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The seasonal foot printing mechanism of spring Arctic sea ice in the Bergen climate models

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Abstract The influence of spring Arctic sea ice variability on the Pacific Decadal Oscillation (PDO) like sea surface temperature (SST) variability is established and investigated using an Atmosphere Ocean General Circulation Model (AOGCM) of the Bergen Climate Model version 2 (BCM2). The spring Arctic sea ice variability affects the mid-latitudes and tropics through the propagation of the anomalous Eliassen-Palm (E-P) flux from the polar region to mid- and low-latitudes during boreal spring. The pathway includes anomalous upward wave activity, which propagates to the high troposphere from near the surface of the polar region, turns southward between 500 hPa and 200 hPa and extends downward between 50°N and 70°N, influencing the near surface atmospheric circulation. The alteration of the near surface atmospheric circulation then causes anomalous surface ocean circulation. These circulation changes consequently leads to the SST anomalies in the North Pacific which may persist until the following summer, named seasonal "foot printing" mechanism (SFPM).

Keywords **Arctic sea ice, seasonal foot printing mechanism, North Pacific, sea surface temperature, E-P flux**

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1 Introduction

Arctic sea ice is an important component of climate system. During the past decade, Arctic sea ice has dramatically retreated associated with Arctic amplification[1]. Early studies indicated that the change of Arctic sea ice could potentially influence climate and weather in the northern mid- and high-latitudes[2]. Several studies have indicated that the North Pacific and East Asian summer climate was connected to the status of the spring Arctic sea ice[3]. For instance, a significant correlation (*r*=+0.83) was found between the leading singular value decomposition (SVD) of spring Arctic sea ice concentration (SIC) and summer rainfall over China[4]. A linkage between the spring sea ice in the high latitudes of North Pacific and the East Asian summer monsoon (EASM) rainfall was also investigated using an Atmosphere General Circulation Model (AGCM) and observational data[5]. Vimont et al.[6-7] first discovered that winter time internal atmospheric variability in the mid-latitudes could impart a sea surface temperature (SST) "foot printing" onto the ocean. This anomalous SST could persist until the following summer. This process was named the seasonal "foot printing" mechanism (SFPM). The SFPM provides a framework to investigate the physical mechanism that links the spring sea ice to the following summer climate in the North Pacific. A series spring sea ice perturbation experiments performed

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using both a AGCM and an Atmosphere Ocean General Circulation Model (AOGCM) suggested that the North Pacific sea surface temperature (SST) anomalies linked the spring Arctic sea ice to the EASM rainfall[3], but did not demonstrated how the anomalous spring Arctic sea ice influenced the spring North Pacific SST and its pathway.

The main aim of this paper is to address the pathway of the influence of the spring Arctic sea ice on spring North Pacific SST using the Bergen Climate Model version 2 (BCM2)[8]. The remainder of the paper is organized as follows: A brief introduction of the BCM2 and the experimental design is presented in Section 2. Section 3 demonstrates the SFPM of the spring Arctic sea ice and the pathway of its influence. Discussions and conclusions are presented in Section 4.

2 Models and Experiments

2.1 Model description

BCM2[8] is employed in this study. It has been improved in various aspects compared to the original version of BCM[9], which was one of the contributing models to the 4th report of the Intergovernmental Panel on Climate Change (IPCC) and was widely applied in climate studies[10].

2.2 Experimental design

The numerical technique so-called 'Atmospheric Bridge and Oceanic Tunnel' (ABOT)[11], which has been successfully applied to address the climate interactions between the tropics and the extra-tropics[12], is implemented in the sea ice perturbation experiment. In this study the ABOT region (Figure 1) is defined as the maximum extent of sea ice in a present-day coupled control experiment, in which the greenhouse gas concentration is fixed at the level of A.D. 2 000. Inside the ABOT region, the flux from the ocean to the atmosphere is calculated by the climatological ocean surface status of the present-day coupled control experiment. The model is fully coupled outside the ABOT region[3]. Two numerical experiments are included in this analysis.

