Combined impact of Greenland sea ice, Eurasian snow, and El Niño–Southern Oscillation on Indian and Korean summer monsoons

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Abstract
The combined impact of Greenland sea ice, Eurasian snow, and the El Niño–Southern Oscillation (ENSO) on the out-of-phase relationship between the Indian summer monsoon (ISM) and Korean summer monsoon (KSM) were investigated through numerical experiments. The results revealed that Indian and Korean summer rainfalls showed nonlinear responses to ENSO and Greenland sea ice forcing when the events co-occurred. Above-normal Greenland sea ice and a concurrent La Niña showed a distinct in-phase relationship with ISM and out-of-phase relationship with KSM. Below-normal and above-normal Greenland sea ice during boreal autumn surrounded the Greenland region with anomalous low pressure and high pressure, respectively. These were associated with a barotropic +west/−east or −west/+east dipole pattern, respectively, over Eurasia during the subsequent winter and spring seasons. Furthermore, these patterns led to positive and negative snow depth anomalies, respectively, over western Eurasia and the opposite snow tendency over eastern Eurasia during the subsequent spring. This variability in Eurasian snow patterns may play a crucial role in ISM and KSM. The co-occurrence of ENSO variability also generates high- and low-pressure anomaly patterns over the Indian Ocean that may be related to unfavourable or favourable ISM, respectively, while influencing the negative or positive phases of a Pacific Japan (PJ)-like teleconnection pattern that may be related to unfavourable or favourable KSM, respectively. Therefore, coexisting ENSO forcing may play a dominant role in ISM and KSM, but Greenland sea ice forcing and Eurasian snow variation intensify the out-of-phase relationship between ISM and KSM.

KEYWORDS
ENSO, Eurasian snow, Greenland sea ice, Indian summer monsoon, Korean summer monsoon

1 | INTRODUCTION

The Asian summer monsoon (ASM) can be roughly classified into two subsystems: South Asian summer monsoon (SAM) and East Asian summer monsoon (EASM). SAM covers the Arabian Sea, Indian subcontinent, and Bay of Bengal, while EASM includes China, Korea, and Japan. Although the South Asian and East Asian regions are...
geographically distant and independent from each other, their monsoon systems interact with each other on different timescales. Multiple studies have examined the in-phase and out-of-phase inter-annual variations between SAM and EASM (Kripalani and Kulkarni, 2001; Wu, 2002; Ha et al., 2012; Greatbatch et al., 2013; Ha et al., 2017; Wu, 2017; Prabhu et al., 2018). The out-of-phase relationship between SAM and EASM has strengthened recently (Yun et al., 2014; Preethi et al., 2016). Although several studies have considered the linkages between SAM and EASM, the actual physical mechanism has not yet been completely identified.

Earlier studies have revealed a large-scale teleconnection related to ASM, especially with regard to its association with Arctic sea ice, Eurasian snow, and the El Niño–Southern Oscillation (ENSO). The winter variability of Arctic sea ice is connected to mid-latitude weather and climate by anomalous wave trains, changing storm tracks, and the jet stream (Cohen et al., 2014; Chen et al., 2016; Nakamura et al., 2016). Several studies have explained the role of Arctic sea ice in ASM. For example, Arctic sea ice loss in spring reinforces Chinese summer monsoon through land surface processes and Rossby wave dynamics (Zhao et al., 2004; Wu et al., 2009), which indicates teleconnection between the spring Arctic sea ice and EASM through sea surface temperature (SST) variability over the North Pacific. On the other hand, the boreal autumn variability of ice in the Kara and Barents Seas has a strong relationship with the subsequent Indian summer monsoon rainfall (Prabhu et al., 2012). He et al. (2018) performed numerical experiments to demonstrate that ice in the Kara and Barents Seas in June influences East Asian summer rainfall through wave train propagation.

Earlier studies focused on the impact of Eurasian snow variability on ASM. Recently, a west–east dipole-type snow pattern over the Eurasian region was found as the second mode of an empirical orthogonal function (EOF) for snow distribution, and it was observed to have a significant influence on monsoons. More snow over western Eurasia and less snow over eastern Eurasia were unfavourable for Indian summer monsoon (ISM) (e.g., Kripalani and Kulkarni, 1999; Dash et al., 2005; Singh and Oh, 2005) while being favourable for EASM (e.g., Kripalani et al., 2002; Yim et al., 2010; Wu et al., 2014). Halder and Dirmeyer (2017) proposed that winter and spring Eurasian snow cover and snow melt have a delayed hydrological effect on the ensuing ISM. Zhang et al. (2017) showed through observations and numerical experiments that the west–east dipole structure of Eurasian snow may significantly affect EASM (especially over China) through anomalous mid-latitude Eurasian wave propagation.

Many previous studies have investigated the physical mechanism of the relationship between ENSO-SAM and ENSO-EASM. Hu et al. (2005) investigated the influence of ENSO on the relationship between the summer monsoon rainfall variations of India and East Asia. They suggested that ENSO generally reinforces the links between ISM and EASM. Yun et al. (2014) demonstrated the strengthening of the zonal SST gradient in association with the recent mega-La Niña trend, which tends to enhance the negative connection between SAM and EASM by enhancing convection over the maritime continent and propagating Rossby waves northwestward.

