Abstract

Contemporary climate science seeks to understand the rate and magnitude of a warming global climate and how it impacts regional variability and teleconnections. One of the key drivers of regional climate is the observed reduction in end of summer sea-ice extent over the Arctic. Here the authors show that interannual variations between the September Arctic sea-ice concentration, especially in the East Siberian Sea, and the maximum Okhotsk sea-ice extent in the following winter are positively correlated, which is not explained by the recent warming trend only. An increase of sea ice both in the East Siberian Sea and the Okhotsk Sea and corresponding atmospheric patterns, showing a seesaw between positive anomalies of sea level pressures over the Arctic Ocean and negative anomalies over the midlatitudes, are related to cold anomalies over the high-latitude Eurasian continent. The patterns of atmospheric circulation and air temperatures are similar to those of the annually integrated Arctic Oscillation (AO). The negative annual AO forms colder anomalies in autumn sea surface temperatures both over the East Siberian Sea and the Okhotsk Sea, which causes heavy sea-ice conditions in both seas through season-to-season persistence.

1. Introduction

Changes in the Arctic sea-ice extent have been dramatic; in particular, the September Arctic sea-ice extent has been rapidly decreasing and its year-to-year variations of sea-ice concentration over the marginal seas to the northern coast of Alaska and Siberia have declined since 1979. The

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variability (Honda et al. 2009; Orsolini et al. 2011). Arctic warming is generally consistent with reductions in the Arctic sea-ice cover (Ogi and Wallace 2007; Serreze et al. 2009; Screen and Simmonds 2010), concurrently affecting snowfall, precipitation, and vegetation cover over the Arctic and midlatitudes in summer to winter (Orsolini et al. 2011; Screen 2013; Bhatt et al. 2013).

The Okhotsk Sea, which is located between the eastern end of the Eurasian continent and the North Pacific (Fig. 1), is the southernmost ocean in the Northern Hemisphere that is covered with sea ice during winter (Fig. 1b). The sea ice begins to form over the northwestern coast of the Okhotsk Sea in November, and reaches a maximum in February or March, and mostly disappears in June. The Okhotsk sea-ice cover has also experienced a significant decline for recent several decades. It is suggested that the Okhotsk sea-ice variability is related to the Arctic and sub-Arctic sea-ice variability through atmospheric and oceanic processes on multyear time scales (e.g., Parkinson et al. 1999; Ukita et al. 2007). Thus, the study of mutual connections between the Arctic and Okhotsk sea-ice variability is important for understanding recent dramatic evidence of climate change.

The interannual variability of sea-ice extent in general is very large because its variability is associated with both large- and local-scale atmospheric circulations. The decrease in the Arctic sea-ice coverage during summer has been attributed to changing patterns of surface winds associated with the dominant patterns of atmospheric circulation (Rigor et al. 2002; Ogi et al. 2010; Wu et al. 2006; L’Heureux et al. 2008). The sea-ice extent in the Okhotsk Sea is also influenced by interannual variability in the atmospheric patterns (Fang and Wallace 1994; Tachibana et al. 1996, 2008). In contrast, recent model studies have suggested that the sea-ice variability influences the atmospheric circulation through the formation of stationary Rossby wave trains and modification of the storm track (e.g., Honda et al. 1999; Alexander et al. 2004). It is also suggested that initializing the sea-ice variability may in turn enhance the predictability of atmospheric circulations in seasonal forecasts (Balmaseda et al. 2010; Doblas-Reyes et al. 2013). Recently, Honda et al. (2009) examined impacts of the summertime Arctic sea-ice reduction on the wintertime climate over Eurasia based on a reanalysis dataset and numerical experiments using an atmospheric general circulation model. Their results show that the decrease of the Arctic sea-ice extent along the Siberian coast in September is associated with significant cold anomalies over the Far East and high pressure anomalies over Siberia in early winter. Sasaki et al. (2007) showed that autumnal wind anomalies flowing from Siberia into the Okhotsk Sea bring cold air temperatures and heavy sea-ice conditions there. Those former studies have implied that the interannual variability of the atmospheric circulation might connect the September Arctic sea-ice variations and the Okhotsk sea-ice expansion in the following winter. In this study, we consider how atmospheric variability influences the year-to-year variations of interseasonally linked sea-ice extent between the Arctic Ocean and Okhotsk Sea.

