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• Original Paper •

Precursor Role of Winter Sea-Ice in the Labrador Sea for Following-Spring Precipitation over Southeastern North America and Western Europe

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ABSTRACT

The role of winter sea-ice in the Labrador Sea as a precursor for precipitation anomalies over southeastern North America and Western Europe in the following spring is investigated. In general terms, as the sea ice increases, the precipitation also increases. In more detail, however, analyses indicate that both the winter sea-ice and the sea surface temperature (SST) anomalies related to increases in winter sea-ice in the Labrador Sea can persist into the following spring. These features play a forcing role in the spring atmosphere, which may be the physical mechanism behind the observational relationship between the winter sea-ice and spring precipitation anomalies. The oceanic forcings in spring include Arctic sea-ice anomalies and SST anomalies in the tropical Pacific and high-latitude North Atlantic. Multi-model Coupled Model Intercomparison Project Phase 5 and Atmospheric Model Intercomparison Project simulation results show that the atmospheric circulation response to the combination of sea-ice and SST is similar to that observed, which suggests that the oceanic forcings are indeed the physical reason for the enhanced spring precipitation. Sensitivity experiments conducted using an atmospheric general circulation model indicate that the increases in precipitation over southeastern North America are mainly attributable to the effect of the SST anomalies, while the increases over Western Europe are mainly due to the sea-ice anomalies. Although model simulations reveal that the SST anomalies play the primary role in the precipitation anomalies over southeastern North America, the observational statistical analyses indicate that the area of sea-ice in the Labrador Sea seems to be the precursor that best predicts the spring precipitation anomaly.

Key words: winter Labrador sea ice, spring precipitation, air-sea interaction

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1. Introduction

Sea ice is a critical component of Earth's climate system, and its variation has been found to be significantly correlated with local and remote climate anomalies (Huang et al., 1992; Alexander et al., 2004; Magnusdottir et al., 2004; Deser et al., 2004; Conil and Li, 2005; Honda et al., 2009; Liu et al., 2012; Li and Wang, 2013; Guo et al., 2014; Mori et al., 2014). Owing to the large heat capacity of the ocean, sea ice can often persist for several months (e.g., Honda et al., 2009; Strong and Magnusdottir, 2011; Wu et al., 2013) and thus can be considered as an indicator of the subsequent climate. Many studies have investigated the role of sea ice as an indicator of winter climate (e.g. Honda et al., 2009; Wu and Zhang, 2010; Wu et al., 2011; Liu et al., 2012; Mori et al., 2014); however, there have been few studies on the role of sea ice as a precursor for spring climate.

Strong sea-ice variability exists in winter in the North Atlantic sector of the Arctic (Fig. 1), and the role of winter sea-ice in the Barents Sea as a precursor for spring climate has been investigated by Strong and Magnusdottir (2011). Meanwhile, in another region—the Labrador Sea—large quantities of sea–air heat exchange can be found (Kvamstø et al., 2004) and this may also influence spring climate. Although the spring atmospheric circulation related to the winter sea-ice anomaly in the Labrador Sea has been studied by Wu et al. (2013), the atmospheric circulation in their study did not show classical modes of large-scale circulation. Therefore, the related spring precipitation and temperature anomalies remain poorly understood and need to be further investigated. Moreover, an observational linkage between winter

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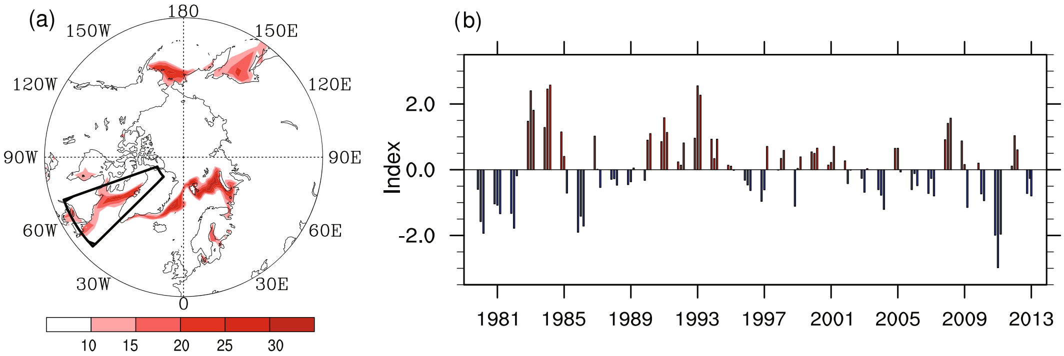

Fig. 1. The (a) winter mean of the monthly standard deviation of sea-ice concentration (%) and (b) normalized sea-ice area in the Labrador Sea [black box in (a)] in December, January, and February.

sea-ice in the Labrador Sea and spring climate may be impacted by other external drivers of the atmosphere, such as the Atlantic SST tripole anomaly, which was mentioned but not investigated in Wu et al. (2013). In the present study, we use model simulations to quantitatively investigate whether the relationship obtained from observations is contributed by both the sea-ice and SST anomalies, and examine their respective roles.

The remainder of this paper is organized as follows: Following this introduction, in section 2 we describe the observational datasets, methodologies and models used. Section 3 investigates, from observational data, the nature of the spring precipitation anomalies that follow winter sea-ice anomalies in the Labrador Sea. In section 4, the possible physical mechanism responsible for their connection is investigated, and then the findings are verified in section 5 via atmospheric general circulation model results. A summary and discussion are provided in section 6.