Previous studies have shown that the aforementioned variabilities of Arctic sea ice, Eurasian snow, and ENSO are closely linked with each other, although the mechanisms of the underlying connections are complex. Recent studies have suggested a similar chain of events from boreal autumn to winter for both snow cover and sea ice (Cohen et al., 2014; Wegmann et al., 2015; Gastineau et al., 2017). Arctic sea ice changes can occur independently but sometimes co-occur with ENSO. For example, substantially less sea ice occurred in 2007 autumn, which was followed by a strong La Niña event in the subsequent winter. More sea ice appeared in 1997 autumn, which was accompanied by a strong El Niño in the following winter. Ding et al. (2014) suggested that their observations and model experiments showed that the central tropical Pacific SST may affect the recent Arctic warming over northeastern Canada and Greenland through Rossby wave propagation. The cooling trend over equatorial Pacific is strongly coupled with winter sea ice melting in the Barents Sea and anticyclone formation over Scandinavia (Dobricic et al., 2016).

Prabhu et al. (2018) suggested a physical mechanism for the out-of-phase relationship between ISM and Korean summer monsoon (KSM) through observation of the Greenland sea ice variation. They demonstrated that negative extreme cases of boreal autumn Greenland sea ice trigger an anomalous zonal wave over higher latitudes in the Northern Hemisphere with a descending motion over Pacific Ocean. Anomalous highs over high-latitude regions confined to the Pacific longitudes trigger anomalous meridional waves from the subpolar to mid-latitudes from SON(0) to JJA(1), where “0” represents months of the current year while “1” corresponds to months of the subsequent year. This is associated with central Pacific warming, which results in deficient ISM. Below-normal Greenland sea ice conditions can induce sufficient Korean monsoon rainfall (KMR) through an anomalous zonal wave descending over Eurasian snow. Anomalous high pressure zones over the Eurasian region confined above the Korea region trigger an anomalous meridional wave from the subpolar to mid-latitudes from
SON(0) to JJA(1) with an ascending branch over Korea, which leads to above-normal rainfall.

The objective of the present study is to understand the proposed mechanisms for the combined impact of Greenland sea ice, Eurasian snow, and ENSO on the diverse natures of ISM and KSM via numerical experiments. The rest of this paper is organized as follows. Section 2 describes the methodology, model, and experiment design. Section 3 describes the individual impacts of Greenland sea ice, Eurasian snow, and ENSO. Section 4 describes the teleconnection mechanism for the combined impact. Finally, Section 5 presents the summary and conclusions.

2 | METHODOLOGY AND DATASETS

2.1 | Model description

Sensitivity experiments were performed with Community Atmospheric Model 5 developed at the National Center for Atmospheric Research (Neale et al., 2012). The horizontal resolution of the model was maintained by finite volume grids of 0.47° latitude and 0.63° longitude. The vertical resolution was set to 30 vertical levels with a lid at 5 hPa. In addition, the merged version climatological sea ice concentration and SST dataset of Hadley Centre (HadISST1) (Hurrell et al., 2008) were utilized.

2.2 | Experimental design

The numerical experiments were in three parts: (a) individual impact experiments, (b) combined impact experiments with climatology snow depth, and (c) combined impact experiments with prognostic snow. More details are summarized in Tables 1–3. The individual impact experiments were conducted to ascertain which climate factor is more dominant with regard to ISM and KSM. The individual experiments were performed with Greenland sea ice, Eurasian snow, and ENSO as single forcings. The combined experiments were performed to examine the response of ISM and KSM to the effects of Greenland sea ice, Eurasian snow, and ENSO simultaneously. In particular, two sets of combined impact experiments were designed: with and without sea ice perturbation induced by snow depth variation. Based on previous studies (Cohen et al., 2014; Wegmann et al., 2015; Gastineau et al., 2017), the large-scale variation

### TABLE 1 Description of the individual impact experiments

| Name                        | Prescribed forcing                                      | Snow                              | SST                 |
|-----------------------------|---------------------------------------------------------|-----------------------------------|---------------------|
| CTRL                        | Climatology sea ice                                     | Climatology snow depth            | Climatology SST     |
| Low Greenland SICE_C        | Low sea ice over Greenland                              | Climatology snow depth            | Climatology SST     |
| High Greenland SICE_C       | High sea ice over Greenland                             | Climatology snow depth            | Climatology SST     |
| ElNino_C                    | Climatology sea ice                                     | Climatology snow depth            | El Niño             |
| LaNina_C                    | Climatology sea ice                                     | Climatology snow depth            | La Niña             |
| High WEur and low EEur_C    | Climatology sea ice                                     | Heavy snow depth over western Eurasia | Climaology SST |
| Low WEur and high EEur_C    | Climatology sea ice                                     | Light snow depth over eastern Eurasia | Climaology SST |
| Low Greenland SICE_P        | Low sea ice over Greenland                              | Prognostic snow (time-varying)    | Climatology SST     |
| High Greenland SICE_P       | High sea ice over Greenland                             | Prognostic snow (time-varying)    | Climatology SST     |
| ElNino_P                    | Climatology sea ice                                     | Prognostic snow (time-varying)    | El Niño             |
| LaNina_P                    | Climatology sea ice                                     | Prognostic snow (time-varying)    | La Niña             |