It is known that the Okhotsk sea-ice extent is negatively correlated with the Amur River discharge on interannual time scales, mainly through the atmospheric circulation change in summer, the season when the discharge peaks (Ogi et al. 2001). This indicates that the Okhotsk sea ice could also be related to the atmospheric conditions in the preceding summer. On the other hand, onset of sea-ice formation is well predicted by local turbulent heat fluxes in relation to atmospheric conditions in the preceding autumn (Ohshima et al. 2006). Regarding such atmospheric forcing on different seasons, Ogi and Tachibana (2006) showed that an annual-mean atmospheric pattern defined as the January–December mean Arctic Oscillation (AO)
pattern (Thompson and Wallace 1998) is significantly related to both the summer discharge of the Amur River and sea-ice extent in the Okhotsk Sea in the following winter. This study indicated that atmospheric patterns on the annual time scale could influence the season-to-season link of the atmosphere–land–ocean system. In this paper, we argue that the September Arctic sea ice and the Okhotsk sea ice in the following wintertime are also related to each other via interseasonally persistent atmospheric variations in summer through winter.

Our paper is set out as follows: in section 2 we describe datasets used in the present study. Section 3a shows the relationship between the September Arctic sea-ice concentrations and the maximum Okhotsk sea-ice extent in the following winter. The atmospheric patterns in relation to the year-to-year variations in sea-ice variability both in the Arctic and the Okhotsk Sea are given in section 3b. In section 4, we also discuss the relationship between autumn sea surface temperature (SST) associated with the annual-mean AO and the atmospheric patterns correlated with sea-ice variations in the Arctic and the Okhotsk Sea shown in section 3b. Section 5 summarizes and discusses the role of the annual AO on year-to-year covariations between the September Arctic sea-ice concentrations and the maximum Okhotsk sea-ice extent in the following winter.

2. Data

We used the monthly data of atmospheric fields from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset from 1970 to 2012 (Kistler et al. 2001). The AO index from 1970 to 2012 defined by Thompson and Wallace (1998) is taken from the Climate Prediction Center. The annual mean (January–December) of sea level pressure (SLP), air temperature at 850 hPa, and the AO index are used in this study. Monthly mean sea-ice concentration data and SST data used in this study are based on the Met Office Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1 (HadISST1) provided as the monthly fields of sea-ice extent from 1970 to 2012 (Rayner et al. 2003). Maximum sea-ice coverage data in the Okhotsk Sea is obtained from the Japan Meteorological Agency (JMA) for 1971 to 2013.

3. The relationship between Arctic and Okhotsk sea ice

a. September Arctic sea-ice concentration and the maximum Okhotsk sea-ice extent in the following winter

In this section, we examine the sea-ice covariations in different seasons between the Arctic Ocean and the Okhotsk Sea. The year-to-year variations in sea-ice concentrations are large in the marginal seas to the north of Alaska’s and the Siberian coast in autumn (Fig. 1a) and in the Okhotsk Sea in winter (Fig. 1b). Therefore, variations in the September Arctic sea-ice extent mainly reflect the behaviors in these marginal seas. Figure 2 shows September sea-ice concentration regressed on the maximum Okhotsk sea-ice coverage in the following winter. The regression and correlation patterns yield a large loading and high correlation over the East Siberian Sea. Figure 3 shows the time series of the September sea-ice concentration averaged over the East Siberian Sea (the box area in Fig. 2) and the maximum Okhotsk sea ice in the following winter. These time series are hereafter referred to as “the Arctic sea-ice index” and “the Okhotsk sea-ice index,” respectively. The choice of averaging area for the former index is based on its regional importance for climate variability as revealed in previous studies (e.g., Ogi and Wallace 2007). The interannual variations of both the Arctic and Okhotsk sea-ice indices are positively correlated ($R = 0.54, P < 0.01$); when the September sea-ice concentrations are large over the East Siberian Sea, the maximum Okhotsk sea-ice coverage in the following winter also yields a larger area than normal. Since decreasing tendencies shown in both indices may reflect recent global warming, we removed each of linear trends from the original indices, respectively. As inferred, the correlation coefficient between the detrended time series becomes weaker ($R = 0.33$), yet statistically...
significant ($P < 0.05$). Note that we made an a priori selection of the region for our correlation analysis and, hence, the statistical significance of the detrended correlation is robust. The result indicates that there exists an unignorable relationship between the sea-ice variability in the autumn Arctic Sea and the winter Okhotsk Sea, which cannot be explained by the recent warming trend only. Because we would like to focus on the year-to-year variations of sea ice between the East Siberian Sea and Okhotsk Sea, the interannual variability in the detrended Arctic and Okhotsk sea-ice indices are used in this study.

b. Annual mean atmospheric patterns in relation to the sea ice in the Arctic and the Okhotsk Seas