(1) In the ABOT-control coupled experiment (AO-CTRL), the spring Arctic SIC and SST are taken from the daily climatology of the present-day coupled experiment in the ABOT region.

(2) In the ABOT-coupled sea ice perturbation experiment (AO-SICE), the setup is similar to AO-CTRL, except for that the projected spring Arctic SIC and SST are taken from the daily climatology of future day coupled experiment, in which the CO_2 concentration is fixed at 997 ppm, and the Arctic becomes open water during July, August and September.

The difference between AO-SICE and AO-CTRL shows the response for a light sea ice case, while the difference between AO-CTRL and AO-SICE shows the response for a heavy sea ice case.

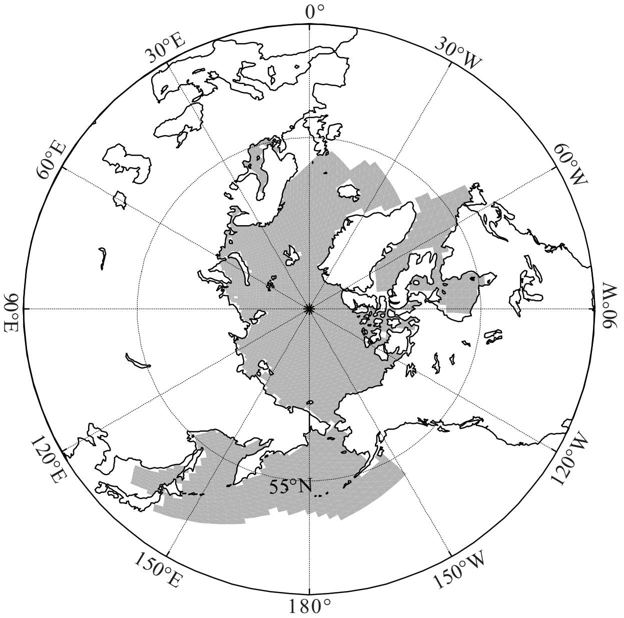

Figure 1 The Atmospheric Bridge and Oceanic Tunnel (ABOT) region (shaded area).

3 SFPM of spring sea ice

The SFPM was originally identified by Vimont et al.[6]. The SFPM can be described as follows. During boreal winter, mid-latitudes atmospheric variability can cause SST "foot printing" on the ocean surface by changing the near surface heat flux and ocean current. The anomalous SST persists into the following spring and summer in subtropics and tropics. Then the anomalous SST can force residual atmospheric circulation[7].

Spring Arctic sea ice anomalies can also cause a "foot printing" on the North Pacific SST in BCM2. In the light ice case, the spatial distribution of the anomalous SST is similar to the cold phase Pacific decadal oscillation (PDO) pattern in mid- and high-latitudes of the North Pacific. An anomalous warm tongue expands from the east coast of Japan. Other parts of mid- and high-latitudes of the North Pacific are dominated by cold SST anomalies (Figure 2). A weak anomalous warm SST is present in the tropic North Pacific. These predominant features of anomalous SST in the North Pacific can persist from spring until summer (not shown). These SST anomalies can act as local thermal forcing, which leads to anomalous atmospheric circulation over the North Pacific. In this way, the signal of the spring sea ice anomalies is preserved until the summer, which impacts the summer climate of the East Asian and the North Pacific regions. The method by which the spring sea ice anomalies can induce the SST anomalies in the North Pacific during boreal spring is explored below.

