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RESEARCH ARTICLE

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Preceding winter Okhotsk Sea ice as a precursor to the following winter extreme precipitation in South China

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Abstract

The winter extreme precipitation over South China (SC) experiences a large year-to-year variability, causing uncertainty in its prediction. Here, we find that the boreal winter sea ice concentration (SIC) in the Okhotsk Sea can serve as a precursor to the following winter's extreme precipitation frequency (EPF) over SC, which has important implications for its prediction. Further analysis reveals that the Okhotsk Sea SIC anomalies help to reinforce North Pacific Oscillation-like atmospheric variability over the North Pacific, which induces the development of El Niño-Southern Oscillation (ENSO)-like SST anomalies in the equatorial eastern Pacific. The ENSO may act as a "power amplifier" to boost the impact of the Okhotsk Sea winter SIC anomalies on the following winter EPF over SC via a positive atmosphere–ocean feedback process. Our findings suggest that the Okhotsk Sea SIC may act as a potential precursor for the winter EPF over SC leading by about 1 year, and further improve our understanding of extratropical-tropical interactions and aid predictability of winter extreme precipitation over SC.

KEYWORDS

air–sea–ice interactions, Okhotsk Sea, sea ice concentration, winter extreme precipitation frequency

1 | INTRODUCTION

The frequency and intensity of weather and climate extremes, such as extreme precipitation events, have increased in recent decades (IPCC, 2013). Thus, the worldwide response of the extremes to climate change and its critical influences on people and livelihoods receive increasing attention. In particular, given its large population, South China (SC) can be especially vulnerable to extreme precipitation events (Gemmer et al., 2011; Ning & Qian, 2009; Wu et al., 2020; Zhang et al., 2015; Zhang et al., 2018a).

Numerous works have focused on a large amount of summer rainfall over SC (Chan & Zhou, 2005; Chang et al., 2000; Wu et al., 2003; Zhou et al., 2007). In contrast, less attention has been given to the effects of winter precipitation over SC. Although winter precipitation is far less than summer rainfall, it experiences a large interannual variability over SC (Ge et al., 2016; Jia et al., 2015). Moreover, due to the lower temperatures in winter, extreme precipitation and its related phenomena are of particular concern. In early 2008, a severe rain- and snow-freezing disaster in SC affected more than 100 million people and resulted in a considerable economic loss (Zhang et al., 2015; Zhou et al., 2011; Zhou et al., 2018). It is, therefore, important to pay attention to the extreme precipitation variability in winter over SC and its driving factors. Some work has focused on the impact of tropical climatic factors on winter extreme precipitation events over SC (Gao et al., 2020; Huang et al., 2018; Yang et al., 2019). For instance, Zhang et al. (2015) analyzed the contributions of tropical sea surface temperature (SST) anomalies in the Pacific and Indian Oceans to the variability of winter extreme precipitation in SC. Generally, winter extreme precipitation related to large-scale atmospheric circulation over SC is modulated by these factors almost simultaneously. Given the severe impacts on the economy and agriculture in SC, however, finding potential predictors for winter extreme precipitation over the region is of great importance.

In recent years, increasing numbers of studies have suggested that sea ice in high latitudes should be considered to be a key indicator of the extreme events due to its large interannual variability (Cohen et al., 2018; Li et al., 2020; Muyuan et al., 2020; Ogawa et al., 2018; Overland et al., 2016; Zhang et al., 2018b). As a major component of the Earth's energy budget system, sea ice is sensitive to the conditions in both the atmosphere and ocean, and may in turn modulate climate by altering the exchange of heat, moisture, and momentum between the atmosphere and ocean (Deser et al., 2000; Guemas et al., 2016). In particular, sea ice cover in the Okhotsk Sea, which is located on the northwest rim of the Pacific Ocean, plays a crucial role in the East Asian climate (Honda et al., 1996; Liu et al., 2007; Nakanowatari et al., 2010). Sea ice extent in the Okhotsk Sea shows seasonal variation, which reaches its maximum in late winter (January–March; JFM), covering 50%–90% of the region (Nakanowatari et al., 2010; Ogi et al., 2015). Honda et al. (1999) demonstrated that sea ice anomalies in the Okhotsk Sea lead to anomalous heat fluxes at the ocean surface, and subsequently exert substantial feedback forcing on the local and remote response. However, it is unclear whether the variability of sea ice cover in the Okhotsk Sea affects winter extreme precipitation over SC.