2. Datasets and methods

This study uses monthly sea-ice concentration (SIC) and SST datasets from the Hadley Center, Meteorological Office, United Kingdom (Rayner et al., 2003), as well as an additional SIC dataset from the National Snow and Ice Data Center (NSIDC; Cavalieri et al., 1996). The two precipitation datasets used are from the Climate Prediction Center Merged Analysis of Precipitation (CMAP; Xie and Arkin, 1997) and the Global Precipitation Climatology Center (GPCC; Schneider et al., 2011). The monthly surface air temperature (SAT), sea level pressure (SLP), 500-hPa geopotential height (Z500), and surface heat flux (sensible and latent heat flux, shortwave, and longwave radiation flux), as well as daily Z500 datasets, are from the European Center for Medium-Range Weather Forecasts interim reanalysis (Dee et al., 2011). We select the period from 1979 to 2013 for our analyses, because of the better quality of sea-ice data since 1979. Since the present study focuses on the interannual timescale, we apply a detrending process prior to performing all the analyses. In this paper, "winter" refers to the months of December through February and "spring" is the months from March through May. The Niño3.4 index is defined as the monthly average SST anomaly in the Niño3.4 region (5°S–5°N, 170°–120°W), which is used to represent the El Niño–Southern Oscillation (ENSO).

The atmospheric general circulation model (AGCM) used in this study is ECHAM5 (Roeckner et al., 2003; 2006). The horizontal and vertical resolution used here are the same as in Han et al. (2016b), and we conduct four sets of experiments:

(1) In the control experiment (CTRL_Exp), the AGCM is driven by the mean monthly sea-ice and SST climatology for the period 1979–2010.

(2) In the sea-ice and SST experiment (SST_SIC_Exp), the AGCM is driven by perturbed sea-ice and SST. The perturbed sea-ice is the sum of the monthly sea-ice climatology and sea-ice anomalies in the Arctic, which is double the regression against winter sea-ice area in the Labrador Sea. The perturbed SST is the sum of the monthly SST climatology and SST anomalies in the tropical Pacific and high-latitude North Atlantic, which is double the regression against LabSIA.

(3) In the sea-ice experiment (SIC_Exp), the procedure is the same as that for SST_SIC_Exp, but only the sea ice is perturbed.

(4) In the SST experiment (SST_Exp), the procedure is again the same as for SST_SIC_Exp, but only the SST is perturbed.

There are 80 ensemble members with different initial conditions in each experiment. The monthly outputs from March to May are used for our analyses. The anomalies used in the experiments are doubled to obtain significant atmospheric responses. The stronger the oceanic forcing, the more significant the response will be. Oceanic forcing doubling has also been used in many previous studies (e.g. Magnusdottir et al., 2004; Han et al., 2016b). Moreover, winters with two-standard-deviation sea-ice anomalies also exist in the observations (Fig. 1b).

3. Precursor role of winter sea-ice for spring precipitation

To analyze the precursor role of winter sea-ice anomalies in the Labrador Sea, an index (Fig. 1b) is defined as the sea-ice area in the domain (50°–80°N, 45°–75°W)—black box in Fig. 1a, and referred to as Lab-SIA. The region selected here differs somewhat from that in Wu et al. (2013), and the correlation coefficient between the indexes defined in these two different regions is 0.88. The lag autocorrelation of the index shows that it has a long timescale, with a coefficient of 0.48 at a lag of three months (i.e., spring versus winter). Figure S1 shows the correlation coefficients between spring SAT anomalies and Lab-SIA in the previous winter. There are no significant anomalies over land. Moreover, the correlation coefficients are very small, with values between −0.1 and 0.1. Figures 2a and b show the correlation between the CMAP precipitation in spring and the winter Lab-SIA index defined by the Hadley and NSIDC sea-ice datasets. As winter sea-ice increases in the Labrador Sea, there are significant increases in precipitation over southeastern North America and Western Europe. Given the insignificant SAT anomaly, we focus on the spring precipitation anomalies and the possible mechanism behind this linkage.

When the Lab-SIA increases by one standard deviation, the precipitation anomaly reaches a maximum of about 14 mm every month in southeastern North America (Fig. 3a), which is about 27% of one standard deviation of precipitation (Fig. 3c), and a maximum of 16 mm every month in Western Europe (Fig. 3a), which is about 32% of one standard deviation of precipitation (Fig. 3c). The precipitation anomalies explained by Lab-SIA do not seem to be very large. However, there are several years when the Lab-SIA is about 2 (or −2) times the standard deviation (Fig. 1b), and the precipitation anomalies explained by the Lab-SIA can exceed half of one standard deviation. Similar results are obtained using the GPCC precipitation dataset (Figs. 3b and d). In addition, there are significant precipitation anomalies in several other regions of the mainland, but these are not investigated any further because the regressions are very small.

To further understand the linkage between the winter sea-ice in the Labrador Sea and the spring precipitation over southeastern North America and Western Europe, the spring atmospheric circulation anomalies related to the Labrador Sea's ice in winter are investigated. Figure 4 shows the atmospheric circulation anomalies associated with an increase in winter sea-ice in the Labrador Sea. Significant SLP anomalies exist mainly over the oceans, with positive anomalies over the western Pacific and the oceans west of Greenland, and negative anomalies over the southeastern subtropical Pacific (Fig. 4a). This may be the main reason why there are no significant SAT anomalies over land. In the middle troposphere (Fig. 4c), negative height anomalies exist over southern North America, and positive height anomalies exist over northern North America and the northern North Atlantic. This circulation pattern benefits the increase in precipitation over southeastern North America, as it can bring warm and moist air from the ocean. In addition, anomalies from the North Pacific to North America are similar to the Pacific–North America teleconnection pattern. Over Western Europe and the adjoining Atlantic, there are negative height anomalies, which could bring moist air from the ocean to southeastern Europe and favor an increase in precipitation. The relationship between the associated atmospheric circulation