### TABLE 2 Description of the combined impact experiments with climatology snow

| Name                      | Prescribed forcing                                      | Snow                              | SST                 |
|---------------------------|---------------------------------------------------------|-----------------------------------|---------------------|
| Low Greenland SICE and ElNino_C | Low sea ice over Greenland                         | Climatology snow (fixed snow)    | El Niño             |
| High Greenland SICE and ElNino_C | High sea ice over Greenland                         | Climatology snow (fixed snow)    | El Niño             |
| Low Greenland SICE and LaNina_C | Low sea ice over Greenland                         | Climatology snow (fixed snow)    | La Niña             |
| High Greenland SICE and LaNina_C | High sea ice over Greenland                         | Climatology snow (fixed snow)    | La Niña             |
of Eurasian snow during winter and spring was assumed to be caused by the Arctic sea ice variability of the preceding autumn. Another reason for the experiments was that the snow depth in atmospheric general circulation model is a prognostic variable, unlike the sea ice and SST components.

A control run and perturbation experiments were conducted under slightly varying atmospheric initial conditions. All experiments started in the month of April and were run until the following August. In the individual impact experiments, the responses to individual forcings were defined as the composite differences between related extreme cases. In the combined impact experiments, the atmospheric responses were defined by subtracting the ensemble mean of the perturbation experiments from that of the control run.

The lower boundary forcings for the control run and eight perturbation experiments were designed as follows:

1. The control (CTRL) included a simulation with forced SST, snow depth, and sea ice geographical location, which are easily identified on a map.
2. The sea ice forcing was prescribed by superimposing $\pm 1\sigma$, $\pm 2\sigma$, $\pm 3\sigma$, and $\pm 4\sigma$ from September to December(0) on the daily climatological sea ice concentration over the Greenland region (55°–81°N, 45°W–18°E) in order to identify the Greenland sea ice effect (Figure 1a, b).
3. The snow forcing was prescribed by superimposing anomaly composites related to the west-east dipole-type Eurasian snow from December(0) to April(1) over 30°–110°E, 50°–65°N (Figure 1c, d).
4. The SST forcing was prescribed by superimposing anomaly composites related to ENSO from DJF(0/1) to JJA(1) on the daily climatological SST over the Niño 3.4 region (10°S–10°N, 170°–120°W) in order to consider the ENSO effect (Figure 1e, f).

2.3 | Observations

To verify indices of the ISM and KSM, NCEP–DOE AMIP-II reanalysis (Reanalysis-2) (Kanamitsu et al., 2002) dataset for zonal and meridional wind at 850 and 200 hPa and the Global Precipitation Climatology Project (GPCP) (Adler et al., 2003) version 2.2 are used.

3 | RESPONSES OF ISM AND KSM TO INDIVIDUAL FORCINGS

3.1 | ISM and KSM variations

To examine the variations of ISM and KSM with each individual forcing, their responses were analysed during May–August, which represented the beginning and end of ISM and KSM. Figure 2 shows the spatial pattern of rainfall and wind vectors at 850 hPa for MJJA(1) over the Asian monsoon region for the experiments on the individual forcing impacts of Greenland sea ice, ENSO, and Eurasian snow. The composite differences of Greenland sea ice (Low Greenland SICE_C – High Greenland SICE_C) showed insignificant negative rainfall anomalies (Indian rainfall index [IRI] = −0.26), especially around the Arabian Sea and Bay of Bengal (Figure 2a, Table 4), supplemented by a weakened Somali jet and cross-equatorial flow (Figure 2d). Conversely, extensive positive rainfall anomalies surrounding Korea (Korean rainfall index [KRI] = 0.19) (Figure 2a, Table 4) were complemented by the presence of southeasterly wind anomalies and Bonin high intensification (Figure 2d). This circulation pattern is quite similar to the 500 hPa geopotential height distribution, which demonstrates the position of the Bonin high and its connection with KSM (Ha and Lee, 2007). Thus, the experimental results were consistent with the observed Greenland sea ice variability and its influence on the out-of-phase relationship between ISM and KSM (Table 4, Prabhu et al., 2018). The Eurasian snow anomaly (High WEur and Low EEur_C—Low WEur and High EEur_C) produced a weak response of rainfall over the Indian and Korean regions (Figure 2b). Negative anomalies were observed around the Indian Ocean (10°–20°N), and positive anomalies surrounded the south of the Korean peninsula (IRI = −0.12, KRI = 0.53) (Table 4). The wind anomaly distribution in the lower level showed westerly anomalies over north of India (around

| Name                        | Prescribed forcing                  | Sea ice            | Snow                        | SST          |
|-----------------------------|-------------------------------------|--------------------|-----------------------------|--------------|
| CTRL_P                      |                                     | Climatology sea ice| Prognostic snow (time-varying) | Climatology SST |
| Low Greenland SICE and ElNino_P | Low sea ice over Greenland          | Prognostic snow (time-varying) | El Niño     |
| High Greenland SICE and ElNino_P | High sea ice over Greenland         | Prognostic snow (time-varying) | El Niño     |
| Low Greenland SICE and LaNina_P   | Low sea ice over Greenland          | Prognostic snow (time-varying) | La Niña   |
| High Greenland SICE and LaNina_P   | High sea ice over Greenland         | Prognostic snow (time-varying) | La Niña   |
20°N) and easterly anomalies over the south of the Indian Ocean (around 10°N), which formed a weak cyclonic circulation over the southern Indian region (10–20°N). The Korea region also showed cyclonic circulation anomalies (Figure 2e).