In this study, we establish links between the winter sea ice concentration (SIC) in the Okhotsk Sea and the following winter extreme precipitation over SC. This may further improve our understanding of air-sea-ice interactions and thus aid the predictability of winter extreme precipitation over SC. The reanalysis datasets and numerical models used in our work are introduced in section 2. Section 3 reveals the links mentioned above and the mechanism through which the Okhotsk Sea SIC impacts winter extreme precipitation over SC. A brief summary and discussion are provided in section 4.

2 | DATA AND METHODS

2.1 | Observations

The daily precipitation dataset was provided by the National Meteorological Information Center of the China Meteorological Administration (CMA; http://data.cma.cn). We excluded stations with missing values and temporal inhomogeneity. As a result, 96 stations in SC (108°–120°E, 22°–26°N) with precipitation records for 40 years (1 January 1979 to 31 December 2018) have been extracted. The monthly mean SIC data and SST data were from the Met Office Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST1) dataset with a horizontal resolution of 1° for the 1979–2017 period (Rayner et al., 2003). Atmospheric circulation data with a 2.5° horizontal resolution, including horizontal wind, vertical velocity, specific humidity, and sea level pressure (SLP) for the same period were provided by the U.S. National Centers for Environmental Prediction (NCEP)–Department of Energy (DOE) Reanalysis 2 dataset (Kanamitsu et al., 2002).

In this study, only daily precipitation in winter (December–February; DJF) was considered. To assess winter extreme precipitation events over SC, we computed the extreme precipitation frequency (EPF) of each station in SC, defined as the number of days when the daily precipitation amount was greater than the 95th percentile of all rain days (above 0.1 mm) at the same station in 39 winters during 1979–2018 (winters of 1979/1980–2017/2018). A SIC index is used to describe the variation of sea ice cover in the Okhotsk Sea, which is defined as SIC anomalies (SICAs) averaged in the Okhotsk Sea (141°–155°E, 44°–59°N). To reduce the effect of global warming, the linear trend of the SIC index was removed.

2.2 | Numerical models

To confirm our hypothesis and further identify the role of SICAs in the Okhotsk Sea, control and sensitivity experiments were performed with the Community Atmosphere Model Version 5 (CAM5; Neale et al., 2010), which has 30 hybrid sigma-pressure vertical levels with the horizontal resolution of 0.937° × 1.25° (latitude × longitude). The control run was forced by the climatological monthly mean SST and sea ice boundary conditions of observations with a 50-year integration. In the sensitivity experiment, an observational sea ice is constructed by imposing the composite difference of SIC anomalies in the Okhotsk Sea between heavy and light sea ice events (defined as years when the JFM-averaged SIC index was greater than 0.5 positive standard deviation and less than 0.5 negative standard deviation, respectively) on the JFM climatological SIC anomalies; then, a 50-year run was performed with the climatological SST and the SIC anomalies in the Okhotsk Sea forced sea ice boundary conditions and the last 35 years were taken for analyses.

3 | RESULTS

To identify spatial and temporal features of the winter EPF over SC, empirical orthogonal function (EOF) analysis was performed (Figure S1). The two leading modes account for 75.8% and 8.2% of the total variance, respectively. They are well separated from each other according to the criteria of North et al. (1982). The first leading EOF (EOF1) mode is characterized by a spatially coherent pattern with positive anomalous EPF over SC. The leading principal component (PC1) mainly manifests interannual variability and is highly correlated with the area-weighted average of winter EPF over SC ($R = 0.99$). Therefore, the winter EPF index is defined as the normalized PC1 after removing the linear trend. To investigate the relationship between the SIC in the Okhotsk Sea and winter EPF over SC, we calculated the lead–lag correlation between the three-month running averaged SIC index and the winter EPF index (Figure 1a). Hereafter, the year in which the winter (DJF) extreme precipitation occurs is denoted as year 0 (DJF[0]) and the preceding year as year −1. The correlation between the three-month running averaged SIC and DJF(0) EPF indices indicates that the strongest negative correlation occurs when the SIC in the Okhotsk Sea leads winter EPF over SC by around 11 months. The correlation coefficient between the JFM(−1)-averaged SIC index in the Okhotsk Sea and DJF(0)-averaged EPF index over SC is −0.38 (significant at the 95% confidence level), which suggests a close connection between the winter SIC index in the Okhotsk Sea and the following winter EPF index over SC (Figure 1b). These indicate that larger SIC in the Okhotsk Sea favors lower EPF over the SC in the following winter, and vice versa.

