

Article

Modulation of ENSO Teleconnection on the Relationship between Arctic Oscillation and Wintertime Temperature Variation in South Korea

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Abstract: Despite progressing global warming, extreme cold events in East Asia are still occurring frequently with temperature variability enhanced. To understand this situation, it is necessary to determine external and internal climatic factors and their modulation effects that influence regional temperature variability. We found that the positive correlation between Arctic Oscillation (AO) and surface air temperature (SAT) in South Korea during winter is modulated strongly by tropical influences associated with El Niño Southern Oscillation (ENSO). In the case of a negative (positive) SAT anomaly in South Korea during the positive (negative) AO phase, a state that is opposite to the typical relationship between AO and SAT, the tropical sea surface temperature shows a typical negative (positive) ENSO-like pattern. The atmospheric teleconnection associated with the negative (positive) ENSO conditions contributes to a deepening (flattening) of the climatological East Asian trough and an enhancing (weakening) of the East Asian jet, which leads to negative (positive) SAT anomalies in South Korea. This modulation effect is robustly observed in the historical simulations of three different models of CMIP5.

Keywords: El Niño southern oscillation; Arctic Oscillation; wintertime temperature; East Asia; teleconnection; East Asian jet

1. Introduction

The surface air temperature (SAT) variability over East Asia is predominated by the East Asian winter monsoon (EAWM), which is characterized by the variabilities of the Siberian high, the East Asian upper-tropospheric trough, and the East Asian jet stream [1–10]. During the strong EAWM phase, the East Asian trough deepens, the East Asian jet stream strengthens, whereas the Siberian High amplifies and expands toward East Asia. This atmospheric circulation pattern enhances the cold northerly wind toward East Asia, eventually bringing cold conditions over East Asia [11–15].

EAWM is fundamentally a natural variability resulting from a large-scale thermal contrast between the cold Eurasia continent and the relatively warmer conditions over the North Pacific Ocean [16]. It has been suggested that EAWM variability is affected by various low-frequency climate variabilities such as Arctic Oscillation (AO), which is known as one of the important variabilities influencing the EAWM [14,17]. AO is positively correlated with the variability of SAT in East Asia over an interannual time scale through its linkage to EAWM [18–24]. During the negative AO phase, the Siberian high, the Aleutian low, the East Asian jet stream, and the East Asia trough all tend to strengthen, which leads to a strong EAWM and cold conditions in East Asia. Over an intraseasonal time scale, Jeong and Ho [19] suggested that East Asian cold surges occur more frequently during the negative phase of AO than in the positive phase. Even with regards to decadal time scales, Woo et al. [25] found that the

decadal change in the frequency and duration of the East Asian cold surge is significantly related to the decadal change in the particular dominance of the AO phase.

Although EAWM linked to AO dominates the SAT variability over the entirety of East Asia and the adjacent ocean, the significant impact of AO on the SAT exists primarily over the northern part of East Asia, such as southern Siberia or northeastern China (Figure 1a). The relationship between AO and wintertime SAT in South Korea, the region of focus in the present study, is weaker than that in the northeastern part of China (Figure 1b). This may imply a modulation effect from climate factors other than AO. Many previous studies have suggested the influences of ENSO on EAWM and SAT variabilities. For instance, ENSO-related convection over the western Pacific influences the atmospheric circulation over Northeast Asia during the wintertime [26–32]. Wang et al. [26] highlighted that the EAWM is influenced by the southerly wind along the northwestern border of anticyclonic circulation from the Philippine Sea to Japan, which is a part of the Pacific–East Asian teleconnection (PEA) associated with warm ENSO conditions. Park and An [28] suggested that the local Hadley circulation from the western Pacific to East Asia, induced by subtropical convection over the western Pacific, modulates the meridional movement of the East Asian jet stream. Son et al. [29] suggested that the Kuroshio anticyclonic anomaly induced by convection in the western Pacific during early winter contributes to the enhancement of southerly wind toward South Korea, which indicates favorable conditions for a weak EAWM and positive SAT anomalies over East Asia. Although many previous studies have suggested AO or ENSO directly influences atmospheric conditions over East Asia, a comprehensive understanding of whether there is an interplay between these two influences is still lacking. Quadrelli and Wallace [33] addressed that the structure of the Northern Hemisphere annular mode is significantly different according to ENSO phases. Bond and Harrison [34] showed that the ENSO teleconnection contributes substantially to AO-related circulation over the North Pacific, particularly in out-of-phase cases of two climate factors, and this interaction between AO and ENSO influences Alaska’s winter SAT variability. These previous studies focus on the North Pacific region where AO’s Pacific pole is located, and ENSO teleconnection is most pronounced. In the present study, we investigate whether there is a modulation effect of ENSO on the relationship between AO and SAT variability in South Korea through analyzing observational data and climate model simulations.

