ice in recent Arctic
 temperature amplification *Nature* 464:1334–1337.
<https://doi.org/10.1038/nature09051>

Screen JA, Simmonds I (2010b) Increasing fall-winter energy loss from the Arctic
 Ocean and its role in Arctic temperature amplification *Geophysical Research
 Letters* 37. <https://doi.org/10.1029/2010GL044136>

Screen JA, Simmonds I (2013) Exploring links between Arctic amplification and mid-
 latitude weather *Geophysical Research Letters* 40:959–964.
<https://doi.org/10.1002/grl.50174>

Screen JA, Simmonds I (2014) Amplified mid-latitude planetary waves favour
 particular regional weather extremes *Nature Climate Change* 4:704–709.
<https://doi.org/10.1038/nclimate2271>

Serreze MC, Barrett AP, Stroeve JC, Kindig DN, Holland MM (2009) The emergence
 of surface-based Arctic amplification *The Cryosphere Discussions* 2:601.
<https://doi.org/10.5194/tc-3-11-2009>

Serreze MC, Francis JA (2006) The Arctic Amplification Debate *Climatic Change*
 76:241–264. <https://doi.org/10.1007/s10584-005-9017-y>

Tilinina N, Gulev SK, Rudeva I, Koltermann P (2013) Comparing Cyclone Life Cycle
 Characteristics and Their Interannual Variability in Different Reanalyses
Journal of Climate 26:6419–6438. <https://doi.org/10.1175/jcli-d-12-00777.1>

Vavrus SJ (2018) The Influence of Arctic Amplification on Mid-latitude Weather and
 Climate *Current Climate Change Reports* 4:238–249.
<https://doi.org/10.1007/s40641-018-0105-2>

- Walsh JE (2014) Intensified warming of the Arctic: Causes and impacts on middle latitudes Global and Planetary Change 117:52-63.
<https://doi.org/10.1016/j.gloplacha.2014.03.003>
- Wang J, Kim H-M, Chang EKM (2017) Changes in Northern Hemisphere Winter Storm Tracks under the Background of Arctic Amplification Journal of Climate 30:3705-3724. <https://doi.org/10.1175/jcli-d-16-0650.1>
- Wills RCJ, White RH, Levine XJ (2019) Northern Hemisphere Stationary Waves in a Changing Climate Current Climate Change Reports 5:372-389.
<https://doi.org/10.1007/s40641-019-00147-6>
- Woods C, Caballero R (2016) The Role of Moist Intrusions in Winter Arctic Warming and Sea Ice Decline Journal of Climate 29:4473-4485.
<https://doi.org/10.1175/jcli-d-15-0773.1>
- Zhang X, He J, Zhang J, Polyakov I, Gerdes R, Inoue J, Wu P (2013) Enhanced poleward moisture transport and amplified northern high-latitude wetting trend Nature Climate Change 3:47-51. <https://doi.org/10.1038/nclimate1631>

716 Table 1. Detailed information of the five atmospheric reanalyses used in the study.

Reanalysis name	Organization	Date range	Horizontal resolution	Vertical layer	Products resolution	Assimilation Algorithm	Satellite data
NCEP-DOE2	NCEP/DOE	1979-2017	T62 (~210km)	28 levels	2.5°x2.5°	3DVAR	Retrievals
ERA-Interim	ECMWF	1979-2017	T255 (~79km)	60 levels	1.5°x1.5°	4DVAR	Radiances
JRA-55	JMA	1958-2017	T319 (~60km)	40 levels	1.25°x1.25°	4DVAR	Radiances
MERRA-2	NASA GMAO	1980-2017	(2/3)°x0.5° (~50km)	72 levels	0.5°x0.66°	3DVAR	Radiances
CFSR	NCEP	1979-2017	T382 (~38km)	64 levels	0.5°x0.5°	3DVAR	Radiances

717

Figure captions

Figure 1. Surface air temperature anomalies (K) averaged over the globe for (a) DJF, (b) MAM, (c) JJA, and (d) SON. (e)-(h) and (i)-(l) are as in (a)-(d), but for those averaged over $0^{\circ} \sim 60^{\circ}$ N and $60^{\circ} \sim 90^{\circ}$ N, respectively. The climatological means are for 1980–2016. The colored solid lines denote the average of five reanalyses and the shaded envelopes show the spread among the five reanalyses.