To confirm the covariability of the winter SIC and the following winter EPF, we conducted maximum covariance analysis (MCA; Bretherton et al., 1992) between JFM(−1)-averaged SICAs in the Okhotsk Sea and the DJF(0)-averaged EPF over SC. The first leading MCA mode accounts for 95.7% of the total squared covariance (Figures S2a,b). The winter Okhotsk Sea is dominated by a negative SICA pattern, which shares characteristics with the correlation map in Figure 1d. In the following winter, the EPF pattern bears a strong resemblance to the correlation map in Figure 1c, with positive EPF anomalies over SC. The correlation coefficient between the corresponding expansion coefficients is 0.43 (significant at the 99% confidence level), indicating that the two fields included in the MCA are strongly coupled (Figure S2c). Therefore, these results support the finding that the winter (JFM(−1)) SIC in the Okhotsk Sea is significantly related to the following winter (DJF(0)) EPF over SC.

The results presented thus far indicate that the winter SIC in the Okhotsk Sea is closely tied to the following winter EPF over SC. It is thus necessary to examine whether the wintertime Okhotsk Sea SIC and the following winter EPF in SC are physically and dynamically linked. To understand the role of Okhotsk Sea winter SICA forcing in reinforcing the North Pacific anomalies, we began by examining the regression maps of the seasonal evolution of SST and surface wind anomalies against the JFM(−1)-averaged SIC index (Figure 2).

The spatial distribution of surface wind anomalies associated with the SIC index shows an anomalous cyclone and anticyclone pair over the North Pacific during JFM(−1), exhibiting a meridional dipole structure (Figure 2a), which reflects the dominant physical features of the positions of SLP anomalies (SLPAs). The composite differences of SLPAs over the North Pacific between heavy and light sea ice events are consistent with the surface wind anomalies (Figure S3a), which is reminiscent of the negative phase of the North Pacific Oscillation (–NPO; Rogers, 1981; Walker & Bliss, 1932), with a lobe of negative anomalies over the Aleutian Islands and broad positive SLPAs extending from 40°N to as far south