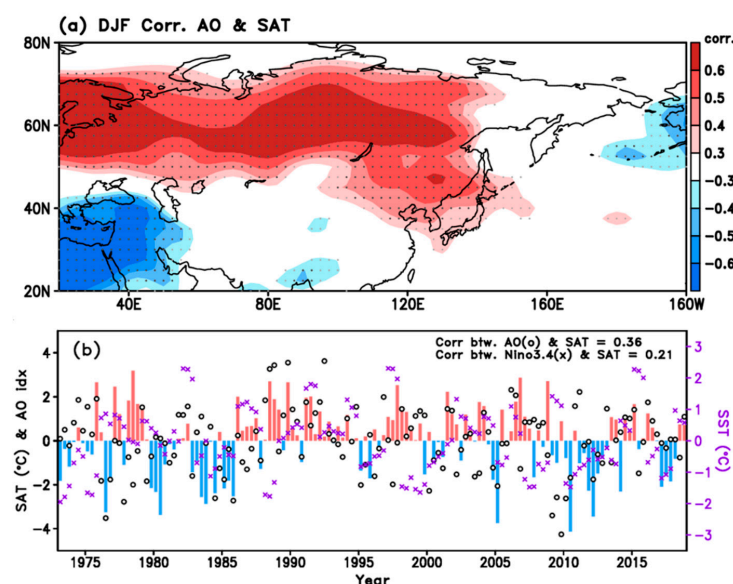


Figure 1. (a) Correlation map between Arctic Oscillation (AO) and surface air temperature (SAT) anomalies in wintertime (December to February) during 1973/74–2018/19 and (b) Timeseries of observational SAT anomalies in South Korea (Bar). AO (black circle), and El Niño Southern Oscillation (ENSO) index (violet cross mark).

The paper is organized as follows. The data and methods used in this study are described in Section 2. The climate variability modulation of the conventional correlation between AO and SAT anomalies in South Korea is presented in Section 3. In Sections 3.2 and 3.3, the impact of ENSO on the relationship between AO and SAT in South Korea and its possible mechanisms are investigated in detail using observations. In Section 3.4, the suggestions of this study are supported by the analysis of the CCSM4 historical run. Finally, the combined effect of AO and ENSO on the SAT variability in South Korea is discussed in Section 3.5, followed by conclusions and discussion of the results in Section 4.

2. Data and Methods

For the observational data, the monthly mean SAT records from 45 synoptic stations over South Korea for the period 1973 to 2019 were utilized. After 1973, a well-distributed observational network was established in South Korea [35]. The observational SAT during the analysis period showed a weak warming trend ($0.095\text{ }^{\circ}\text{C/decade}$); there was little difference in our results, whether or not the trend was removed. The National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I data, which provide long-term data before 1979 [36] with a standard resolution of 2.5° longitude by 2.5° latitude, were used to investigate the atmospheric conditions around South Korea. The Extended Reconstructed Sea Surface Temperature (ERSST) version 5 and NOAA Interpolated Outgoing Longwave Radiation (OLR) were utilized to examine the ENSO-related tropical conditions. To support our suggestions based on observation analysis, historical simulations of CCSM4, GFDL-CM3, and MIROC5 in CMIP5 (Coupled Model Intercomparison Project phase 5) were analyzed for the period 1850 to 2005 (1860 to 2005 for GFDL-CM3) [37].

The monthly AO index is defined as the principal component of the sea level pressure (SLP) anomalies over the Northern Hemisphere, north of 20° N [18]. The phase and amplitude of ENSO (ENSO index) were represented by the three-month running mean of sea surface temperature (SST) anomalies averaged over the Niño 3.4 region (5° N – 5° S , 170° W – 120° W).