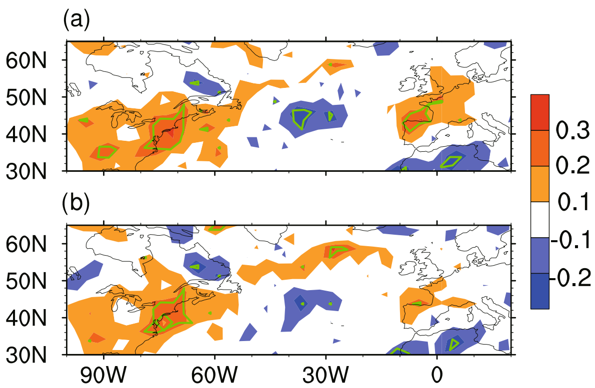

Fig. 2. Correlation coefficients of CMAP precipitation in spring with the Lab-SIA in the previous winter, based on data from (a) the Hadley Center and (b) NSIDC. The green lines indicate statistical significance at the 95% confidence level.

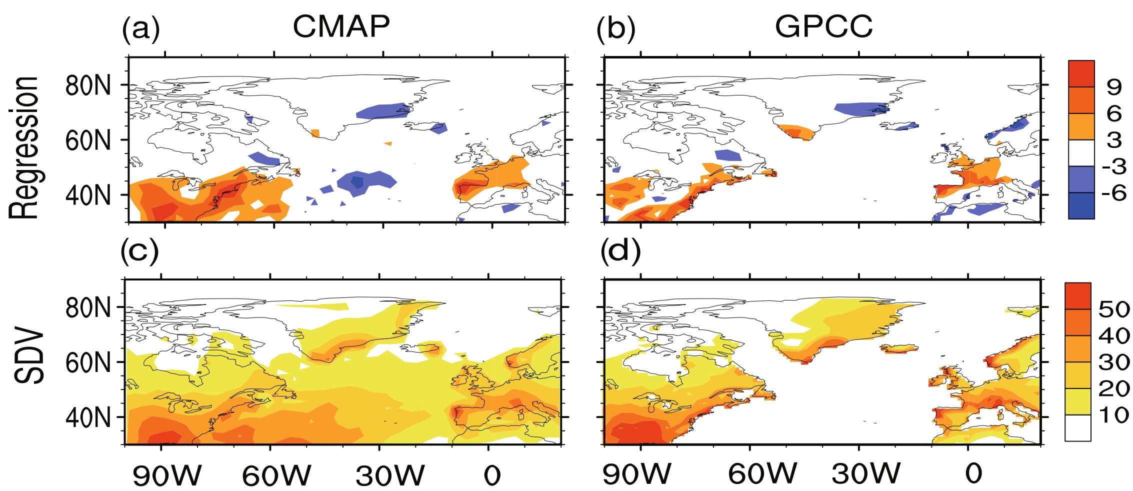

Fig. 3. Regressions of (a) CMAP and (b) GPCC precipitation in spring against previous-winter Lab-SIA, and the winter mean of the monthly standard deviation of precipitation obtained from the (c) CMAP and (d) GPCC datasets.