Figure 2. Wintertime surface air temperature differences (K) between 1999-2016 and 1981-1998 in (a) NCEP2, (b) ERA-Interim, (c) JRA-55, (d) MERRA-2, and (e) CFSR. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 3. Wintertime zonally-averaged temperature (K, left panels) and specific humidity (10^{-4} kg/kg, right panels) differences between 1999-2016 and 1981-1998 in (a, b) NCEP2, (c, d) ERA-Interim, (e, f) JRA-55, (g, h) MERRA-2, and (i, j) CFSR. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 4. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged poleward heat transport (K m/s) by total disturbances (left panels), stationary waves (central panels), and transient eddies (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 5. As in Fig. 4, but for the poleward moisture transport (10^{-4} kg/kg m/s).

Figure 6. As in Fig. 4, but for the convergence (K/day) of poleward heat transport.

Figure 7. As in Fig. 4, but for the convergence (10^{-5} kg/kg/day) of poleward moisture transport.

Figure 8. Wintertime zonally-averaged interannual anomalies of poleward heat (K m/s, upper panels) and moisture (10^{-4} kg/kg m/s, lower panels) transports by total disturbances (left panels), stationary waves (central panels), and transient eddies (right panels), regressed upon a normalized Arctic warming index defined as the surface air temperature anomaly averaged over $75^{\circ}\sim 90^{\circ}\text{N}$ and $0^{\circ}\sim 360^{\circ}$. The zero lines are shown in bold black. The anomalies with values exceeding the 90% ($p<0.1$) significance level according to the Student's t -test are crossed. Note that the CFSR reanalysis dataset is only used here.

Figure 9. As in Fig. 8, but for the convergences of interannual anomalies of poleward heat (upper panels) and moisture (lower panels) transports.

Figure 10. Decadal differences between 1999-2016 and 1981-1998 of the wintertime 500 hPa geopotential height (gpm, left panels) and the amplitude of stationary waves with zonal wavenumber 1~6 (gpm, right panels), with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The contours in left panels are 5100 m and 5180 m for 1999-2016 (black) and 1981-1998 (green), respectively. The bold black lines in right panels indicate the zero lines.

Figure 11. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged poleward heat transport by stationary wave component (K m/s) of zonal wavenumber 1 (left panels), wavenumber 2 (central panels), and wavenumber 3 (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black lines.

Figure 12. As in Fig. 11, but for the poleward moisture transport (10^{-4} kg/kg m/s).

Figure 13. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged maximum Eady growth rate (1/day) (left panels), meridional potential temperature gradient (10^{-4} K/km) (central panels), and Brunt-Väisälä frequency (10^{-4} 1/s) (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p<0.1$) significance level according to the Student's t -test are crossed.

Figure 14. Decadal differences between 1999-2016 and 1981-1998 of wintertime

zonally-averaged eddy kinetic energy (m^2/s^2) of total transient eddies (left panels), high-frequency eddies with time-scale of 2-10 days (central panels), and low-frequency eddies with time-scale of 10-90 days (right panels), calculated with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 15. As in Fig. 14, but for the poleward heat transport (K m/s).

Figure 16. As in Fig. 14, but for the poleward moisture transport (10^{-4} kg/kg m/s).

Figure 17. A schematic diagram for the impact of the amplified Arctic warming on the high latitude poleward heat and moisture transports by stationary waves and transient eddies and their possible feedbacks.

787

788 **Figure 1.** Surface air temperature anomalies (K) averaged over the globe for (a) DJF,
 789 (b) MAM, (c) JJA, and (d) SON. (e)-(h) and (i)-(l) are as in (a)-(d), but for those
 790 averaged over $0^{\circ} \sim 60^{\circ}$ N and $60^{\circ} \sim 90^{\circ}$ N, respectively. The climatological means are
 791 for 1980–2016. The colored solid lines denote the average of five reanalyses and the
 792 shaded envelopes show the spread among the five reanalyses.