For ENSO, significant negative rainfall anomalies prevailed over India that were consistent with easterly anomalies surrounding the Arabian Sea and Bay of Bengal (IRI = −0.76) and consistent with observation (IRI = −0.55) (Table 4). This rainfall anomalies are relevant to weakened
Somali jet and deficient supply of moisture flux towards the Indian region (Figure 2c, f). Previous studies have also shown ISM's dependence on Walker circulation changes induced by ENSO variability (Hendon, 2003; Shinoda et al., 2004; Wu et al., 2012). Negative rainfall anomalies were observed over Korea accompanied by anomalous northwesterly winds (KRI = −0.21) (Table 4) unlike the observation (KRI = 0.01), similar to the features highlighted by Yeo et al. (2017) (Figure 2c, f). Unlike Indian Monsoon Rainfall (IMR), however, a robust relationship between ENSO and KMR is controversial. Several studies have pointed out the statistically insignificant relationship

| Table 4 | Indices of ISM and KSM for observations and experiments on Greenland sea ice, Eurasian snow, and ENSO variability |
|---------|----------------------------------------------------------------------------------------------------------|
| Index   | Variable                                                                                                    |
|         | Observations | Greenland sea ice | Eurasian snow | ENSO | Experiments | Greenland sea ice | Eurasian snow | ENSO |
| Indian Rainfall Index (IRI) | Precipitation, (65–95°E, 5–35°N) | −0.43 | −0.25 | −0.55 | −0.26 | −0.12 | −0.76 |
| Korean Rainfall Index (KRI) | Precipitation, (120–130°E, 30–38°N) | 0.13 | 0.62 | 0.01 | 0.19 | 0.53 | −0.21 |
| Indian velocity potential Index | Velocity potential at 850 hPa, (65–95°E, 5–35°N) | −0.82 | −0.11 | −1.28 | −0.20 | 0.01 | −1.49 |
| Korean velocity potential Index | Velocity potential at 850 hPa, (120–130°E, 30–38°N) | −0.42 | 0.42 | −1.27 | 0.21 | 0.15 | −1.36 |
| Indian velocity potential Index | Velocity potential at 200 hPa, (65–95°E, 5–35°N) | 3.08 | 0.26 | 3.61 | 0.17 | 0.44 | 3.68 |
| Korean velocity potential Index | Velocity potential at 200hpa, (120–130°E, 30–38°N) | 0.13 | −0.56 | 1.66 | −0.90 | 0.08 | 2.29 |

Note: For observations, 10 strongest episodes each of below and above normal on Greenland sea ice, Eurasian snow, and ENSO are selected based on Prabhuv et al., 2018.
between ENSO and KMR (Ho et al., 2016; Prabhu et al., 2018). Other studies have suggested that the weak relationship between ENSO and KMR may be because the different flavours and evolution of ENSO have not been considered (Kug et al., 2010; Yeo et al., 2017).

Figure 3 shows the responses of the velocity potential at 850 and 200 hPa, which describe the convergence and divergence of wind vectors at the lower and upper levels, respectively. This is closely associated with the convection and monsoon intensity. In the case of Greenland sea ice, a weak dipole pattern was observed over the regions surrounding India and Korea. The spatial distribution of the potential vorticity at 850 hPa displayed negative anomalies over India (−0.20) and positive anomalies over Korea (0.21). The anomalies of the velocity potential at 200 hPa over India (0.17) and Korea (−0.90) were opposite to the pattern at 850 hPa (Figure 3a, d, Table 4). Hence, the pattern implies the occurrence of a lower-level divergence and upper-level convergence surrounding the Indian region, which is not conducive for rainfall. The opposite situation occurred for the Korean region. The spatial patterns had opposite signatures with lower level convergence and upper level divergence leading to favourable conditions for excessive rainfall.

In the case of Eurasian snow, a weak in-phase anomaly pattern was observed between India and Korea at 850 and 200 hPa (Figure 3b, e, Table 4). In the case of ENSO forcing, an out-of-phase velocity potential pattern between India and Korea did not appear, but a large Asian domain encompassing both India and Korea was fully covered by significant negative anomalies at the lower level (India: −1.49, Korea: −1.36) and equally significant positive anomalies at the upper level (India: 3.68, Korea: 2.29) (Table 4). This implies the occurrence of lower-level divergence and upper-level convergence over the entire domain (Figure 3c, f). This in-phase relationship between India and Korea in the experiment is consistent with observation at 850 hPa.
(India: −1.28, Korea: −1.27) and 200 hPa (India: 3.61, Korea: 1.66). This uniform pattern over the Asian domain further implies that ENSO, although a dominant factor especially for ISM, may not independently address the diverse natures of the Indian and Korean monsoons. Hence, the individual forcing experiments showed that only the Greenland sea ice variability has the capability of inducing an out-of-phase pattern between the Indian and Korean monsoon domains. Nevertheless, ENSO had a markedly stronger impact in the regions of interest compared to the Greenland sea ice and Eurasian snow forcings.