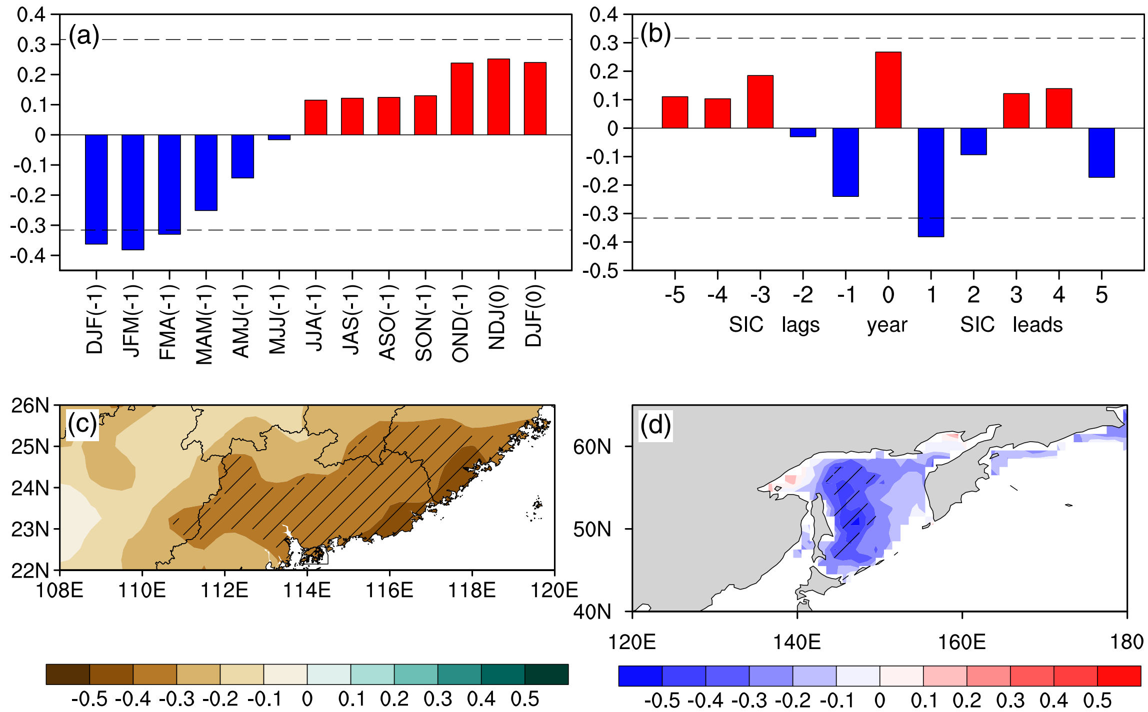

FIGURE 1 Relationship of winter EPF over SC with the Okhotsk Sea SIC. (a) Lead–lag correlations of the winter (DJF(0)) EPF index with overlapping three-month averaged values of the SIC index. (b) Lead–lag correlations of the winter (DJF(0)) EPF index with the JFM (−1) SIC index. In (a) and (b), the horizontal black dashed lines show the 95% significance level. Positive (red) and negative (blue) values of the correlation coefficients are indicated by colored bars. (c) Correlations of the JFM(−1)-averaged SIC index with the following DJF(0) EPF over SC. (d) Correlations of DJF(0)-averaged EPF index with the previous JFM(−1)-averaged SIC anomalies in the Okhotsk Sea. In (c) and (d), the oblique lines denote values that exceed the 95% confidence level

as the equator. While the NPO-like SLPAs primarily result from internal atmospheric variability, the circulation anomalies are reinforced by atmospheric teleconnections from the change in the SICAs (Kim et al., 2020; Yeo et al., 2014). Sea ice can help to reinforce the atmosphere above by regulating energy flux transfer. For example, the presence of sea ice significantly reduces heat and moisture fluxes from the sea surface and consequently acts to cool the atmosphere above the ice (Honda et al., 1996; Yeo et al., 2014). Thus, the remote SIC-forced effects from the Okhotsk Sea may contribute to these SLPAs over the North Pacific. To validate our hypothesis and verify the diagnostic analysis results, numerical simulation experiments were conducted using the CAM5 model to analyze the atmospheric response in the North Pacific to the SICA forcing in the Okhotsk Sea. The differences between the sensitivity and control experiments were considered to be the anomalies forced by the winter sea ice anomalies in the Okhotsk Sea. Under the winter Okhotsk Sea SICA forcing, the simulated response of the JFM-averaged SLPAs over the North Pacific was properly captured by the model (Figure S3b), which is roughly characterized as an −NPO-like pattern, with out-of-phase SLP variations over the northern and southern poles with a nodal point near 45°N. Although the simulated center of the northern SLPA pole over the Aleutian Islands is somewhat weaker and shifted eastward compared with that in the observations, the spatial pattern of the simulated SLPAs shares characteristics with the SLPAs seen in Figure S3a, which is further supported by the strong correlation of the SLPA patterns ($R = 0.53$; significant at the 99% confidence level). Therefore, this experimental result supports that the winter SICAs in the Okhotsk Sea can help to reinforce the −NPO-like atmospheric circulation over the North Pacific.

The −NPO generated by the concurrent Okhotsk Sea SICAs can then force an apparent Victoria mode (VM)-like SST footprint over the North Pacific in spring through modulating surface heat fluxes (Vimont et al., 2001, 2003), with a tilted SSTA dipole pattern in the extratropical Pacific and negative SSTAs in the northeast Pacific (Figure 2b; Bond et al., 2003; Ding et al., 2015). This SST footprint persists until summer in the subtropics via a wind-evaporation-SST feedback mechanism (Xie & Philander, 1994; Figures 2c,d). The negative SSTAs in the subtropical northeast Pacific, combined with positive SSTAs in the western North Pacific, increase the zonal SSTA gradient along the western-central tropical Pacific