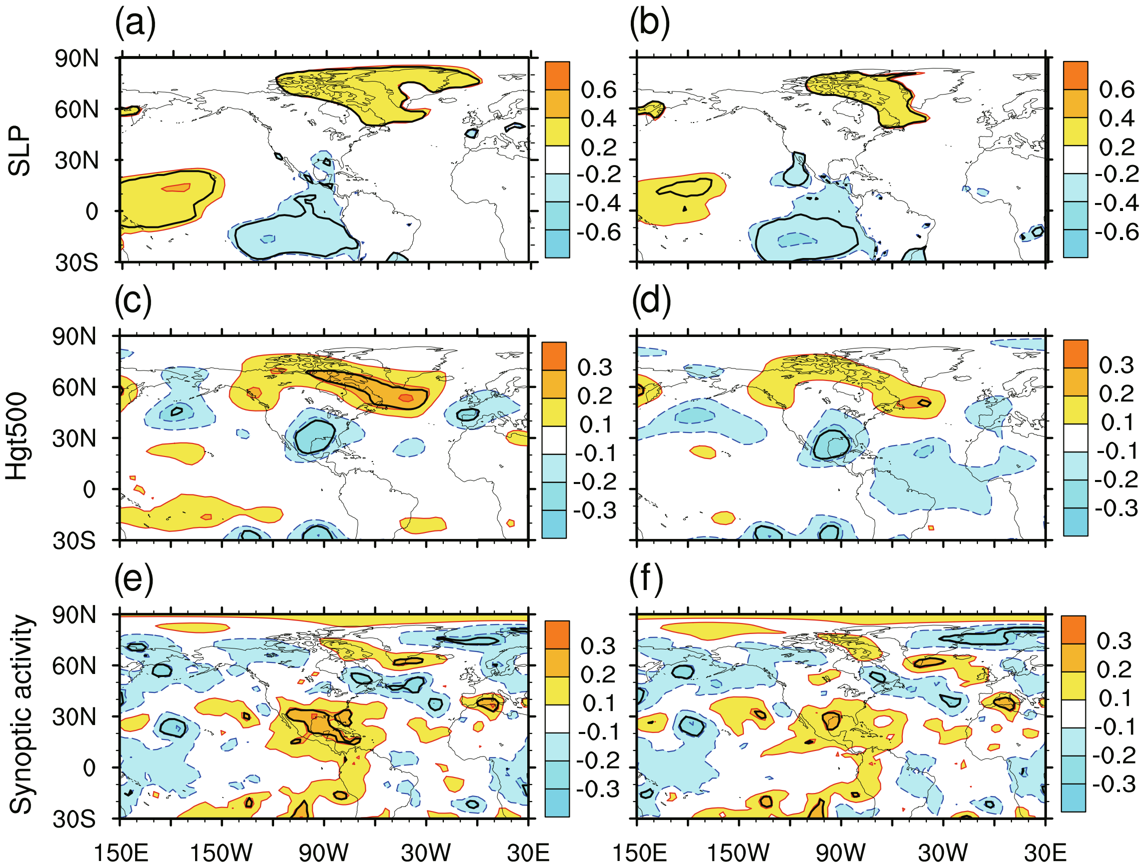

Fig. 4. As in Fig. 2, but for (a, b) SLP, (c, d) Z500 and (e, f) storm track, defined as the variance of bandpass-filtered Z500. The black contours indicate statistical significance at the 95% confidence level.

and the Lab-SIA defined by the NSIDC dataset (Figs. 4b and d) is consistent with that indicated above. This means that the connection between the atmospheric circulation anomalies and the sea-ice anomalies in the Labrador Sea is reliable. The atmospheric circulation anomalies are basically consistent with those in Wu et al. (2013), with only slight differences between them that may be related to the different domains used for the Lab-SIA index, as well as the use of a monthly rather than seasonal mean. Some studies have suggested that the precipitation anomalies in the midlatitudes are strongly impacted by storms (e.g. Hawcroft et al., 2012). Figures 5e and f show the storm track related to the sea-ice area in the Labrador Sea, which is defined as the variance of synoptic Z500 with periodicity of 2–8 days using a Lanczos filter with 21 weights (Duchon, 1979). As we can see, the storm track becomes strengthened in Western Europe and adjoining regions, and in southern North America, where the precipitation anomalies are, which means the storm track may play an important role in determining the precipitation anomalies.

4. Possible physical mechanism behind the observational relationship

As the boundary of the atmosphere, the ocean has a large heat capacity and sea ice may persist for several months and continuously drive the atmosphere. Thus, the persistence of the ocean thermal state may be the reason for the close observational connection indicated in section 3. First, the sea-ice and SST anomalies associated with winter sea-ice are investigated. The reason for studying the SST is that there are significant atmospheric anomalies in spring over the tropical oceans (Fig. 4a), which may be caused by the SST anomalies. Because there are both sea-ice and SST anomalies, the question naturally arises as to whether winter sea-ice is more suitable than SST as an observational precursor for the precipitation anomalies of the following spring (subsection 4.1). After that, we investigate the possible forcing effects of both sea-ice and SST anomalies on the atmosphere during spring (subsection 4.2).

4.1. *Sea-ice and SST anomalies*

In winter, the sea ice decreases in the Greenland and Barents (G–B) seas (Fig. 5a), along with an increase in sea ice in the Labrador Sea. In the remote open oceans, there are significant SST anomalies in the North Atlantic and tropical Pacific. In the North Atlantic, the SST anomalies show a tripole pattern in winter, which is similar to that reported in Wu et al. (2013). The physical mechanism behind the relationship between sea ice and SST in winter is not investigated because it is beyond the scope of the present study.

Given that there are significant SST anomalies in the remote oceans, it is necessary to identify whether it is the sea