3.2 | Seasonal evolution of atmospheric circulation

To ascertain how the delayed response evolves to each forcing for the following three seasons, the large-scale circulation patterns were analysed for the geopotential height at 500 hPa. Figure 4 shows the response of the geopotential heights at 500 hPa from SON(0) to JJA(1) for the experiments involving Greenland sea ice, Eurasian snow, and ENSO as independent forcings. For Greenland sea ice, negative anomalies were evident surrounding this region (0–60°W, 50–70°N), while positive anomalies were over western Eurasia (0–60°E, 50–70°N) during SON(0) and intensified for the ensuing winter DJF(0/1). These spatial patterns persisted during MAM(1) with a slight eastward movement towards central-eastern Eurasia and displayed a zonal wave connecting Greenland with Eurasia. However, this spatial pattern disappeared during the ensuing JJA(1) (Figure 4a). Generally, Greenland sea ice loss during autumn and winter is associated with the negative phase of the North Atlantic Oscillation (NAO) (Hurrell et al., 2003; Alexander et al., 2003; Germe et al., 2011). However, here the response to Arctic sea ice was different; there was a normal mode of the NAO pattern with a subpolar low (approximately 60°N) and mid-latitude high (approximately 40°N) (SON(0) and DJF(0/1) panels in Figure 4a). Several other

FIGURE 4 Response of the geopotential heights at 500 hPa (m) from SON(0) to JJA(1) for (a) Greenland Sea ice experiments (Low Greenland SICE_C—High Greenland SICE_C) and, (b) Eurasian snow experiments (High WEur and Low EEur_C—Low WEur and High EEur_C) and (c) ENSO experiments (ElNino_C—LaNina_C)
studies have also pointed out that sea ice variations around the eastern part of Greenland induce a local response in the atmospheric circulation unlike the NAO entity (Deser et al., 2000; Ogi et al., 2016).

Next, in the case of Eurasian snow, a dominant zonal wave train-like positive Eurasian teleconnection pattern (EU) (Wallace and Gutzler, 1981) appears over 30°–70°N for MAM(1) and was weakly sustained until JJA(1) (Figure 4b). The positive EU phase displayed negative centres over the Indian longitudes and positive centres over the East Asia longitudes. The EU pattern is known to be an important low-frequency pattern affected by atmospheric circulation over the Eurasian region as a classic three-centre structure. Wang et al. (2017) pointed out that the variation in the Eurasian snow cover induced by the positive EU pattern during spring along with El Niño triggered the North China drought. The west–east dipole pattern pertaining to Eurasian snow depth anomalies causes the EU pattern, which may influence the subsequent ISM and KSM. In particular, this analysis fostered an idea about the springtime responses of 500 hPa geopotential anomalies to the combined effect of both Greenland sea ice and Eurasian snow forcings, which may enhance positive anomalies around the longitudes of Korea (100°–130°E).

For ENSO (Figure 4c), a poleward-moving meridional wavelike teleconnection pattern from DJF(0/1) to JJA(1) was evident over the western North Pacific and East Asia, which is referred to as the Pacific-Japan (PJ) pattern (Nitta, 1987). Further, high-pressure anomalies from MAM(1) to JJA(1) were observed over the Indian Ocean, which implies weakened monsoon circulation. Kubota et al. (2016) suggested that ENSO may be a major driver of the PJ pattern. Moreover, some previous studies have shown a close association between the Indian Ocean and Pacific Ocean, where ENSO variations through anomalous Walker circulations influence the atmospheric patterns over the Indian Ocean (Clarke et al., 1998; Krishnamurthy and Kirtman, 2003). In addition, as ENSO signals evolve from DJF(0/1) to MAM(1), strong positive and negative anomalies were observed over the subpolar and mid-latitude regions, respectively; this resembled a negative mode of the Arctic Oscillation (AO) pattern with a subpolar high and mid-latitude low. Such patterns generally lead to the Ferrel cell breaking, which causes an exchange of mass and momentum from higher northern latitudes towards the equator. Because of this pattern, a weak Rossby wave train was seen for JJA(1) from the sea around Greenland to East Asia and the adjoining western Pacific region. This implies that SST over the central Pacific may cause variations in the atmospheric circulation over the subpolar region and intensify it from DJF(0/1) to JJA(1). Previous study has also indicated an inter-relationship between AO and ENSO (Li et al. 2014).

### 4 | RESPONSES OF ISM AND KSM TO COMBINED FORCINGS

#### 4.1 | Relationship between ENSO and Greenland Sea ice

To understand the aforementioned synchronicity between Arctic sea ice and ENSO, the combined impact of Greenland sea ice and ENSO was analysed through sensitivity experiments. Figure 5 shows the relationship between Greenland sea ice for Oct(0) and ENSO for JJA(1). The Greenland sea ice showed an inverse correlation with the Niño3.4 index at a correlation coefficient of −0.34, which is statistically significant at a 90% level of confidence. Below-normal Greenland sea ice with El Niño and above-normal Greenland sea ice with La Niña were dominant in the observation dataset for 1980–2009. Specifically, the extreme cases of Greenland sea ice and ENSO taken together showed a markedly closer relationship than their normal cases. Although an inverse relationship was observed between Greenland sea ice and ENSO, there were some instances where this did not hold true, such as the years depicted in quadrants I and III. It may be noted (Figure 5) that there are few cases of above (below) SICE associated with El Niño (La Niña) cases. The next section focuses on the cases of below-normal Greenland sea ice accompanied with El Niño and above-normal Greenland sea ice with La Niña.
4.2 ISM and KSM variations

Figure 6 indicates the responses of IMR and KMR to combined forcings related to Greenland sea ice and ENSO along with the climatological snow depth in the background. In the case of below-normal Greenland sea ice and El Niño (Figure 6a), below-normal rainfall was observed over the south of India and above-normal rainfall was observed over Korea. This probably suggests some indication of the diverse natures over the two regions. In both cases of above-normal sea ice and El Niño and below-normal sea ice and La Niña, mixed responses were observed in terms of the rainfall distribution over the two countries (Figure 6b, c). For the case of above-normal Greenland sea ice and La Niña, the rainfall was intense in both India and Korea (Figure 6d). However, the diverse natures of the two countries were lost. In the combined impact experiments with the climatological snow depth, the ENSO phase had a more dominant effect on ISM than the Greenland sea ice.

