Impact of interannual variations of spring sea ice in the Barents Sea on East Asian rainfall in June

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ABSTRACT
This study reveals a significant relationship, on the interannual timescale, between a dipole mode, the second leading mode, of spring sea-ice anomalies in the Barents Sea and the following-summer rainfall in East Asia. Related to the dipole mode, with the heavier sea ice in the north and lighter sea ice in the southeast Barents Sea in spring, the East Asian summer subtropical rainy belt tends to move northward. The significant relationship is established through a wave train over northern Eurasia in the lower troposphere in June. The wave train enhances the northern East Asian low, which induces more rainfall to the north of the East Asian subtropical rainy belt and then attracts the subtropical rainy belt to move northward. This study suggests that the dipole mode of spring sea-ice anomalies in the Barents Sea may be a good precursor for the prediction of East Asian summer rainfall.

1. Introduction
The Barents Sea is a marginal sea of the Arctic Ocean, where the frozen Arctic interfaces with open water of the North Atlantic. The advance and retreat of the sea-ice edge in the Barents Sea causes strong year-to-year variability in this region. Many earlier studies have highlighted the impact of winter sea-ice loss over this region on midlatitude circulation and climate over Eurasia (Deser, Tomas, and Peng 2007; Gao and Wu 1998; Han and Li 2013; Inoue, Hori, and Takaya 2012; Kug et al. 2015; Li and Wang 2012; Liptak and Strong 2013; Mori et al. 2014; Ruggieri et al. 2017; Screen 2017; Sorokina et al. 2015; Wu, Huang, and Gao 2001; Wu et al. 2013). Mori et al. (2014), for example, revealed a robust winter surface air cooling in midlatitude Asia in response to a lighter sea-ice cover in the Barents Sea. In addition, reduced winter sea ice in the Barents Sea tends to enhance the Siberian high (Wu, Su, and Zhang 2011) and cause a cold surge in East Asia (Song and Wu 2017; Takaya and Nakamura 2005). Wu et al. (2016) also revealed a significant relationship between winter Arctic sea ice in the Barents Sea and East Asian spring precipitation. Similarly, in spring, sea ice still covers the Barents Sea with strong interannual variability (Figure 1; Wang and Yang 2002; Wu, Gao, and Huang 2000). Several studies have pointed out the possible relationship between spring sea ice in the Barents Sea and East Asian summer rainfall (Li and Zeng 2008; Wang and Guo 2004; Wu, Zhang, and Wang 2009; Zheng and Wang 1996). Wang and Guo (2004) noticed an anomalous early-summer rainfall response in eastern China to spring sea-ice change in the Barents Sea. The spring sea-ice anomaly in the Barents Sea has been used as a precursory signal for the statistical prediction of East Asian summer rainfall (Li and Zeng 2008). However, most of these studies used raw data and focused mainly on the influence of the decreasing trend in sea-ice extent in the Barents Sea since 1979 (Wang and Guo 2004) or the decadal changes around 1978 and 1992 (Wu, Zhang, and Wang 2009). Whether there is a significant relationship, on the interannually timescale, between spring sea ice in the Barents Sea and East Asian summer climate is unclear. In this study, we try to answer the following questions: What are the main
To focus on interannual variations, trend and decadal signals with periods beyond eight years are excluded using a low-pass filter based on Fourier harmonics analysis. The data used in this study therefore refer to their interannual components unless otherwise stated. Spring is defined as the mean of March, April, and May; and summer as the mean of June, July, and August. The Student’s $t$-test is used to test the significance of the correlation coefficients and regressions.

3. Results

In this section, we first examine the dominant modes of the interannual variability of spring sea ice in the Barents Sea (Section 3.1), and then investigate their possible impacts on East Asian summer rainfall (Section 3.2) and related circulation (Section 3.3).

Figure 1. (a) Climatology, (b) interannual standard deviation, and the (c) first and (d) second EOF modes of spring sea-ice concentration in the Barents Sea during the period 1979–2015. Notes: The explainable variances by the first and second EOF mode are shown in the brackets of (c) and (d), respectively. (e) Principal components corresponding to the first (PC1, black line) and the second (PC2, bar) EOF modes.

features of the interannual variability of spring sea ice in the Barents Sea? And what is its possible impact on East Asian summer rainfall?