In an ocean model, the SST is determined by ocean

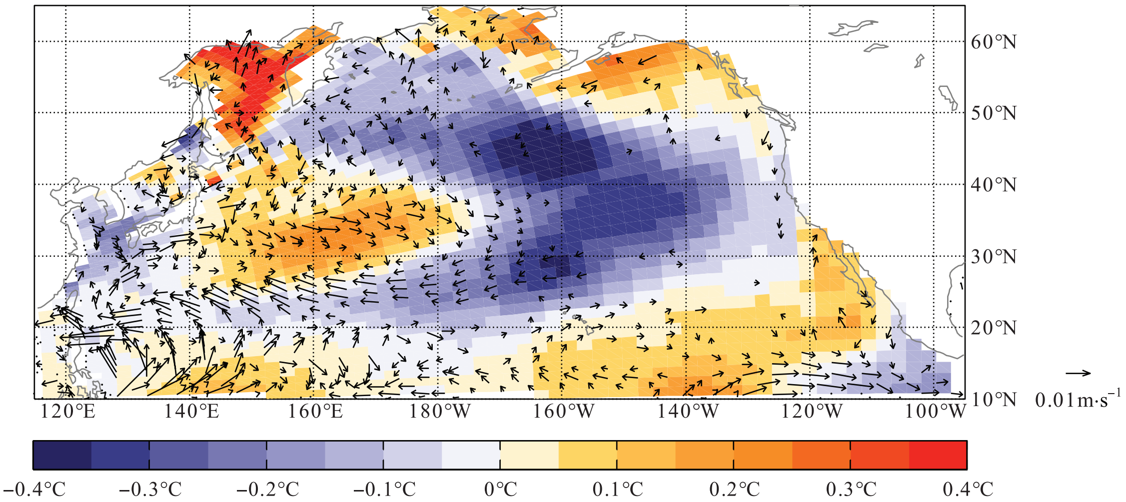

Figure 2 Vectors showing the anomalous ocean current and colors showing the anomalous sea surface temperature (SST) for the light sea ice case during boreal spring.

advection, air-sea heat exchange and mixing. The advection is determined by the velocity of ocean mixed layer. The vectors of the anomalous current in the North Pacific in the light spring sea ice case are shown in Figure 2. The main feature is the anomalous gyre in the mid-latitudes of the western North Pacific. The anomalous gyre intensifies the North Pacific gyre, especially in western part of the North Pacific. It begins off the east coast of the Philippine Islands and flows northeastward past Japan. The path of this anomalous gyre over the western North Pacific is with the same as the Kuroshio current. Because the Kuroshio current transports warm tropical water northward, a strengthened Kuroshio current can induce a warmer SST over the area east of Japan. In the light spring sea ice case, the sensitive experiment also indicates a warmer SST in this area (Figure 2). The anomalous current in other part of mid- and high-latitudes of the North Pacific mainly flows south-eastward and south-westward with the corresponding cold anomalous SST. This pattern of SST anomalies generally resembles a cold phase of a PDO-like pattern. Therefore, the change of the ocean current likely causes the SST anomalies.

The air-sea heat exchange is examined further. Heat loss mainly occurs in the area east of Japan, as shown in Figure 3, which suggests that the mixed layer of ocean becomes warmer (Figure 2) and releases its heat into the atmosphere. This indicates that the warmer SST causes the