Figure 7 shows the responses of IMR and KMR to combined forcings related to Greenland sea ice and ENSO considering the prognostic snow depth. For the case of below-normal Greenland sea ice and El Niño, a spatial rainfall distribution of positive rainfall anomalies over central India flanked with negative anomalies over Northern India and equatorial Indian Ocean was observed (Figure 7a). This tripod structure resembles the second mode of EOF associated with dominant modes of SST over the Pacific and Indian Oceans (Mishra et al., 2012). With below-normal Greenland sea ice, positive rainfall anomalies were spread across the regions surrounding Korea (Figure 7a, c), while opposite signatures prevailed over East Asia with above-normal Greenland sea ice (Figure 7b, d).

Among the four cases, above-normal Greenland sea ice with La Niña clearly showed diverse natures between the rainfall anomalies of India and Korea (Figure 7d); the spatial structures of positive and negative rainfall anomalies surrounding India and Korea, respectively, clearly agreed with the results of Prabhu et al. (2018) (Figure 7d). The below-normal Greenland sea ice cases clearly showed positive anomalies over Korea (Figure 7a, c), whereas negative anomalies prevailed in the above-normal Greenland sea ice cases (Figure 7b, d). Although the observation statistically showed the out-of-phase relationship between ISM and KSM on Greenland sea ice anomalies (Prabhu et al., 2018),

**Figure 6** Response of the precipitation anomalies (mm/day) in MJJA(1) related to climatological snow depth experiment for (a) below Greenland sea ice and El Niño case (Low Greenland SICE and ElNino_C), (b) above Greenland sea ice and El Niño case (High Greenland SICE and ElNino_C), (c) below Greenland sea ice and La Niña case (Low Greenland SICE and LaNina_C) and (d) above Greenland Sea ice and La Niña case (High Greenland SICE and LaNina_C)
among the four experiments the above-normal Greenland sea ice with La Niña indicated a distinct out-of-phase relationship between ISM and KSM.

4.3 | ISM and KSM variations: Teleconnection mechanism for combined impact

To comprehend the physical mechanism for the out-of-phase relationship of ISM and KSM from combined forcings in the sensitivity experiments, the spatial features of the related atmospheric circulation were examined. Here, we tried to focus below-normal Greenland sea ice with El Niño and above-normal Greenland sea ice with La Niña cases to follow the hypothesis of previous studies (Prabhu et al., 2018).

Figure 8 presents the composite differences in the turbulent heat flux, 2 m air temperature, sea level pressure (SLP), and geopotential height at 500 hPa for late boreal autumn from October through December [OND(0)] between the cases of below-normal Greenland sea ice with El Niño and above-normal Greenland sea ice with La Niña. There were significant positive turbulent heat flux anomalies over Greenland sea for OND(0) owing to an excess area covered by ocean with a large heat absorbing capability compared to sea ice (Figure 8a). Negative anomalies were observed around the Barents Sea and Norwegian Sea (Figure 8a). These anomalous heat flux anomalies over the ocean gradually weakened from DJF(1) to MJJA(1), but significant anomalies emerged over the Eurasian continent (Figures 9a, 10a, and 11a).

Simmonds and Keay (2009) found that a smaller extent of September sea ice is associated with deeper and larger cyclones because of an increase in the latent heat flux from the open ocean and absence of sea ice. The positive turbulent heat flux anomalies resulted in positive anomalies of the 2 m air temperature for the sea surrounding Greenland through an exchange of the heat flux from the surface to the atmosphere. Significance negative temperature anomalies over western Eurasia (30–60°E, 40–60°N) and eastern Eurasia (90–140°E, 30–60°N) were observed along with positive anomalies over the East Asian domain. This resembles a Rossby wave train pattern from the polar to mid-latitudes. Jaiser et al. (2012) investigated the atmospheric response to sea ice variation over the Arctic and showed that, during periods with a low sea ice concentration, the stronger heat

**FIGURE 7** Response of the precipitation anomalies (mm/day) in MJJA(1) related to prognostic snow depth experiment for (a) below Greenland sea ice and El Niño case (Low Greenland SICE and ElNino_P), (b) above Greenland sea ice and El Niño case (High Greenland SICE and ElNino_P), (c) below Greenland sea ice and La Niña case (Low Greenland SICE and LaNina_P) and (d) above Greenland Sea ice and La Niña case (High Greenland SICE and LaNina_P)
release to the atmosphere reduces the vertical static stability. This strengthens the atmosphere under the baroclinic instability condition, which results in Rossby wave structures. In the SLP and 500 hPa geopotential height anomalies for OND(0), there were distinct negative anomalies in the surrounding Greenland sea ice and west–east dipole-type Eurasian pattern (positive anomalies over western Eurasia and negative anomalies over eastern Eurasia) (Figure 8c, d). This means that the Greenland sea ice variation is intimately associated with the west–east dipole-type Eurasian pattern. This may also imply that these circulation anomalies for OND(0) influence the snow depth variation over Eurasia for the following winter and spring. According to Wu et al. (2013), the west–east dipole-type wintertime circulation over Northern Eurasia is significantly related to the Arctic sea ice anomalies of the preceding autumn.