To elucidate the detailed relationship between AO and SAT anomalies over South Korea, the analysis period of 126 months was classified into four groups according to the combination of the AO index (phase) and SAT anomalies. The positively (negatively) in-phase cases are defined when the AO and SAT anomalies in each month both individually have a positive (negative) standard deviation that is larger (less) than 0.5. Out-of-phase cases are defined when the AO index and SAT over South Korea have the opposite sign. The out-of-phase groups represent the cases uncomplying with the conventional relationship between AO and SAT in South Korea. Hereafter, the four groups are denoted by +AO+T, +AO−T, −AO−T, and −AO+T, which have 19, 4, 17, and 8 cases, respectively. Notably, the number of in-phase months (+AO+T and −AO−T) is more than that of out-of-phase months (+AO−T and −AO+T) because the positive relationship between AO and SAT dominates in South Korea. Furthermore, to examine the impact of the ENSO teleconnection, positive and negative ENSO phases are defined with the ENSO index. The positive (negative) ENSO cases are identified when the monthly ENSO index is larger (smaller) than a standard deviation of 0.5 (−0.5) in wintertime. According to these criteria, 40 and 51 positive and negative ENSO months, respectively, are identified during the wintertime of 1973–2019.

Composite analyses were conducted to examine the atmospheric circulation, SAT, and SST anomalies according to the combination of AO and SAT in South Korea as well as ENSO phases. The statistical significance of the composite anomalies was evaluated based on the two-tailed Student's *T*-test.

3. Results

3.1. East Asian Circulation Features According to AO and SAT in South Korea

To obtain the factor modulating the positive relationship between AO and SAT variability in South Korea, we compared atmospheric circulation features for the four groups in Figure 2. In the in-phase groups, +AO+T and −AO−T, the positive–negative contrast of geopotential height anomalies between the Arctic and mid-latitude regions, which is a typical circulation pattern related to AO, is clearly manifested in the Northern Hemisphere. In the +AO+T group, negative geopotential anomalies are significant over the Arctic, whereas positive anomalies are distributed from East Asia to the North Pacific as well as from the western United States to Europe through the North Atlantic (Figure 2a). The −AO−T group evidently shows the opposite pattern (Figure 2d). In out-of-phase groups, the opposite geopotential anomaly pattern still exists between the Arctic and mid-latitude regions, however, there is a distinct difference over the East Asian region. Despite the positive (negative) phase of AO, negative (positive) geopotential anomalies are prominent over East Asia, including South Korea and Japan, for the +AO−T (−AO+T) group (Figure 2b,c). It appears that the positive (negative) anomalies over East Asia, which are related to the positive (negative) phase of the conventional AO, are shifted northward to northern Siberia. The different atmospheric circulation features over East Asia can be more clearly observed in zonal wind anomalies (Figure 3). In +AO+T (−AO−T) cases, the negative (positive) anomalies of zonal wind are mainly observed in the location of the East Asian jet stream, whereas positive (negative) anomalies are found over the regions of Lake Baikal to the Bering Sea. This anomalous pattern can be interpreted as the northward (southward) shift of the East Asian jet, which is closely related to the weakening (deepening) of the East Asian trough and the resultant positive (negative) anomaly over South Korea. Siberia and East Asia are dominated by the anomalous lower-tropospheric southerly (northerly) wind in the +AO+T (−AO−T) group, resulting in warmer (colder) conditions throughout the whole of East Asia, including South Korea (Figure 4a,d). In contrast to the in-phase groups, the positive (negative) anomalies of zonal wind are enhanced locally over central China to South Korea in the +AO−T (−AO+T) group, despite the positive (negative) phase of AO (Figure 3b,c). The East Asia region is dominated by northerly (southerly) anomalies in the lower-troposphere and thus, experiences conditions that are colder (warmer) than normal (Figure 4b,c). However, the regions affected by the northerly (southerly) wind are confined to China, South Korea, and Southern Japan. These circulation features in the out-of-phase groups imply that the relationship between AO and SAT in South Korea can be modulated by other climate factors. We also checked the sensitivity of the above results to classifying the groups with ± 0.25 standard deviation. Overall, the out-of-phase group's composites selected based on ± 0.25 standard deviation criteria are similar to those based on 0.5 standard deviation, even though SST anomalies over the tropical eastern Pacific and teleconnection patterns toward East Asia are somewhat weakened in the +AO−T group (not shown).