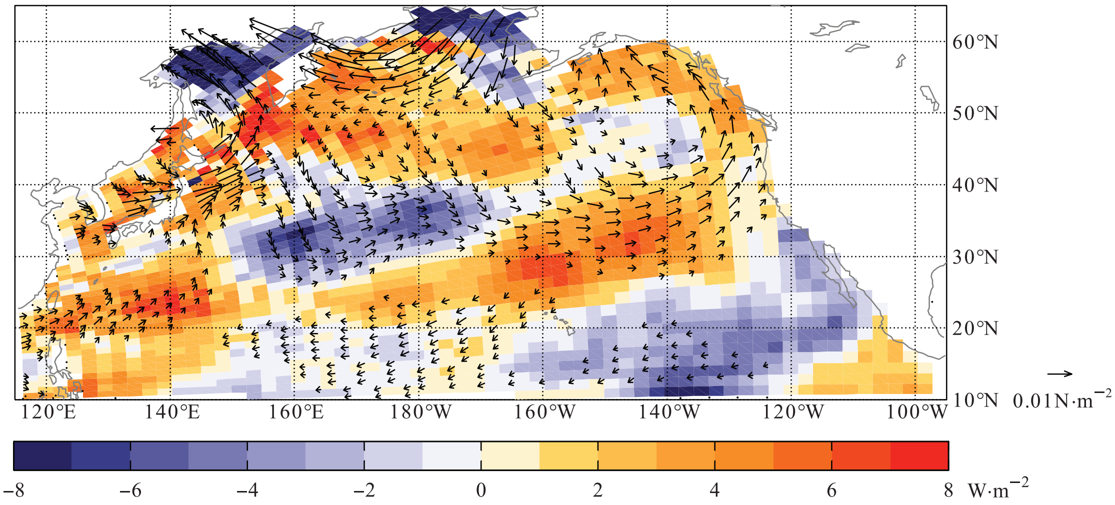

Figure 3 Vectors showing anomalous momentum flux received by the ocean and colors showing the anomalous non-solar heat flux received by the ocean for the light sea ice case during boreal spring.

air-sea heat flux. The heat exchange between the ocean and the atmosphere cannot explain the anomalous warm SST. If only the heat change between the atmosphere and the ocean is considered without any other processes, the SST would be colder when the heat flux was transferred from the ocean to the atmosphere. The rest part of mid- and high-latitudes North Pacific obtains more heat from atmosphere. This also indicates that the anomalous air-sea heat exchange is the result of the SST anomalies, rather than the cause of the SST anomalies. Hence, the change of ocean circulation (including advection and mixing) is the main cause of the SST anomalies in the North Pacific. Note that only the surface ocean current is investigated in this study.

What causes the change in the ocean current? The first candidate is the anomalous momentum flux received by the ocean. The momentum flux anomalies (Figure 3) are indeed consistent with the change in ocean current. An anticyclone-like anomaly is present in the subtropical western North Pacific, and a cyclone-like anomaly is located in the mid- and high-latitudes of the eastern North Pacific. These features are also consistent with the SST anomalies. Therefore, the anomalous ocean current in the North Pacific is a response to the changes of the spring Arctic sea ice. One immediate cause of anomalous ocean current is an anomalous momentum flux between the atmosphere and the ocean. The velocity of ocean current is generally one order of magnitude less than the velocity of the near surface wind, thus, the momentum flux is dominated by near surface atmospheric circulations.

Figure 4 shows the response of the near surface atmospheric circulation to the decreased spring Arctic sea ice. The near surface wind anomalies form an anticyclone over the subtropical North Pacific that starts from the eastern coast of Philippines along the first island chain, and turns eastward along the eastern coast of Japan, along 40°N. The near surface wind divides into two branches at approximately 140°W. One strong branch turns northward, and the other branch turns southward. The strong branch follows the western coast of North American and it turns to the west along the southern coast of Alaska's Aleutian Islands. Another strong anomalous southeast wind flows from the Bering Strait to eastern coast of the Kamchatka Peninsula. It converges with the anomalous southwest airflow above the eastern coast of Japan. Finally it turns eastward. These patterns of anomalous near surface wind are consistent with the anomalous momentum and ocean current in the North Pacific. The sea level pressure field anomalies also agree with the near surface atmospheric circulation anomalies. An anomalous high pressure field centered at 180°W controls the subtropical North Pacific. An anomalous low pressure field controls the extra-subtropical North Pacific.