As noted above, there may be a physical connection between Arctic sea ice and Eurasian snow. Therefore, the response of the Eurasian snow depth and related atmospheric parameters to the surface change caused by the Greenland sea ice variation of the preceding boreal autumn were investigated from winter to spring. The Eurasian snow anomalies distributions for DJF(0/1) and MAM(1) showed a dipole-type pattern: positive snow depth anomalies over western Eurasia (30°–90°E, 50°–60°N) and negative snow depth anomalies over eastern Eurasia (120°–140°E, 55°–60°N) (Figures 9a and 10a). This dipole pattern and the connection between the Greenland sea ice and Eurasian snow are similar to the monthly evolution of correlation patterns between the two from boreal autumn to the following spring in microwave satellite observations (Refer to fig. 10 of Prabhu et al. (2018)). Further, the snow variability may have decreased

FIGURE 8 Composite differences between below Greenland Sea ice and El Niño case (Low Greenland SICE and ElNino_P) and above Greenland Sea ice and La Niña case (High Greenland SICE and LaNina_P) for (a) the turbulent heat flux (W/m²), (b) the temperature at 2 m (K), (c) the sea level pressure (SLP) (mb) and (d) geopotential height at 500 hPa (m) during OND(0). Statistical significance at 90% confidence level is shown as dash marks.
FIGURE 9  Same as Figure 8 except for (a) the snow depth (cm), (b) the surface solar flux (W/m²), (c) the turbulent heat flux (W/m²), (d) the temperature at 2 m (K), (e) the sea level pressure (SLP) (mb), and (f) geopotential height at 500 hPa (m) during DJF(0/1). Statistical significance at 90% confidence level is shown as dash marks.
FIGURE 10 Same as Figure 9 except for MAM(1). Statistical significance at 90% confidence level is shown as dash marks.
the surface solar flux anomalies over western Eurasia (30–120°E) from DJF(0/1) to MAM(1) (Figures 9b and 10b) and increased them over eastern Eurasia (120–140°E) because of the albedo effect of the snow cover (Figure 10b). The spatial signatures of the turbulent heat flux and air temperature at 2 m during winter and spring over the Eurasian domain were consistent and collocated with snow anomaly patterns; there were significant negative surface temperature anomalies over western Eurasia (30–90°E), similar to earlier studies (Zhang et al., 2017) (Figures 9c, d and 10c, d). These surface conditions made the lower and upper atmospheric layer behaves like a wave-type pattern over the Eurasian domain (Figures 9e, f and 10e, f). Arctic sea ice loss leads to moistening the atmospheric boundary layer, which increased not only the moisture flux into eastern Siberia but also snowfall (Cohen et al., 2014; Wegmann et al., 2015). These atmospheric circulation patterns were sustained by anomalous snow anomalies over the subpolar region for MAM(1) (Figure 10f) and caused the wave train structure penetrating the mid-latitudes to evolve until MJJA (1) (Figure 11d).

In order to further identify the combined impact of Greenland sea ice and ENSO in the presence of snow, the related atmospheric circulation variations in the individual and combined impact experiments of Greenland sea ice and ENSO with prognostic snow were compared, as shown in Figure 12. During the summer monsoon season of MJJA(1), the geopotential height at 500 hPa in response to combined forcing (sea ice and ENSO together [Figure 12a]) and Greenland sea ice forcing (Figure 12b) resembled a wavelike pattern emanating from the subpolar region. A comparison of the two wave types clearly showed that the wave flow took a meridional form with tropical forcing, specifically towards the Korea peninsula (Figure 12a, b). The response
to ENSO in the prognostic snow experiments (Figure 12c) was similar to ENSO in the individual impact experiments with the climatological snow depth (Figure 4c). In the combined impact experiments, an EU-like pattern induced from the Greenland sea ice impact with Eurasian snow and PJ pattern generated from the ENSO impact prevailed (Figure 12a). However, the EU-like pattern was zonally and meridionally shifted when the forcings of Greenland sea ice and ENSO with prognostic snow were combined. This zonal and meridional shift of the wave train may have been caused by the ENSO forcing. The SLP anomaly distribution also presented some evidence for the out-of-phase relationship between ISM and KSM in the combined forcing experiments compared to the individual experiments (Figures 12d–f).