To identify a common forcing field of the sea-ice variability in the different seasons between the Arctic Ocean and Okhotsk Sea, it is useful to examine the annual mean large-scale atmospheric patterns, which represent temporally integrated fields that could exert persistent influences from one season to another (Ogi and Tachibana 2006). Figure 4a shows the patterns in detrended annual mean SLP regressed on the detrended September Arctic sea-ice index for the period 1970–2012. The SLP pattern shows a seesaw between positive anomalies over the Arctic Ocean and an area of negative anomalies over the Pacific and the Atlantic Oceans associated with increase of the Arctic sea-ice extent in September. This pattern exhibits an anticyclonic circulation over the Arctic; in particular, large positive anomalies occur over the northern Europe and Siberian coast. It is suggested that the winds from the north of Greenland to the north of Alaska’s coast could enhance sea-ice cover over the East Siberian Sea through the combined effect of cold air and sea-ice advection. The annual mean SLP anomalies regressed on the maximum Okhotsk sea-ice index in the following winter (Fig. 4b) are characterized by a seesaw pattern between the Arctic Ocean and the midlatitudes. The negative anomalies in the Pacific sector are associated with deepening of the Aleutian low that acts to increase the Okhotsk ice cover with strong cold air advection (Tachibana et al. 1996). Those SLP anomalies regressed on both the September Arctic and the winter Okhotsk sea-ice indices have similar signatures (Figs. 4a and 4b), which suggests that a common annual atmospheric large-scale pattern influences the sea-ice extent in both the Arctic Ocean and the Okhotsk Sea.

Figures 4c and 4d show annual mean air temperature at the 850-hPa regressed on the September Arctic sea-ice index and the maximum Okhotsk sea-ice index in the following winter, respectively. The former (Fig. 4c) shows significant cold anomalies over the high-latitude Eurasian continent and the East Siberian Sea. This cooling over and around the Arctic is effective to generate and expand the sea-ice extent in the East Siberian Sea. Similarly, the latter (Fig. 4d) exhibits negative anomalies over and around the Far East. These air temperature anomalies (Figs. 4c,d) are consistent with heavy sea-ice conditions both in the Arctic Ocean and Okhotsk Sea.

4. Annual AO patterns

a. Annual AO associated with the sea ice in the Arctic Ocean and the Okhotsk Sea

The similarity in the SLP regression patterns shown in the previous section indicates that the seesaw pattern between the Arctic Ocean and the subarctic region especially over the North Pacific and the North Atlantic influences both the Arctic and Okhotsk sea-ice extent (Figs. 4a and 4b). Those SLP patterns—positive anomalies over the Arctic Ocean and negative anomalies over the midlatitudes—are similar to the negative AO pattern (Thompson and Wallace 1998) that is characterized

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1 One may wonder how seasonal mean atmospheric circulation anomalies, rather than the annual mean, are related to the Arctic sea-ice extent in September. We present such a seasonal analysis in the appendix.
by a seesaw of atmospheric mass between mid- and high latitudes. Figure 5a shows an annual mean SLP regressed on the annual AO index (bar graph in Fig. 3). It is noted that the signs in Fig. 5 are reversed to emphasize the negative phase of the AO pattern. Thus, the sea-ice extent in both the Arctic Ocean and Okhotsk Sea tends to increase during the negative AO years.

The pattern of the annual mean 850-hPa air temperature regressed on the annual AO index (Fig. 5b) shows negative anomalies over the Eurasian continent and positive anomalies over North America and Greenland when the AO phase is negative. The pattern, particularly the one over Eurasia, is also similar to ones regressed onto both the Arctic and Okhotsk sea-ice indices that are negative anomalies over the Far East (Figs. 4c and 4d), indicating that both winter and summer AO strongly influences the air temperature over the Eurasia continent (Thompson and Wallace 1998; Ogi et al. 2004). Therefore, positive SLP anomalies over the Arctic Ocean associated with the negative annual AO cause an expansion of sea-ice cover in the East Siberian Sea, and negative SLP anomalies over the Bering Sea also cause an extension of the Okhotsk sea-ice cover.
b. Autumn SST correlated with annual AO

The results in the previous section show that the annual AO is linked to both sea-ice concentrations over the East Siberian Sea in September and over the Okhotsk Sea in the following winter. The correlation coefficients between the annual AO and detrended Arctic and the Okhotsk sea-ice indices are, however, not high ($R = -0.32$ for the Arctic and $R = -0.15$ for the Okhotsk sea ice, respectively). One reason for the low correlation is an indirect effect of the annual AO on the Arctic and Okhotsk sea ice through the ocean. Since the atmosphere itself does not have a long memory, the variations of ocean that have a longer memory are also important for the interseasonal link of year-to-year variations between the Arctic and the Okhotsk sea ice. The Okhotsk Sea is seasonally covered with sea ice from November to June, while sea ice along the Siberian coast in the Arctic Ocean melts during the season from May to September. Therefore, open water appears in both the Siberian coast and the Okhotsk Sea from summer to autumn, which would be influenced by the annual AO.