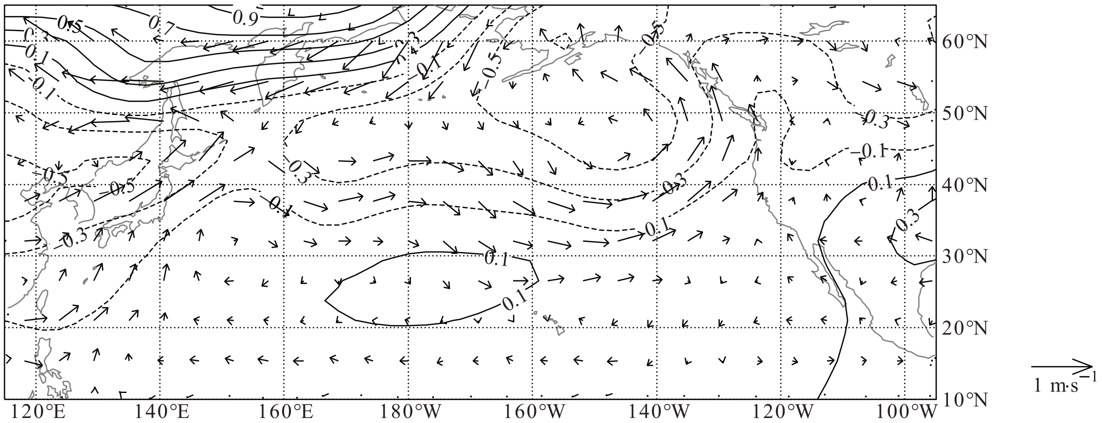

Figure 4 Vectors showing anomalous wind at 850 hPa and contours of anomalous sea level pressure (SLP; units: hPa) for the light sea ice case during boreal spring.

To explore the teleconnection between the spring Arctic sea ice and the near surface atmospheric circulation over the North Pacific, we performed an Eliassen-Palm (E-P) flux analysis. The E-P flux has been extensively used in analyses of the propagation of wave activity since 1967[13]. The E-P flux is a physical quantity that relates momentum flux and heat flux, thus, it can indicate the transfer of energy. It can also indicate the propagation direction of waves. An important application of the E-P flux is to investigate the acceleration and deceleration of basic flow.

In this study the flux *F*s takes the three-dimension form as follows[14].

$$Fs = p\cos\varphi \times \begin{pmatrix} v'^2 - \dfrac{1}{2\omega a \sin 2\varphi}\dfrac{\partial v'\Phi'}{\partial\lambda} \\ -u'v' + \dfrac{1}{2\omega a \sin 2\varphi}\dfrac{\partial u'\Phi'}{\partial\lambda} \\ \dfrac{2\omega a \sin\varphi}{\dfrac{\partial\hat{T}}{\partial z} + \dfrac{0.286\hat{T}}{H}}\left[v'T' - \dfrac{1}{2\omega a \sin 2\varphi}\dfrac{\partial T'\Phi'}{\partial\lambda}\right] \end{pmatrix} \quad (1)$$

$$p = \text{pressure}/1000 \quad (2)$$

$$z = -H \ln p \quad (3)$$

where ω is the Earth's rotation rate, a is the Earth's radius, Φ is the geopotential, H is a constant scale height, (φ, λ) are the latitude and longitude respectively, and a caret indicates an average area.

Figure 5 shows the zonal average spring climatological E-P flux from 120°E to 100°W. At approximately 55°N in the North Pacific, the northern portion of the E-P flux radiating slightly northward and upward into the stratosphere, and a weak branch turns downward in the polar region. These results from BCM2 are consistent with observations (refer to Figure 6b of Plumb et al.[14]). The features of stationary wave flux anomalies in the spring sea ice perturbation simulation are demonstrated in Figure 6 for the heavy sea ice case. The main feature is the anti-clockwise vortex flow at 45°N to 90°N in the pressure levels from 1 000 hPa to 200 hPa. Anomalous wave flux propagated near the surface of the polar region, radiating upward straight. It then propagates southward between approximately 500 hPa and 200 hPa, and turns downward between approximately 50°N to 70°N. This feature of the anomalous wave flux illustrates that high latitudes sea ice perturbations can induce an atmospheric bridge that connects the spring sea ice and the surface atmospheric circulation in the North Pacific. An anomalous E-P flux generally accompanies acceleration and deceleration of the basic flow, so the near surface wind and pressure (Figure 4) will respond to the E-P flux anomalies. In the spring sea ice sensitive experiments, we only perturb the spring sea ice, thus the spring sea ice perturbation forces all subsequent circulation. The influence of the sea ice begins near the surface of polar region, moves upward to mid- and high-levels of troposphere, and then turns downward at mid- and low-latitudes to near surface of the North Pacific. Finally, a "foot printing" is put on the North Pacific surface.