The wind vector anomalies of the lower troposphere in the combined forcing experiments represented anomalous easterlies over 30°–90°E, 10°S–10°N. This is consistent with weak ISM and intensification of the western Pacific subtropical high (WPSH) over 120°–160°E, 10°–40°N corresponding to strong KSM (Figure 13a). The response to combined forcings was similar to the influence of ENSO alone over the tropics (including India), but combining the Greenland sea

FIGURE 12 Composite differences of the 500 hPa Geopotential heights (m) and the Sea level pressure (mb) between below Greenland sea ice and El Niño case (Low Greenland SICE and ElNino_P) and above Greenland sea ice and La Niña case (High Greenland SICE and LaNina_P) during MJJA(1) for (a, d) Combined response, (b, e) Greenland sea ice response and (c, f) ENSO response. Statistical significance at 90% confidence level is shown as dash marks.
ice and ENSO forcings enhanced WPSH and in turn KSM (Figure 13a, c). Although the Greenland sea ice clearly impacted modulating features like the weakening of the lower-level southwesterly flow towards the Indian subcontinent and intensification of WPSH, the signals were weaker than those of the combined impact from Greenland sea ice and ENSO. Furthermore, the variation in Greenland sea ice may strengthen KSM’s response to ENSO.

To ascertain the local Hadley circulation, the vertical cross-sections of omega (vertical velocity) differences during MJJA(1), averaged for 70–90°E (Indian longitudes) and 120–135°E (Korean longitudes) in the individual and combined forcings experiments, were analysed (Figure 14). The case with Greenland sea ice showed a weak ascent at 0–10°N and descent at 20–40°N extending to the upper troposphere (Figure 14b). For the case with ENSO, there was an anomalous descending motion over 0–10°N, ascending motion over 20°N, and descending motion over 30°N (Figure 14c).

In the combined forcings case, the vertical distribution was similar to that of the ENSO case, which means that ENSO had a dominant impact on ISM at 0–30°N. However, the descending motion over 20–30°N may have been intensified by the Greenland sea ice forcing, which is associated with ISM weakening (Figure 14a–c). In addition, for the longitudes of 120–135°E, a significant ascending motion strengthened over 20–40°N. This was consistent with the enhanced KSM when the Greenland sea ice and ENSO forcings are combined. This ascending branch pattern surrounding Korea is consistent with the results of Prabhu et al. (2018). In the combined case, the centre of the anomalous upward motion around 20°N in both cases of Greenland sea ice (Figure 14e) and ENSO (Figure 14f) migrated over 30°N, close to the Korean peninsula (Figure 14d).

5 | SUMMARY AND CONCLUSIONS

In the previous study (Prabhu et al., 2018), an out-of-phase relationship was proposed between ISM and KSM based on Greenland sea ice variability in observed datasets. This study demonstrated that the memory of Greenland sea ice in boreal autumn could be sustained and transmitted to ISM and KSM through anomalous zonal and meridional wave propagations triggered via eastern Eurasian snow until the following spring and via the Central Pacific SSTs over the Niño 3.4 region until the ensuing summer.

In the present study, numerical experiments were performed to identify the responses of ISM and KSM to the combined Greenland sea ice, Eurasian snow, and ENSO forcings. With respect to individual forcing events, Greenland sea ice extremes and the west (+)–east (−) dipole Eurasian snow pattern had positive and negative influences on KMR and IMR, respectively. ENSO showed a significant negative relationship with IMR and relatively weak negative relationship with KMR. In the upper level circulation fields, Greenland sea ice forcing for autumn and Eurasian snow forcing for winter and spring produced a wavelike train over Eurasia. The wavelike train triggered by Eurasian snow anomalies persisted from winter until the following summer, while the waves related to Greenland sea ice were sustained until MAM(1). ENSO forcing induced high-pressure anomalies at the upper level over the Indian Ocean and a PJ-like pattern over East Asia during the following summer.
In the experiments, the snow depth variation induced by Greenland sea ice anomalies was considered. ISM and KSM showed nonlinear responses to the ENSO and Greenland sea ice forcings. This implies that the variation in snow depth plays a crucial role in the link between Greenland sea ice and KSM, as revealed by Prabhu et al. (2018). In particular, the case of above-normal Greenland sea ice and La Niña showed a clear out-of-phase relationship between ISM and KSM that agreed with the observations of Prabhu et al. (2018).

The atmospheric circulation field showed that decreases and increases in the Greenland sea ice concentration caused heavier and lighter snow depth anomalies, respectively, in western Eurasia and lighter and heavier snow depth anomalies, respectively, in eastern Eurasia. The Eurasian snow anomalies during the following spring played a crucial role of transmitting the anomalous Greenland sea ice signal of the preceding boreal autumn to the ensuing ISM and KSM through wave-train-like positive and negative EU patterns, respectively. SST warming and cooling over the Niño 3.4 region generated anti-cyclonic and cyclonic circulation patterns, respectively, over the Indian Ocean, which influenced SAM. Meanwhile, they induced negative and positive PJ-like patterns, respectively, which influenced EASM.

In the combined forcings scenario, ENSO dominated ISM and KSM and changed the phase and position of the wave train over the subpolar region for MJJA(1). Greenland sea ice forcing along with Eurasian snow variation may also intensify the diverse relationship between ISM and KSM in terms of the vertical structure. Figure 15 shows a schematic diagram suggested by the results of the sensitivity experiments.

Compared to the single forcing scenarios, combining the effects of Greenland sea ice, Eurasian snow, and ENSO...
triggered different responses from ISM and KSM. This may imply that, to further understand the mechanism for the diverse relationship between ISM and KSM, the combined influences of sea ice, snow, and SST variations need to be considered together. The findings of the present study may provide useful information for predicting ISM and KSM. However, limitations still remain. A coupled model may further improve understanding on the underlying mechanisms related to cryospheric processes integrating the ocean and atmosphere from the polar to tropical latitudes.

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