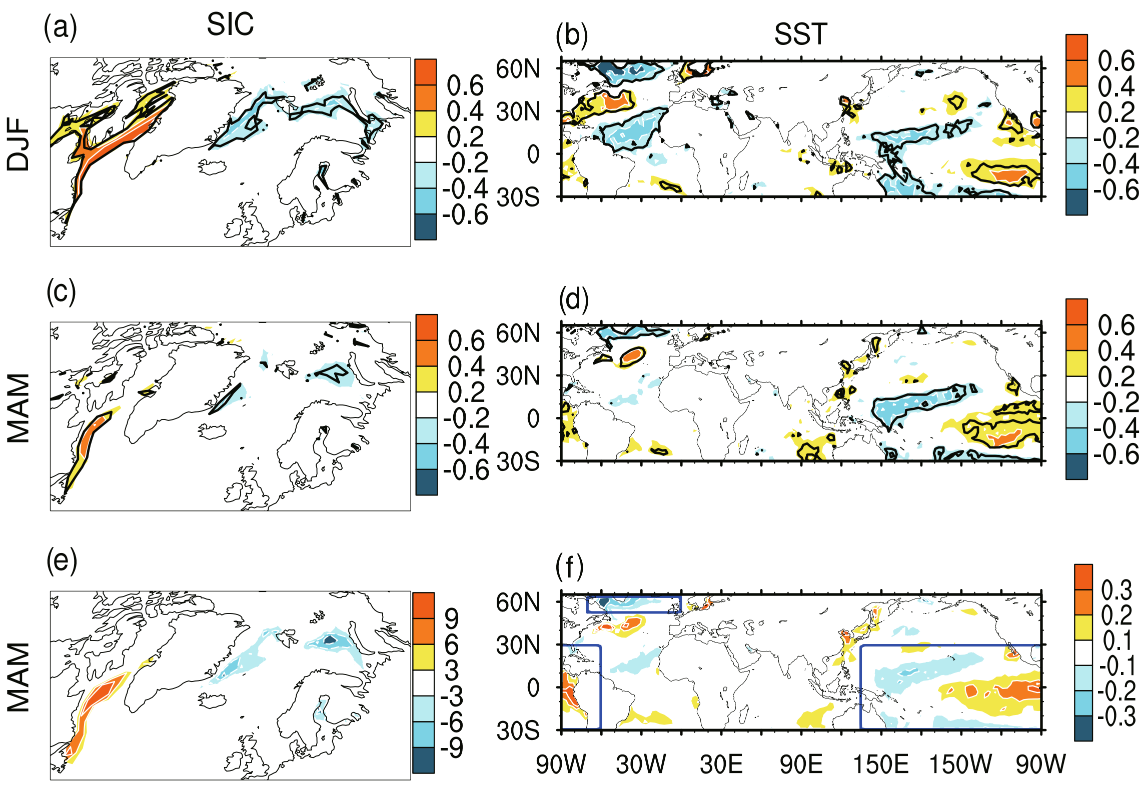

Fig. 5. Correlation coefficients of (a, c) SIC and (b, d) SST with winter Lab-SIA: (a, b) winter; (c, d) following spring. Panels (e, f) are the same as (c, d), but for the regression. The blue boxes are used to mark the regions where the SST anomalies are used in the model experiments. The black contours indicate statistical significance at the 95% confidence level.

ice in the Labrador Sea or the SST in the open oceans that is the better statistical precursor for the following-spring precipitation anomalies. First, the spring precipitation anomalies associated with the North Atlantic SST tripole are largely different from those associated with Lab-SIA (cf. Fig. S2 and Fig. 2). This means that the role played by North Atlantic SST anomalies in the linkage between winter Labrador Sea sea-ice and spring precipitation is weak. Second, the first three modes of the tropical Pacific SST anomalies are not the same as those related to winter Lab-SIA (cf. Fig. S3 and Fig. 5b). The first mode mainly reflects a traditional El Niño–Southern Oscillation (ENSO) event, and the correlation coefficient between ENSO and the Lab-SIA is only 0.15, which is below the 90% significance level. The correlation coefficient between the second mode and Lab-SIA is 0.12, which is also below the 90% significance level. The third mode is insignificant because it cannot be separated from the fourth mode. This means that the winter Labrador Sea sea-ice anomaly, rather than the SST anomaly, is a better index for predicting spring anomalies in southeastern North America and Western Europe.

4.2. *Forcing roles of sea-ice and SST anomalies in the atmosphere during spring*

In spring, there are significant sea-ice and SST anomalies that persist from the previous winter (cf. Figs. 5a, b and c, d), and this persistence may be caused by the large heat content of the ocean. If these persistent features are the drivers of the atmospheric anomalies in spring, the linkage between the winter sea-ice and spring precipitation may be easy to understand. This aspect is investigated next. As a general speculation regarding the large-scale air–sea interaction, if the ocean does influence the atmosphere, there should be heat transfer from the ocean (atmosphere) to the atmosphere (ocean) where sea ice decreases (increases) or where SST is warmer (colder) than normal. Figure 6b shows that there is heat absorption in the Labrador Sea and the adjoining open oceans (blue box in Fig. 6b), and heat release in the G–B seas and the adjoining open oceans (red box in Fig. 6b). The consistent surface heat flux anomalies in the sea-ice region and the adjoining open oceans in spring differ from those in winter. This suggests that the overlying atmospheric conditions may be primarily driven by the sea ice, because the surface heat flux is opposite between the sea-ice region and the adjoining oceans when the sea-ice is forced by the atmosphere (e.g., Deser et al., 2000, Han et al., 2016a). Therefore, the sea-ice anomaly in winter is forced by the simultaneous atmosphere; when it persists into the ensuing spring, it seems to be the driver of the atmosphere.

With respect to the extratropical SST anomalies in the North Atlantic, a cold anomaly at high latitudes can influence the atmosphere by absorbing heat from it, while a warm anomaly at midlatitudes seems to be forced by the atmosphere because warmer SSTs are related to heat absorp-

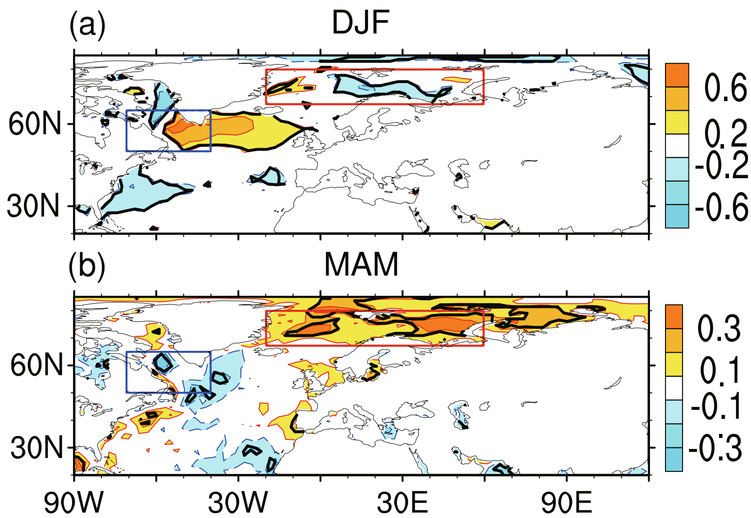

Fig. 6. As in Figs. 5a and c, but for surface heat fluxes. The blue and red rectangles contain the ocean covered by sea ice and the adjoining open ocean.