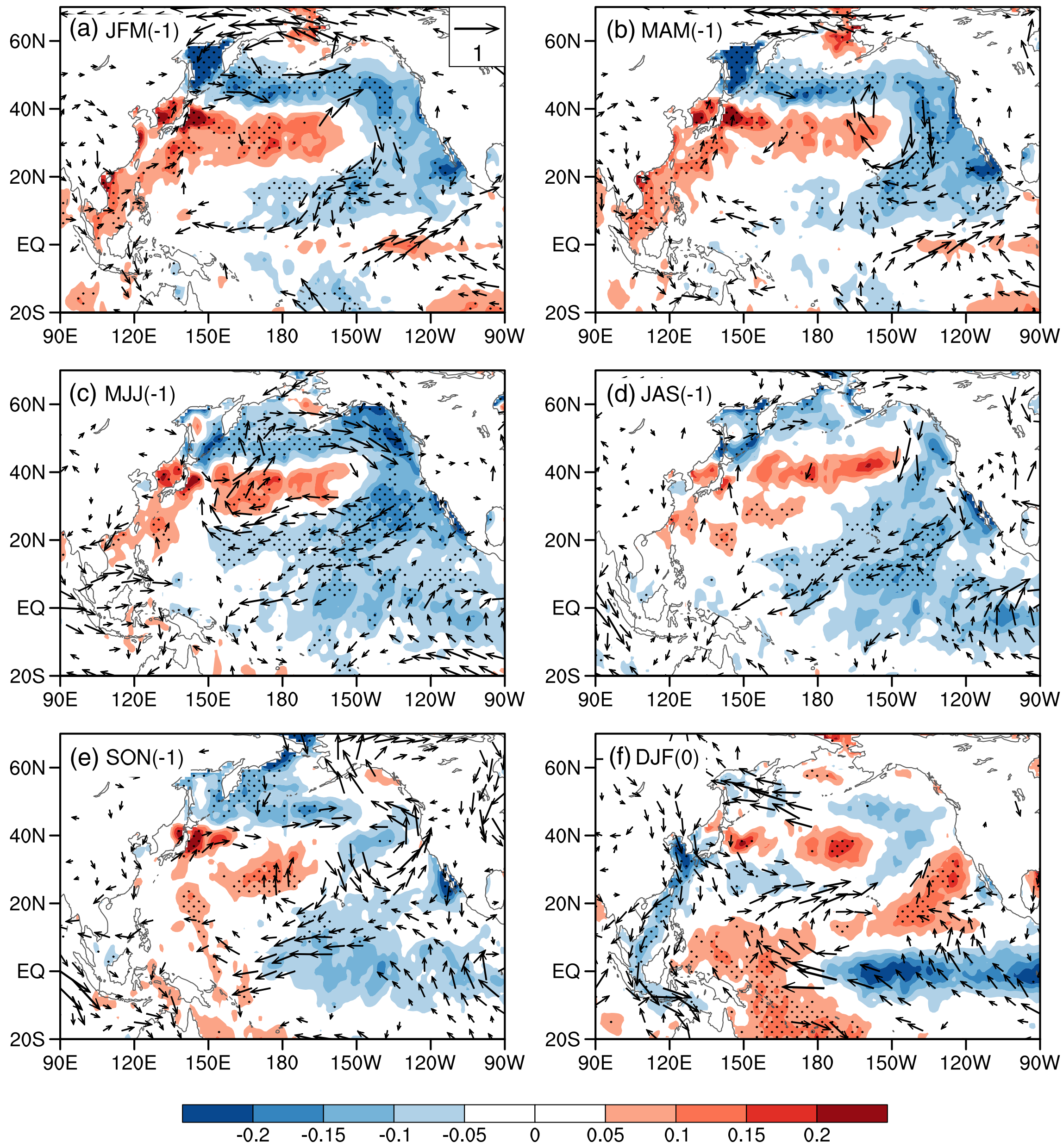

FIGURE 2 Regression maps of the JFM(−1)-averaged SIC index with the three-month averaged SST (shaded) and 850 hPa wind (vectors) anomalies for JFM(−1), MAM(−1), MJJ(−1), JAS(−1), SON(−1), DJF(0). SST anomalies significant at the 90% confidence level are indicated by black dots. Only surface wind vectors significant at the 90% confidence level are shown

that in turn strengthening low-level easterly wind anomalies. Subsequently, the enhanced equatorial easterly wind anomalies are conducive to triggering a positive Bjerknes feedback (Alexander et al., 2010; Bjerknes, 1969; Vimont et al., 2009), which drives the development of La Niña-like cold SSTAs in the equatorial eastern Pacific during the following winter (Figures 2e,f). Therefore, the variability of Okhotsk Sea winter SICAs has the potential to influence tropical Pacific SSTAs (i.e., El Niño–Southern Oscillation (ENSO)) via air-sea-ice coupled processes in the North Pacific.