2. Data and method

The monthly data used in this study include: (1) sea-ice concentration data from HadISST, version 1.1, with a resolution of 1° × 1° (Rayner et al. 2003); (2) atmospheric circulation data from ERA-Interim (Dee et al. 2011); and (3) CMAP data on 2.5° × 2.5° global grids (Xie and Arkin 1997). The data in their common period of 1979–2015 are employed in this study. In addition, we used the atmospheric circulation data from the NCEP–NCAR reanalysis data-set (Kalnay et al. 1996) and obtained similar results to those using ERA-Interim. For brevity, only the results based on ERA-Interim are presented here.

To focus on interannual variations, trend and decadal signals with periods beyond eight years are excluded using a low-pass filter based on Fourier harmonics analysis. The data used in this study therefore refer to their interannual components unless otherwise stated. Spring is defined as the mean of March, April, and May; and summer as the mean of June, July, and August. The Student’s $t$-test is used to test the significance of the correlation coefficients and regressions.
3.1. Dominant modes of interannual variability of spring sea-ice concentration in the Barents Sea

To investigate the interannual variability of spring sea ice, Figure 1(b) shows interannual standard deviation of the spring sea-ice concentration for 1979–2015. Large interannual variability is shown in the eastern and northern Barents Sea (Figure 1(b)), where the climatological sea-ice concentration is relatively low (Figure 1(a)). The interannual variations of spring sea-ice concentration are dominated by two major modes, based on the empirical orthogonal function (EOF) analysis. The first mode shows a coherent decline in sea-ice concentration in the Barents Sea, with its center along the eastern coast (Figure 1(c)), which is referred to here as the ‘basin mode.’ The basin mode of sea ice in the Barents Sea has also been identified in the first EOF mode of spring sea ice in the whole Arctic region by Wang and Yang (2002). The second mode exhibits a dipole pattern, with out-of-phase change between the southeastern and northern Barents Sea (Figure 1(d)). The basin mode and dipole mode explain about 39% and 18% of the total interannual variance, respectively, and are significantly separable from the third one, which explains about 8% of the total variance, based on the criterion of North et al. (1982). Both modes exhibit strong interannual variations (Figure 1(e)).

3.2. Impact of the dipole mode of spring sea ice on East Asian summer rainfall

Section 3.1, above, identifies two major modes, i.e. the basin mode and dipole mode, of interannual variations of spring sea-ice concentration in the Barents Sea. In this section, their possible relationship to East Asian summer rainfall is investigated.

Figure 2 shows the summer rainfall anomalies over East Asia in response to the basin mode (Figure 2(a)) and dipole mode (Figure 2(b)). Related to the basin mode, there is no significant large-scale rainfall signal over East Asia in summer (Figure 2(a)). However, strong rainfall anomalies are apparent in East Asia in relation to the dipole mode (Figure 2(b)). Associated with the lighter sea ice in the southeastern Barents Sea and heavier sea ice in the north, summer rainfall increases in the Huai River valley, South Korea, and west Japan, to the north of the climatological subtropical rainy belt, and decreases in southern China and Taiwan, and the subtropical western North Pacific, to the south of the climatological subtropical rainy belt. Consequently, the subtropical rainy belt tends to shift northward. To quantify this relationship, we depict the northward shift of the East Asian subtropical rainy belt by the difference in summer rainfall averaged over the northern region (30°–40°N, 115°E–140°E) and southern region (20°–30°N, 115°–140°E). The correlation coefficient between the northward shift of the subtropical rainy belt and the dipole mode of spring sea ice is 0.56, significant at the 99% confidence level.

Figure 2. Regressed anomalies of summer (June–July–August, JJA) rainfall in East Asia against the (a) PC1 and (b) PC2. (c) As in (b) but for regressed June rainfall anomalies. Shading depicts statistically significant rainfall anomalies at the 95% confidence level.

Notes: The two boxes represent the northern and southern flanks of the East Asian subtropical rainy belt (dotted), where daily precipitation exceeds 6 mm d⁻¹ (b) JJA and (c) June.
We further analyze the sub-seasonal change in East Asian summer rainfall in response to the dipole mode of spring sea ice in the Barents Sea. Significant rainfall responses are obtained in June (early summer) (Figure 2(c)), with a similar pattern to those in summer (Figure 2(b)), while no significant rainfall anomaly is found in July and August (figures not shown). The correlation coefficient between the dipole mode of spring sea ice and the northward shift of the subtropical rainy belt in June is 0.52, significant at the 99% confidence level; and 0.25 in July and 0.26 in August, non-significant at the 90% confidence level.