tion (cf. Figs. 5d and 6b). These results indicate that the role played by North Atlantic SST anomalies in the linkage between winter sea-ice and spring atmospheric conditions is weak, which is consistent with the results reported by Frankignoul et al. (2014). In the tropical Pacific, there is heat release (more precipitation) in the western region and heat absorption (less precipitation) in the eastern region (not shown), which corresponds to warmer and cooler SSTs, respectively. This means that the tropical SST anomalies are forcing factors with respect to the atmosphere. Further proof of the forcing role played by the Pacific SST is provided by the SLP anomaly, which is above normal over regions with colder SSTs and below normal over regions with warmer SSTs (cf. Figs. 4a and 5d). Such atmospheric circulation anomalies are consistent with the direct thermal response of the atmosphere to tropical SST anomalies. Therefore, the possible oceanic forcings in spring include the sea-ice anomalies in the Labrador and G–B seas, an SST anomaly over the North Pole of the North Atlantic, and SST anomalies in the tropical Pacific.

The results of the analyses carried out in section 4 indicate that both sea ice and SST might play roles in determining the atmospheric conditions during spring, and the winter Lab-SIA is a better observational precursor of spring precipitation than SST in the open oceans. However, the above analyses cannot clarify whether the spring atmospheric anomalies are really caused by collaborative roles of the sea-ice and SST anomalies. Atmospheric model simulations are a useful tool for solving such issues, which is discussed in the next section.

5. Roles of sea ice and SST revealed by model simulations

The Coupled Model Intercomparison Project Phase 5 (CMIP5) and Atmospheric Model Intercomparison Project (AMIP) experiments support many available datasets in analyzing the atmospheric response to oceanic forcings. Although the oceanic forcings in the CMIP5 and AMIP experiments include the warm SST anomalies in the midlatitude North Atlantic (Fig. 5f), which is not a driver of the atmosphere, the simulated results should be qualitatively consistent with those forced by the oceanic anomalies excluding the warm SST anomaly, since its area is so much smaller than that of the other forcings. Figure 7 shows the response of the spring Z500 anomalies to the oceanic forcings (Figs. 5e and f), from which it can be seen that the response is very similar to that regressed on the Lab-SIA index (cf. Figs. 7a and b). Also, the correlation coefficient between the observations and the model simulation is 0.72 over the region from the central Pacific to Western Europe (0°–80°N, 180°–0°E).

As the oceanic forcings include both sea-ice anomalies in the Arctic and SST anomalies in the remote open oceans, the role of each forcing cannot be identified by observational analyses and the CMIP5 and AMIP experiments. To investigate this issue, we use an AGCM model, ECHAM5, to carry out sensitivity experiments. We first evaluate the atmospheric response to the combined sea-ice (Fig. 5e) and SST anomalies (blue box in Fig. 5f), and compare them with the observational results. Figure 8a shows the precipitation response to the combined sea-ice and SST anomalies, which is above normal in southern North America and Western Europe, and is consistent with the observational regression (Fig. 3a). Figure 8b is the Z500 response, which also resembles the observational regression (Fig. 7b), with a correlation coefficient of 0.65 over the domain (0°–80°N, 180°–0°E). Besides the spatial similarity, the amplitude of the response is also comparable to the observational regression. For example, the maximum Z500 response over the midlatitude North Pacific is about twice that of the regression, because the amplitude of the oceanic forcings driving the AGCM doubles that of the regression. Consistency between the simulation and

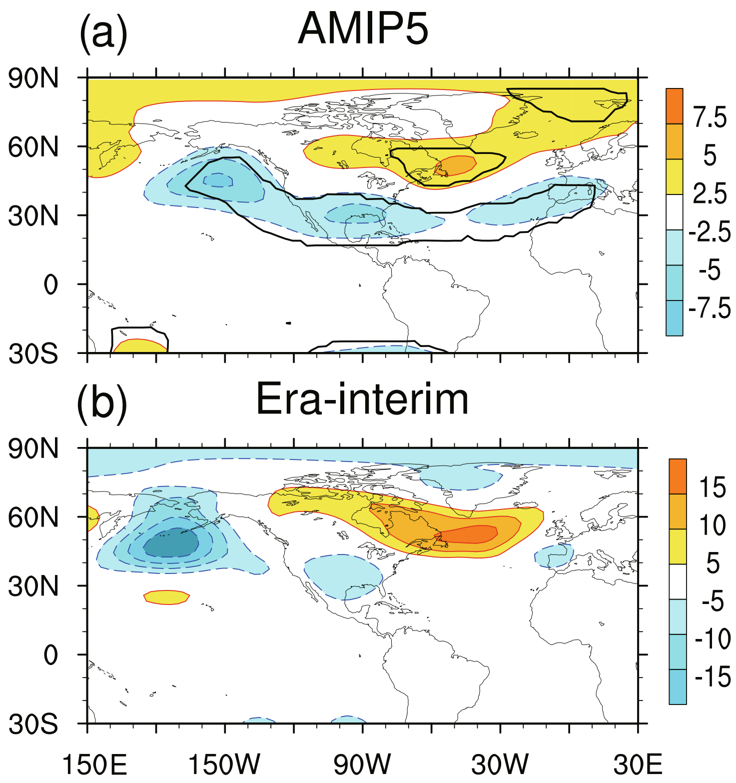

Fig. 7. Regressions of Z500 in spring against the Lab-SIA index in the previous winter for the multi-model ensemble means of (a) CMIP5 and AMIP and (b) ERA-Interim. The black contours in (a) indicate statistical significance at the 95% confidence level.

observational regression means that the model simulation is reliable.