793

Figure 2. Wintertime surface air temperature differences (K) between 1999-2016 and 1981-1998 in (a) NCEP2, (b) ERA-Interim, (c) JRA-55, (d) MERRA-2, and (e) CFSR. The differences with values exceeding the 90% ($p<0.1$) significance level according to the Student's t -test are crossed.

Figure 3. Wintertime zonally-averaged temperature (K, left panels) and specific humidity (10^{-4}kg/kg , right panels) differences between 1999-2016 and 1981-1998 in (a, b) NCEP2, (c, d) ERA-Interim, (e, f) JRA-55, (g, h) MERRA-2, and (i, j) CFSR. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 4. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged poleward heat transport (K m/s) by total disturbances (left panels), stationary waves (central panels), and transient eddies (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 5. As in Fig. 4 , but for the poleward moisture transport (10^{-4}kg/kg m/s).

Figure 6. As in Fig. 4 , but for the convergence (K/day) of poleward heat transport.

821

822 **Figure 7.** As in Fig. 4 , but for the convergence ($10^{-5} \text{ kg/kg/day}$) of poleward moisture
823 transport.

Figure 8. Wintertime zonally-averaged interannual anomalies of poleward heat (K m/s, upper panels) and moisture (10^{-4} kg/kg m/s, lower panels) transports by total disturbances (left panels), stationary waves (central panels), and transient eddies (right panels), regressed upon a normalized Arctic warming index defined as the surface air temperature anomaly averaged over $75^{\circ}\sim 90^{\circ}\text{N}$ and $0^{\circ}\sim 360^{\circ}$. The zero lines are shown in bold black. The anomalies with values exceeding the 90% ($p<0.1$) significance level according to the Student's t -test are crossed. Note that the CFSR reanalysis dataset is only used here.

Figure 9. As in Fig. 8, but for the convergences of interannual anomalies of poleward heat (upper panels) and moisture (lower panels) transports.

Figure 10. Decadal differences between 1999-2016 and 1981-1998 of the wintertime 500 hPa geopotential height (gpm, left panels) and the amplitude of stationary waves with zonal wavenumber 1~6 (gpm, right panels), with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The contours in left panels are 5100 m and 5180 m for 1999-2016 (black) and 1981-1998 (green), respectively. The bold black lines in right panels indicate the zero lines.

Figure 11. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged poleward heat transport by stationary wave component (K m/s) of zonal wavenumber 1 (left panels), wavenumber 2 (central panels), and wavenumber 3 (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black lines.

Figure 12. As in Fig. 11, but for the poleward moisture transport ($10^{-4} \text{ kg/kg m/s}$).

Figure 13. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged maximum Eady growth rate (1/day) (left panels), meridional potential temperature gradient (10^{-4} K/km) (central panels), and Brunt-Väisälä frequency (10^{-4} 1/s) (right panels) with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 14. Decadal differences between 1999-2016 and 1981-1998 of wintertime zonally-averaged eddy kinetic energy (m^2/s^2) of total transient eddies (left panels), high-frequency eddies with time-scale of 2-10 days (central panels), and low-frequency eddies with time-scale of 10-90 days (right panels), calculated with five atmospheric reanalyses (NCEP2, ERA-I, JRA-55, MERRA-2, and CFSR; from upper to lower panels). The zero lines are shown in bold black. The differences with values exceeding the 90% ($p < 0.1$) significance level according to the Student's t -test are crossed.

Figure 15. As in Fig. 14, but for the poleward heat transport (K m/s).

Figure 16. As in Fig. 14, but for the poleward moisture transport (10^{-4} kg/kg m/s).

Figure 17. A schematic diagram for the impact of the amplified Arctic warming on the high latitude poleward heat and moisture transports by stationary waves and transient eddies and their possible feedbacks.