As La Niña reached its peak during winter (DJF(0)), an anomalous cyclone appeared in the western North Pacific (WNP; Figure 2f). It is well-known that the anomalous anticyclone over the WNP (WNPAC) is an important system that bridges the ENSO and East Asian climate (Wang & Weisberg, 2000; Wu et al., 2009, 2017; Xie & Wang, 2020; Yuan et al., 2012). The WNPAC during an El Niño mature winter is regarded as a Rossby wave response to the negative heating anomalies via local thermodynamic atmosphere–ocean interaction (T. Li et al., 2017; Wang & Weisberg, 2000; Wu et al., 2010; Wu et al., 2017; Zhang et al., 1996). In the opposite phase, the anomalous cyclone induced by La Niña enhances northeasterly anomalies on the northwest flank that weaken the water vapor transport from the Indian Ocean and the South China Sea to SC (Figures 2f, 3c). Meanwhile, the East Asian winter monsoon (EAWM) induced by La Niña-like SSTAs is significantly enhanced (Figure 2f; Wen et al., 2000), which further reduces winter rainfall over SC (Jia et al., 2015; Wang & Chen, 2010; Wen et al., 2000; Zhou & Wu, 2010). Additionally, the divergence at low-level and convergence at high-level in SC result in descending motion, suppressing convection over SC (Figures 3a,b), which further sets up a favorable condition for the decreasing winter EPF over SC. The above analyses indicate that the ENSO (i.e., La Niña) may act as a key "power amplifier," which increases the signal from the extratropical North Pacific to a level that is strong enough to drive the East Asian climate, boosting the potential impact of the winter SICAs in the Okhotsk Sea on the following winter EPF over SC via a positive atmosphere–ocean feedback process.

One may argue whether such a relationship between the winter SICAs in the Okhotsk Sea and the following winter EPF in SC can be reproduced in climate models from the Coupled Model Intercomparison Project phases 5 or 6 (CMIP5 or CMIP6). We further examined this relationship using the CMIP6 (5) historical experiments (details are given in Table S1) from 1979–2014 (1970–2005). Figure S4 shows that 1 out of the 12 CMIP6 (EC-Earth3-Veg-LR) and 2 out of the 19 CMIP5 (MIROC-ESM-CHEM; MPI-ESM-LR) models can reasonably simulate the observed SIC-precipitation relationship, and the multi-model ensemble (MME) mean of this three models of the correlation map of the JFM(−1)-averaged SIC index with the DJF(0)-averaged EPF over SC (Figure S3c) can reasonably reproduce the observed results (Figure 1c). Although the negative MME mean precipitation anomalies occur over the greater part of SC, most of the models