Figure 9a shows the precipitation response to the sea-ice anomalies in the Labrador and G–B seas. Precipitation increases significantly over Western Europe, but is insignificant over North America. Figure 9c shows the Z500 response; a negative height response over Western Europe and the adjoining Atlantic benefits the transfer of moist air from the subtropical Atlantic, and results in a significant increase in precipitation (Fig. 9a). Meanwhile, the center of the negative height response over southern North America is eastwards relative to observations, as well as the response to the combined sea-ice and SST anomalies. This means that moist air cannot be transferred from the subtropical ocean to southern North America, and so the positive precipitation anomaly in that region is insignificant. The differences in the center of the negative height response between the model simulation and observation were also seen in Wu et al. (2013), but they did not indicate this can lead to different precipitation anomalies or what causes the inconsistency. The following investigation shows that the SST anomalies are responsible for the differences (Fig. 9d). Figure 9b shows the precipitation response to the SST anomalies in the tropical Pacific and high-latitude North Atlantic, which is above normal in southern North America, and indicates that the observed precipitation anomalies in southern North America that are linked to the increase in sea-ice in the Labrador Sea are mainly caused by the SST anomalies. The precipitation response over Western Europe is much weaker than that caused by the sea-ice anomalies. The Z500 response indicates that the positive precipitation in southern North America is related to the moist air transfer from the subtropical ocean (Fig. 9d), which is consistent with observations. The center of the negative Z500 response over the eastern North Atlantic is shifted westwards relative to the observations, and this is the reason for the weak precipitation response in Western Europe relative to the observations.

6. Summary and discussion

In this study, we investigate the role played by the winter sea-ice in in the Labrador Sea ice as a precursor for following-spring precipitation, and analyze the possible underlying physical mechanism. The SAT anomalies are not discussed, as there are almost no significant anomalies over land. Consistent with this, there are almost no significant SLP anomalies over land too. Observational analyses indicate that there are increased precipitation anomalies in southeastern North America and Western Europe as the sea ice in the Labrador Sea increases. Correspondingly, the atmospheric circulation shows a negative height anomaly over southern North America, which supports the transfer of warm and

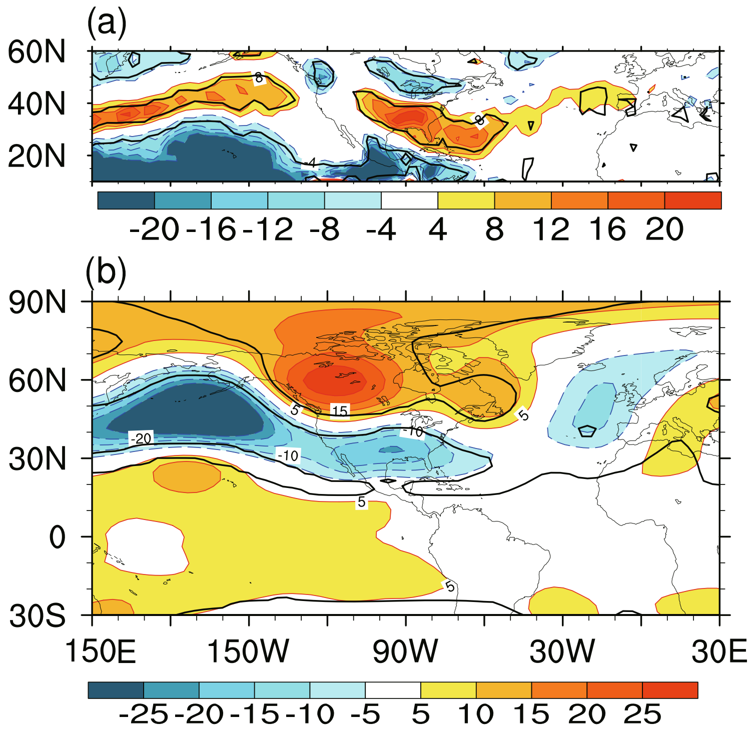

Fig. 8. Atmospheric responses to the combined sea-ice and SST anomalies (difference between SST_SIC_Exp and CTRL_Exp) for (a) precipitation and (b) Z500. The black contours indicate statistical significance at the 95% confidence level.