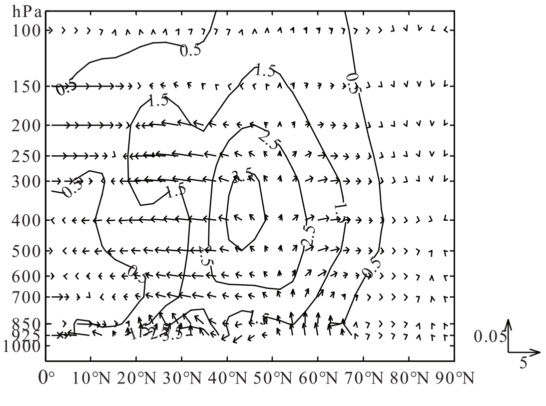

Figure 5 Latitude-height projections of the zonal average of the spring climatological Fs (units: $\mathrm{m^2 \cdot s^{-2}}$) for 120°E−100°W.

4 Discussions and conclusions

An early study[3] suggested that the spring Arctic sea ice could influence the EASM rainfall through the SST anomalies in the North Pacific. However, the pathway of this influence has not been demonstrated. Another study[15] suggested that the SST of the North Pacific could retain the signal of the spring Arctic Oscillation and affect the EASM rainfall. Arctic warming could likely cause more persistent extreme weather patterns at mid-latitudes through the slowing of planetary wave propagation due to the reduced meridional temperature gradient[16], although this is still under debate[17]. In this paper, we use the BCM2 to perform the sea ice perturbation experiments to demonstrate the spring sea ice SFPM and a possible linkage between the spring Arctic sea ice and the SST anomalies in the North Pacific. The connection starts near the surface of polar region, propagates upward to mid- and high-levels of the troposphere, and then turns downward and southward to mid- and low-latitudes of the North Pacific. It finally put "foot printing" on the surface of North Pacific.

This is a preliminary work, and we only state that spring sea ice anomalies can cause a "foot printing" mechanism in our coupled climate model with the ABOT technique. The results from the sensitive experiment indicate that "Atmospheric Bridge" is one possible connection between the spring Arctic sea ice and the North Pacific SST. These results form a foundation for further studies of the multi-season teleconnection between the spring sea ice and summer climate. The next step is to investigate how the anomalous SST can persist to summer and how the anomalous SST influence the summer climate. In another study, we carefully discussed this lagged response of the summer climate and precipitation in China and the western North Pacific using both observational data and numerical simulations[3].

In our experiments, AO-SICE represents the low sea ice extent conditions during spring, and AO-CTRL uses the present day climatology. For the sake of simplicity, the difference between the two experiments (AO-SICE minus AO-CTRL) shows the response for the light sea ice case. Accordingly AO-CTRL minus AO-SICE represents the response for the heavy sea ice case. Thus the difference between these two cases is negative. The pattern of anomalous E-P flux for the heavy sea ice case is easier to understand and explain, so we only demonstrate the anomalous E-P flux in the heavy ice case (Figure 6).

In this study, we investigated the E-P flux anomalies and discovered a possible pathway for the propagation of the anomalous E-P flux from the polar region to the mid-latitudes of the North Pacific. This pathway indicates that the spring sea ice perturbation induces anomalous energy transport from the polar region to the mid-latitudes of the North Pacific via an "Atmospheric Bridge".

We only investigated this possible "Atmospheric Bridge" between the spring sea ice and the mid- and low-latitudes of the North Pacific. The "Oceanic Tunnel" may also play a role in this teleconnection, but we have not investigated it. In future work, we will explore whether the "Oceanic Tunnel" may also contribute to the linkage between the spring sea ice and the North Pacific SST.