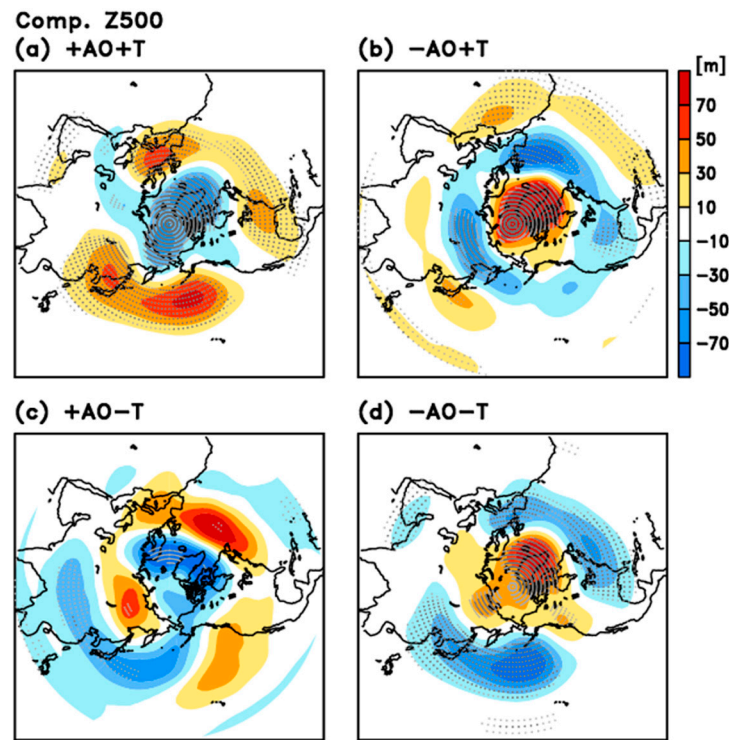


Figure 2. Composite maps of geopotential height anomalies at 500 hPa in winter season for (a) +AO+T, (b) -AO+T, (c) +AO-T, and (d) -AO-T group. Light (dark) gray dots denote grid points which satisfy 90% (95%) confidence level through the two-tailed Student's *T*-test.

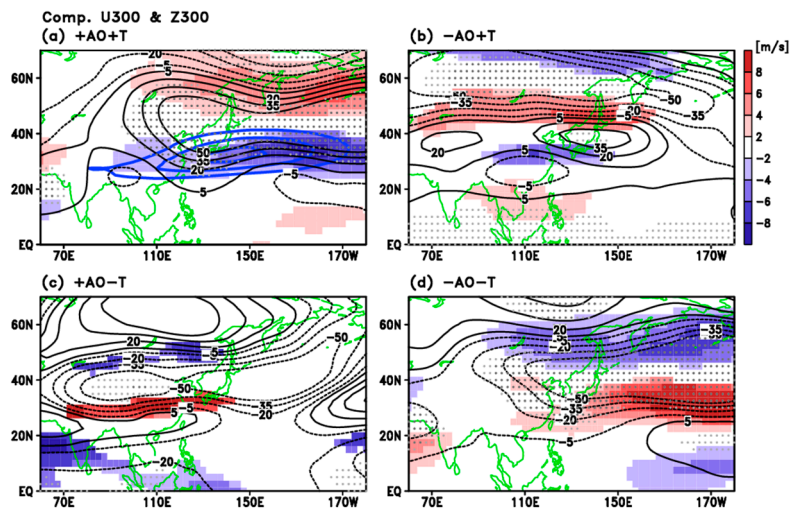


Figure 3. Composite maps of zonal wind (shading) and geopotential height (black contour) anomalies at 300 hPa in winter season for (a) +AO+T, (b) -AO+T, (c) +AO-T, and (d) -AO-T group. Blue contours in (a) indicate climatological zonal wind at 300hPa in winter season (larger than 40m/s with interval 10 m/s). Light (dark) gray contours denote boundaries of area which satisfy 90% (95%) confidence level through the two-tailed Student's *T*-test. Zonal wind is shaded only for the grids which satisfy 90% confidence level.