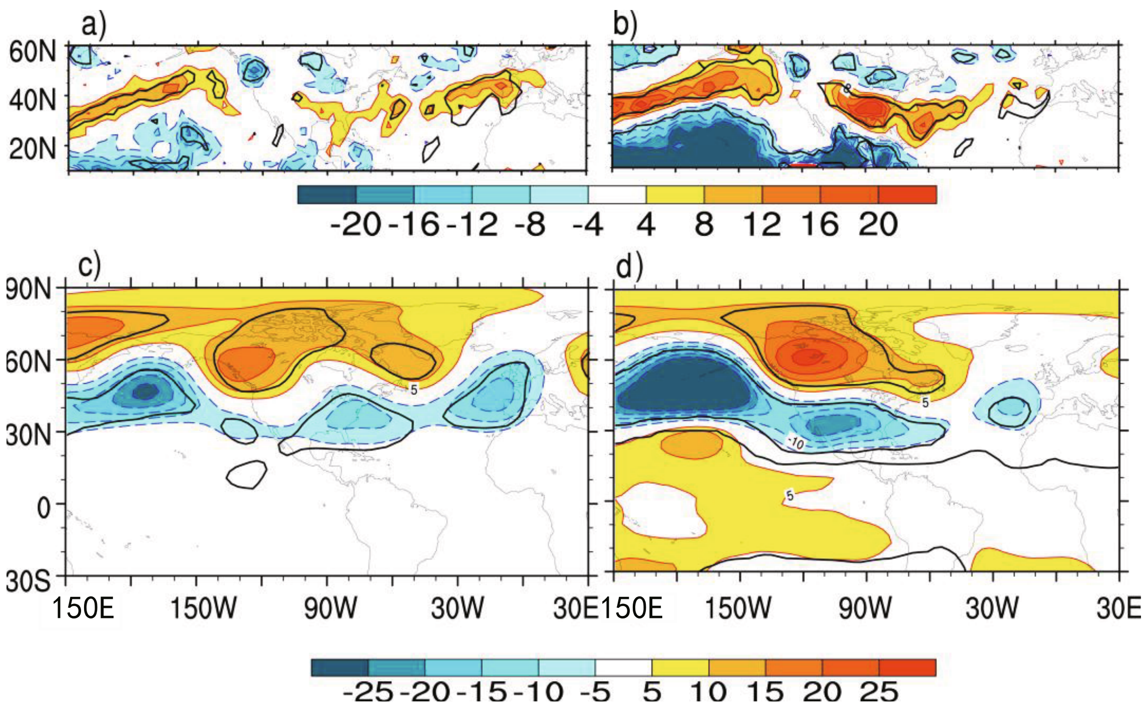

Fig. 9. As in Fig. 8, but for the response to (a, c) sea-ice and (b, d) SST anomalies.

moist air from the subtropical ocean. The increased precipitation over Western Europe is associated with the negative height anomalies there and in the adjoining North Atlantic, which facilitates the transport of warm and moist air from the subtropical North Atlantic. Moreover, the storm activity strengthens over the regions with precipitation anomalies, and this may have an important impact on the precipitation anomalies.

Next, we investigate the possible physical mechanism behind this relationship. Along with the increased winter sea-ice in the Labrador Sea, there is decreased sea-ice in the G–B seas, and the SST anomaly shows a tripole pattern in the North Atlantic and a dipole pattern in the tropical Pacific, with colder SSTs in the western region and warmer SSTs in the eastern region. The oceanic anomalies, except for the tropical SST anomaly in the North Atlantic, persist into the following spring. By analyzing the surface heat fluxes and SLP, we identify the oceanic forcings in spring, which contain both the sea-ice and SST anomalies mentioned above, except for the positive SST anomaly in the midlatitude North Atlantic. This also indicates that the role played by the North Atlantic SST is relatively weak for the spring climate, which is consistent with the findings of Frankignoul et al. (2014). Although the role played by sea ice and SST as a forcing is identified, whether the atmospheric circulation is really caused by oceanic forcing must be studied further.

Multi-model CMIP5 and AMIP simulations suggest that oceanic forcing is indeed the reason for the atmospheric circulation anomalies. Furthermore, we carry out sensitivity experiments using ECHAM5 to investigate the relative roles played by the sea-ice and SST anomalies. Their combined role is consistent with observational analyses, indicating the reliability of this model simulation. The results show that sea-ice anomalies play a strong role in the increased precipitation in Western Europe, but only a relative weak role in the precipitation anomalies in southern North America. The atmospheric circulation response resembles that indicated in Wu et al. (2013). It should be noted that, because the sea-ice forcings in this experiment contain sea-ice anomalies in the Labrador and G–B seas, the experiment cannot determine which region plays the most important role in the increased precipitation in Western Europe. Different from the sea-ice anomalies, the SST anomalies play a dominant role in the increased precipitation over southern North America, but a relatively weak role in the precipitation anomalies over Western Europe. This indicates that the sea-ice and SST anomalies play independent and dominant roles in the increased spring precipitation in the two regions. This work also explains the reason for the shift in Z500 over southeastern North Atlantic between the observation and the atmospheric response in Wu et al. (2013), which are the SST anomalies responsible for this shift. Most of Western Europe experienced severe drought in spring 2011, which resulted in fire risk in some regions (WMO, 2012). The south-central United States was also extremely dry for the whole of 2011 (WMO 2012). In winter 2010/11, there was a strong La Niña event, but the significant effects of ENSO cannot explain the extreme drought in the south-central United States and Western Europe (Fig. S4). The results of this study suggest that the extreme drought in the southern United States and Western Europe in spring 2011 may to a certain extent have been predictable from the sea-ice and SST anomalies related to winter sea-ice in the Labrador Sea.

It should be noted that the sea ice in the Labrador Sea is a better observational precursor for spring climate relative to SST anomalies (i.e., in terms of the statistical relationship). Although model simulations indicate that the role played by SST anomalies in the tropical Pacific is apparently more important than that of sea ice, the observational analyses suggest that the SST anomalies cannot be defined as a precursor because there is no significant mode of tropical Pacific SST that shows a similar spatial pattern with that related to the Labrador Sea sea-ice. In other words, if we establish an empirical model to predict the spring precipitation anomaly, the sea-ice area in the Labrador Sea is the better precursor.

Recently, many studies have indicated that uncertainties exist in the linkage between Arctic sea-ice and large-scale circulation anomalies (Walsh, 2014; Overland et al., 2015; Wu et al., 2015; Wu et al., 2016). For the linkage indicated here, the sea ice in the Labrador Sea is not the only driver of the atmosphere. Therefore, if the relationship between it and other drivers, such as the SST anomaly, changes, its role as a precursor for spring precipitation will also change. This indicates that the relationships among the Labrador Sea sea-ice anomaly and remote sea-ice and SST anomalies should be further investigated and, in doing so, it should be possible to reduce the level of uncertainty involved in the connection.

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