In addition, previous studies have reported significant responses of East Asian summer rainfall to an El Niño event in the preceding winter (e.g. Lin and Lu 2009; Wu et al. 2009) and the Arctic Oscillation (AO) in the preceding winter and spring (e.g. Gong et al. 2011; He et al. 2017; Qiao et al. 2017). To exclude the possible impact of ENSO and AO, we further calculate the partial correlation coefficient between the northward shift of the subtropical rainy belt in June and the dipole mode of spring sea ice. The significant relationship remains stable, with partial correlation coefficients of 0.54, 0.52, and 0.49, after removing the effects of winter and spring AO index and winter Niño3.4 sea surface temperature (SST) index, respectively, highlighting the impact of spring sea ice in the Barents Sea on East Asian early-summer rainfall. The Niño3.4 SST index and AO index used here are obtained from the CPC website: http://www.cpc.ncep.noaa.gov/.

In short, the dipole mode of spring sea ice in the Barents Sea plays a crucial role in East Asian rainfall in the following June, but not in July and August. In contrast, the summer rainfall response in East Asia is weak in response to the basin mode of spring sea ice in the Barents Sea. In the next section, the possible physical processes linking the spring sea-ice dipole mode and East Asian summer rainfall is explored, with a focus on early summer.

### 3.3. Circulation anomalies linking the dipole mode of spring sea ice in the Barents Sea and East Asian early-summer rainfall

Figure 3 shows the atmospheric circulation responses in June to the dipole mode of spring sea ice in the Barents Sea. In the mid troposphere, there is a wave train in mid-to-high latitudes of the Eurasian continent (Figure 3(a)). This wave train can be seen more clearly in the lower troposphere in the regressed anomalies of geopotential height at 850 hPa (Figure 3(b)) and sea level pressure (Figure 3(c)). A significant, positive anomaly is observed over northern Siberia and a downstream negative anomaly over northern East Asia (Figure 3(b)). The negative anomaly then enhances the climatological northern East Asian low (NEAL) (Du, Lin, and Lu 2016; Lin and Wang 2016). To illustrate the three-dimensional structure of the wave train, a vertical section of the geopotential height anomalies along the red line linking the two centers is drawn (Figure 3(d)). The out-of-phase change in northern Siberia and northern East Asia is clearly identifiable, with significant signals confined to the lower troposphere below 700 hPa.

Lin and Wang (2016) highlighted the important role of NEAL in East Asian summer rainfall. An intensified NEAL not only increases the local rainfall, but also tends to shift the East Asian subtropical rainy belt northward, with a similar pattern related to the dipole mode of spring sea ice in the Barents Sea (Figure 2(b)). As shown in Figure 3(b), the dipole mode of spring sea ice is related to an enhanced NEAL, suggesting a bridging role played by NEAL in linking the spring sea ice in the Barents Sea and summer rainfall in...
East Asia. To confirm this hypothesis, we regress the June rainfall and horizontal wind vectors at 850 hPa against the dipole mode of spring sea ice in the Barents Sea (Figure 4(a)), the northward shift of the East Asian subtropical rainy belt in June (Figure 4(b)), and the June NEAL’s intensity (Figure 4(c)), defined as the geopotential height at 850 hPa, with a reversed sign, averaged over the region (40°–60°N, 110°–140°E), similar to Lin and Wang (2016). The reversed sign is added to the NEAL’s intensity so that a positive index means a stronger NEAL and vice versa.

Related to the dipole mode of spring sea ice in the Barents Sea, rainfall increases to the north of 30°N in June, which is attributable to a cyclonic anomaly over northern East Asia (Figure 4(a)) corresponding to an enhanced NEAL (Figure 3(b)). The positive vorticity in the lower troposphere may enhance ascending motion to the north of the climatological East Asian rainy belt (Figure 2(c)) through Ekman pumping (Lin and Wang 2016). In addition, a stronger NEAL can also suppress rainfall to the south of 30°N through shifting the East Asian subtropical rainy belt northward (Figure 4(c); Lin and Wang 2016), which can also be inferred from the cyclonic anomaly over northern East Asia associated with the northward shift of the subtropical rainy belt (Figure 4(b)). Figure 4(b) also shows a significant anticyclonic anomaly in the subtropical western North Pacific, which is probably related to reduced rainfall to the south of 30°N accompanying the northward shift of the subtropical rainy belt (Lin, Su, and Lu 2016).