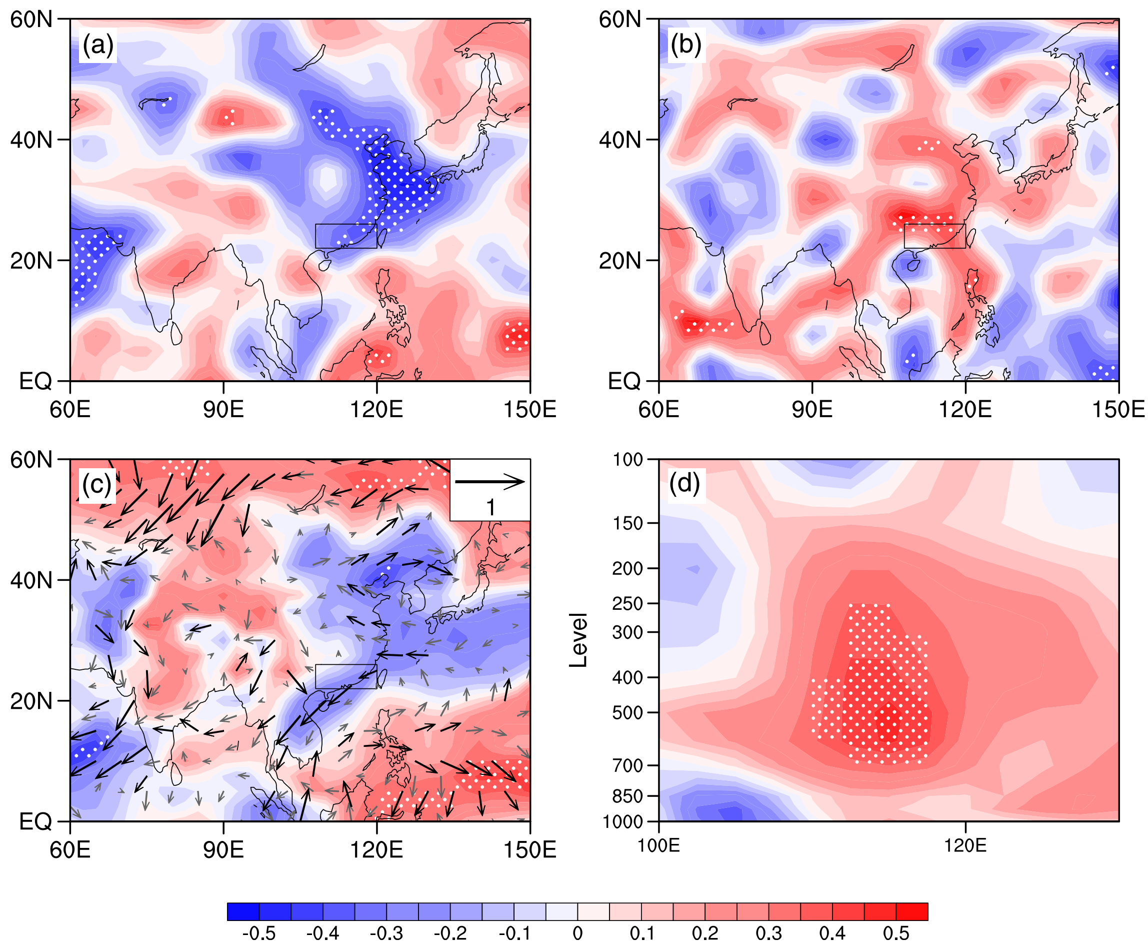

FIGURE 3 Correlation maps of the JFM(−1)-averaged SIC index with DJF(0) divergence (positive values denote divergence) over East Asia at (a) 200 and (b) 700 hPa, (c) vertically integrated (from 1000 to 500 hPa) water vapor transport flux (shaded and vectors), and (d) vertical velocity averaged between 22°N and 26°N (shaded), respectively. Areas exceeding the 90% confidence level are stippled by white dots in the above plots. The black boxes denote the SC region (108°–120°E, 22°–26°N)

have difficulty reproducing the relationship due to uncertainty about the simulated NPO-like atmospheric variability in the CMIP6 (5) models. Despite this, as expected, the MME mean of the correlation map of the JFM(−1)-averaged SIC index with the SLPAs over the North Pacific (Figure S3d) is very similar to the observed pattern shown in Figure S3a, which implies that the simulated atmospheric circulation anomalies can be reinforced by the change in the Okhotsk Sea SICAs. The stimulated –NPO-like atmospheric circulation in turn induces the La Niña-like SST anomalies in the following winter (results of the three models are given in Figures S5, S6, and S7). Therefore, further modeling studies are required to improve understanding of the air-ice-sea processes in the North Pacific.