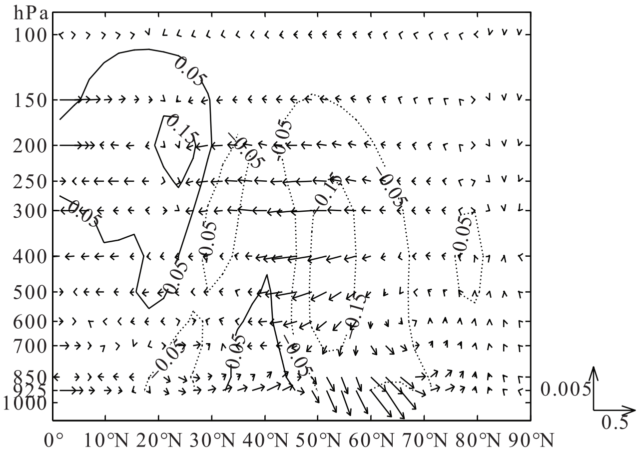

Figure 6 Latitude-height projections of the zonal average of the spring *F*s (units: $m^2 \cdot s^{-2}$) for 120°E−100°W for the heavy spring sea ice case.

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References

1 Bekryaev R V, Polyakov I V, Alexeev V A. Role of polar amplification in long-term surface air temperature variations and modern Arctic warming. Journal of Climate, 2010, 23(14): 3888-3906.

2 Vihma T. Effects of Arctic sea ice decline on weather and climate: A review. Surveys in Geophysics, 2014, doi: 10.1007/s10712-10014-19284-10710.

3 Guo D, Gao Y, Bethke I, et al. Mechanism on how the spring Arctic sea ice impacts the East Asian summer monsoon. Theoretical and Applied Climatology, 2014, 115(1-2): 107-119.

4 Wu B, Zhang R, Wang B, et al. On the association between spring Arctic sea ice concentration and Chinese summer rainfall. Geophysical Research Letters, 2009, 36(9): L09501.

5 Zhao P, Zhang X, Zhou X, et al. The sea ice extent anomalies in the north pacific and its impact on the east Asian summer monsoon rainfall. Journal of Climate, 2004, 17(17): 3434-3447.

6 Vimont D J, Battisti D S, Hirst A C. Footprinting: A seasonal connection between the tropics and mid-latitudes. Geophysical Research Letters, 2001, 28(20): 3923-3926.

7 Vimont D J, Wallace J M, Battisti D S. The seasonal footprinting mechanism in the pacific: Implications for ENSO. Journal of Climate, 2003, 16(16): 2668-2675.

8 Otterå O H, Bentsen M, Bethke I, et al. Simulated pre-industrial climate in Bergen Climate Model (version 2): model description and large-scale circulation features. Geoscientific Model Development, 2009, 2(1): 507-549.

9 Furevik T, Bentsen M, Drange H, et al. Description and evaluation of the Bergen Climate Model: ARPEGE coupled with MICOM. Climate Dynamics, 2003, 21(1): 27-51.

10 Bentsen M, Drange H, Furevik T, et al. Simulated variability of the Atlantic meridional overturning circulation. Climate Dynamics, 2004, 22(6-7): 701-720.

11 Yang H, Liu Z. Tropical–extratropical climate interaction as revealed in idealized coupled climate model experiments. Climate Dynamics, 2005, 24(7-8): 863-879.

12 Su J, Wang H, Yang H, et al. Role of the atmospheric and oceanic circulation in the tropical pacific SST changes. Journal of Climate, 2008, 21(10): 2019-2034.

13 Andrews D G, McIntyre M E. Planetary waves in horizontal and vertical shear: the generalized eliassen-palm relation and the mean zonal acceleration. Journal of the Atmospheric Sciences, 1976, 33(11): 2031-2048.

14 Plumb R A. On the three-dimensional propagation of stationary waves. Journal of the Atmospheric Sciences, 1985, 42(3): 217-229.

15 Gong D, Yang J, Kim S, et al. Spring Arctic Oscillation—East Asian summer monsoon connection through circulation changes over the western North Pacific. Climate Dynamics, 2011, 37(11-12): 2199-2216.

16 Francis J A, Vavrus S J. Evidence linking Arctic amplification to extreme weather in mid-latitudes. Geophysical Research Letters, 2012, 39(6): L06801.

17 Barnes E A. Revisiting the evidence linking Arctic amplification to extreme weather in midlatitudes. Geophysical Research Letters, 2013, 40(17): 4734-4739.