Figure 6 shows the patterns for monthly detrended SSTs for July, August, and September regressed on the annual AO index. Note that the signs are reversed to emphasize the negative phase of the AO. All SST patterns show cold anomalies over the Okhotsk Sea and East Siberian Sea when the annual AO is in a negative phase (Fig. 5a), which suggests that the memory of the annual AO is retained in the open water of both seas. The persistent colder SST anomalies favor increased formation of sea ice both in the East Siberian Sea in the following autumn and the Okhotsk Sea in the following winter.

5. Conclusions and discussion

In this paper we have investigated the year-to-year covariations in sea-ice extent between the Arctic Ocean during summer–autumn and the Okhotsk Sea during winter. The September Arctic sea ice in the East Siberian Sea is positively correlated with variations of the maximum Okhotsk sea ice in the following winter. The sea-ice indices both in the Arctic Ocean and the Okhotsk Sea have decreasing trends, which contributes to the high correlation between them. Nevertheless, detrended sea-ice time series still yield a significant correlation, which cannot be explained by the recent warming trend only. We have shown that annual-mean atmospheric circulation anomalies in relation to the detrended sea-ice variability both in the Arctic Ocean and the Okhotsk Sea are characterized by a seesaw-like SLP pattern: a pair of positive and negative SLP anomalies over the East Siberian Sea and the Bering Sea, respectively (Figs. 4a and 4b). The former acts to increase sea-ice extent over the East Siberian Sea through anomalous northeasterly advection from north of Greenland to the East Siberian Sea, and the latter is consistent with the enhanced Aleutian low causing larger-than-normal Okhotsk sea-ice extent. Annual mean air temperatures at the 850-hPa height also become colder over East Siberia and the Arctic (Figs. 4c and 4d).
and 4d) through wind anomalies from north of Alaska to the East Siberian Sea associated with SLP anomalies over the Arctic and North Pacific (Figs. 4a and 4b). The above-mentioned SLP and air temperature anomalies in relation to the sea-ice coverage both in the East Siberia and the Okhotsk Seas resemble those associated with the annual AO pattern. It directly contributes to cooling of SSTs from summer to autumn in both the East Siberian Sea and the Okhotsk Sea when the AO has a negative phase (Fig. 6), which promotes freezing of the ocean.

Ogi and Tachibana (2006) showed the relationship between the summertime Amur River discharge and the wintertime Okhotsk sea-ice extent based on the annual AO. Since their analyses is based on 3-yr running mean data, however, it was still unclear what processes associated with the annual AO would cause relationship between the Amur River discharge and the Okhotsk sea-ice extent. In the present study, we argue that the annual AO causes the interseasonal link of year-to-year variations in sea-ice extent between the Arctic Ocean and the Okhotsk Sea through the persistence of SST anomalies over there based on yearly data. It is an interesting question for future studies whether the imprints of the annual AO in SST and sea ice in turn feed back on the interseasonal memory and interannual variations of the annual AO. A modeling study using a long-term climate model simulation is under way to support the findings obtained from this study based on observations with limited record length, and further elucidate the mechanisms for the interseasonal linkage of the sea-ice variations.

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APPENDIX

Seasonal Mean SLP Anomalies

To complement our analysis on the link between annual mean SLP anomalies and sea-ice variability in the summer Arctic Ocean (section 3b), we further examine the relationship of seasonal mean SLP anomalies with the September Arctic sea ice shown in Fig. A1. All seasonal mean SLP patterns regressed onto the September sea ice over the East Siberian Sea show positive anomalies over northern Europe and the Siberian coast. These positive SLP anomalies over the Arctic are strong in the January–March (JFM) and April–June (AMJ) patterns preceding the September Arctic sea ice. In particular, the JFM SLP pattern strongly reflects the negative AO pattern. Overall, the seasonal regression patterns are similar to the pattern of annual mean in Fig. 4a.

FIG. 6. As in Fig. 5, but for detrended monthly mean sea surface temperature (SST) on (a) July, (b) August, and (c) September. Contours indicate regression coefficients (interval of 0.2 K). Shading indicates correlation coefficients that exceed the 95% confidence level.


Ogi, M., and Y. Tachibana, 2006: Influence of the annual Arctic Oscillation on the negative correlation between Okhotsk Sea...