4 | SUMMARY AND DISCUSSION

The present work investigates the relationship between the winter SIC in the Okhotsk Sea and the EPF over SC during the following winter. The significant negative correlation between the JFM(−1)-averaged SIC anomalies in the Okhotsk Sea and variations of the DJF(0)-averaged EPF over SC indicates that the SICAs in the Okhotsk Sea are closely related to the following winter EPF over SC with a leading time of about 11 months. We argue that winter SICAs in the Okhotsk Sea can serve as a precursor to the following winter EPF over SC. The simulation was conducted to analyze the atmospheric response in the North Pacific to the SICA forcing in the Okhotsk Sea. Similar to the observations, we found that winter SICAs in the Okhotsk Sea may help to reinforce the −NPO-like atmospheric circulation over the North Pacific. The −NPO induces the development of La Niña-like SSTAs in the equatorial eastern Pacific during the following winter by forcing VM-related SSTAs in the extratropical North Pacific. In turn, the cyclonic flow over the tropical western Pacific and enhanced EAWM induced by La Niña weaken the water vapor transport from the Indian Ocean and the South China Sea, which set up a favorable condition for the decreasing winter EPF over SC (Figure 4). These analyses indicate that the ENSO (i.e., La Niña) may act as a key "power amplifier" to boost the impact of the winter SICAs in the Okhotsk Sea on the following winter EPF over SC via a positive atmosphere–ocean feedback process. Thus, Okhotsk Sea winter SIC may act as an effective predictor of winter extreme precipitation over SC.

Given the uncertainty in the prediction of extremes, improving the predictability of extremes is one of the most important issues in climate science. We emphasize in this study that SIC in the Okhotsk Sea help to maintain the –NPO-like pattern that favors the reduction of the winter extreme precipitation over SC. However, we do not downplay other climatic factor in the Atlantic and Indian Ocean that may also play roles in the winter extreme precipitation over SC (Wang, 2019; Zheng & Wang, 2021). Additionally, the sea ice cover in high latitudes has experienced a significant decrease in recent years. The sharp decrease in sea ice cover may be attributed to global warming (Hansen et al., 2010; Screen & Simmonds, 2010; Serreze et al., 2009). Future research is needed to improve understanding of the response of the variability of sea ice cover in high latitudes and other climatic factors and their climate impacts on global warming (Gao et al., 2015; Li et al., 2020; Liu et al., 2012; Ogawa et al., 2018; Sato et al., 2018).

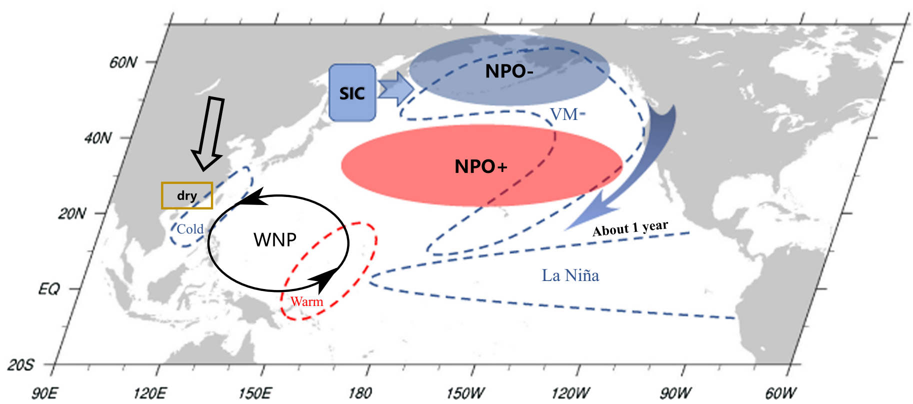

FIGURE 4 Schematic diagram explaining how the winter SIC in the Okhotsk Sea affects the following winter EPF over SC. A strong positive SIC during winter helps to reinforce the negative VM during the following spring via the −NPO-like SLPA variability, which induces the development of La Niña-like cooling SSTAs. The convective warming induced by La Niña triggers the formation of the anomalous cyclone over the WNP. The anomalous northeasterlies associated with the cyclone favor insufficient water vapor and anomalous descending motion over SC, finally resulting in the decrease of winter EPF over SC

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AUTHOR CONTRIBUTIONS

Kai Ji: Conceptualization; Data Curation; Formal Analysis; Methodology; Software; Visualization; Writing—original draft; writing—review and editing. Zhongshi Zhang: Conceptualization; writing—review and editing. Ruiqiang Ding: Conceptualization; Writing—original draft; writing—review and editing. Jianping Li: Conceptualization; writing—review and editing. Yurun Tian: Methodology; Software; writing—review and editing. Yongqi Gao: Software; writing—review and editing. Jiayu Zheng: writing—review and editing.

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