4. Summary and discussion

This study investigates the main features of spring sea ice in the Barents Sea on the interannual timescale. Two major modes are identified: the first, the basin mode, has coherent variations over the whole Barents Sea; and the second, the dipole mode, corresponds to out-of-phase change between the southwestern and northern Barents Sea. The two modes explain 39% and 18% of the total interannual variance, respectively.

Furthermore, the impacts of the two modes on following-summer rainfall in East Asia are investigated. Related to the dipole mode, with heavier spring sea ice in the northern Barents Sea and lighter sea ice in the southwest, the East Asian subtropical rainy belt tends to shift northward in the following summer. The significant summer rainfall response mainly occurs in early summer (June) through a wave train in the lower troposphere over the northern Eurasian continent, which enhances the NEAL. The enhanced NEAL increases the rainfall to the north of the East Asian subtropical rainy belt through Ekman pumping, leading to the northward shift of the subtropical rainy belt. Our results show that there is no significant signal in East Asian rainfall in July and August related to the dipole mode of spring sea ice and in summer related to the basin mode.

Figure 4. Regressed anomalies of rainfall (contours) and horizontal winds at 850 hPa (vectors) in June upon the (a) PC2, (b) meridional location index (MLI) of the East Asian subtropical rainy belt, which is defined as the difference in June rainfall averaged over the regions (30°–40°N, 110°–145°E) and (20°–30°N, 110°–145°E) in Figure 2(c), and (c) intensity of the northern East Asian low (NEAL), calculated as the normalized geopotential height at 850 hPa in June, with a reversed sign, averaged over the region (40°–60°N, 110°–140°E), similar to Lin and Wang (2016). Notes: Shading depicts statistically significant rainfall anomalies at the 90% confidence level. The scale of winds is plotted at the bottom, and wind anomalies of either zonal or meridional wind significant at the 90% confidence level are highlighted by the thick vectors.
The present study highlights the role of a wave train in the lower troposphere over northern Eurasia in June in linking spring sea ice and following-summer rainfall in East Asia. The formation of the wave train is likely induced by a persistent positive sea-ice anomaly in the northern Barents Sea in June (figure not shown). As proposed by He et al. (2018), the persistent positive sea-ice anomaly in June may absorb heat from the atmosphere through surface turbulence heat flux (sensible plus latent heat flux) and induce anomalous descent over the Barents Sea, triggering a southeastward-propagating Rossby wave train. However, more evidence based on observational analysis and model simulations is needed.

Li and Zeng (2008) suggested that spring sea ice in the Barents Sea (the basin mode) can be used as a precursory signal for the statistical prediction of East Asian summer rainfall. The statistical relationship has also been used in real seasonal forecasts of summer rainfall in China by the National Climate Center (e.g. Chen et al. 2016; Ke, Wang, and Gong 2014). This study reveals that a significant relationship, on the interannual timescale, exists between East Asian summer rainfall and the dipole mode, rather than the basin mode, of spring sea ice in the Barents Sea. The correlation coefficient between the dipole mode and the meridional location of the East Asian subtropical rainy belt is 0.56, which indicates an explainable variance more than 30% of the latter by the former. The result suggests that the dipole mode of spring sea ice in the Barents Sea would be a better precursor of East Asian summer rainfall, especially for the meridional location of the subtropical rainy belt.

In this study we focus on the impact of spring sea ice in the Barents Sea on East Asian rainfall in June. This does not, however, mean that sea-ice change over the other Arctic seas is unimportant for East Asian summer climate. Indeed, Zhao et al. (2004) revealed a significant impact of the spring sea-ice extent anomaly in the North Pacific on East Asian summer monsoon rainfall. A decline in sea-ice extent over the Bering Sea and Sea of Okhotsk may lead to enhanced summer monsoon rainfall in southeastern China. A comprehensive understanding of the impact of Arctic sea ice on East Asian climate may include all impacts of regional sea-ice changes in the whole Arctic Ocean.

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No potential conflict of interest was reported by the author.

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