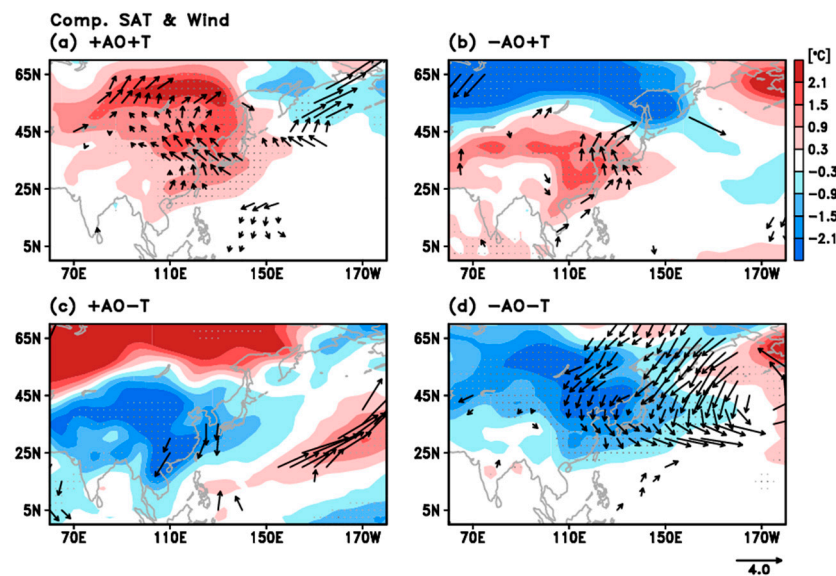


Figure 4. Same as Figure 3, but for SAT (shading) and wind anomalies at 850 hPa (vector). Light (dark) gray dots denote grid points which satisfy 90% (95%) confidence level through the two-tailed Student's *T*-test. Wind vectors are marked only for the grids which satisfy 90% confidence level.

3.2. Tropical Signals in Out-of-Phase Groups

By comparing the zonal winds of in-phase and out-of-phase groups (Figure 3), notable differences can be found. In the in-phase group, the zonal wind anomalies are centered over the northwestern Pacific region expanding to East Asia, whereas those in the out-of-phase groups are located mainly over central China to Japan: a westward shift compared to the in-phase groups. Another difference can be identified over the subtropical western Pacific. The subtropical region in the in-phase groups lacks any significant anomalies; however, they can be observed over the subtropical western Pacific in the out-of-phase groups. This suggests the possibility of remote influences from the subtropical western Pacific on East Asia. This is further examined by composite analysis for SST and OLR, which represent convectional activities in the tropics and subtropics. In the in-phase groups, there are no significant SST anomalies in the tropics (Figure S1), whereas in the out-of-phase group, ENSO-like anomalies are pronounced in the tropical ocean. In the case of +AO−T, the SST anomalies show the typical negative ENSO-like pattern, which is characterized by the positive and negative SST anomaly in the central-eastern Pacific and western Pacific, respectively (Figure 5b). By contrast, the positive ENSO-like SST anomalies are prominent in the case of −AO+T (Figure 5a). These features related to ENSO are manifested in the composite of OLR anomalies. In the case of +AO−T(−AO+T), the negative (positive) and positive (negative) OLR anomalies are clearly found in the central Pacific and western Pacific, respectively. These features are well-known ENSO-related tropical convection patterns, which can play an important role in triggering a teleconnection toward mid-latitude regions [26,27,29,38]. Figure S2 shows the SST anomalies of the individual cases in the out-of-phase groups. In all four cases of +AO−T group, the SST anomalies commonly show a typical negative ENSO pattern characterized by the positive and negative SST anomaly in the central-eastern Pacific and western Pacific, respectively. In the −AO+T group, five out of eight cases show the prominent positive ENSO pattern, and two cases show the ENSO-like SST pattern, even though the Niño 3.4 index values indicate normal conditions. Only one case, January of 2014, shows the negative ENSO pattern. To summarize, the relevance of ENSO to the out-of-phase groups indicates that ENSO is closely linked to the modulation of the positive relationship between AO and SAT in South Korea.

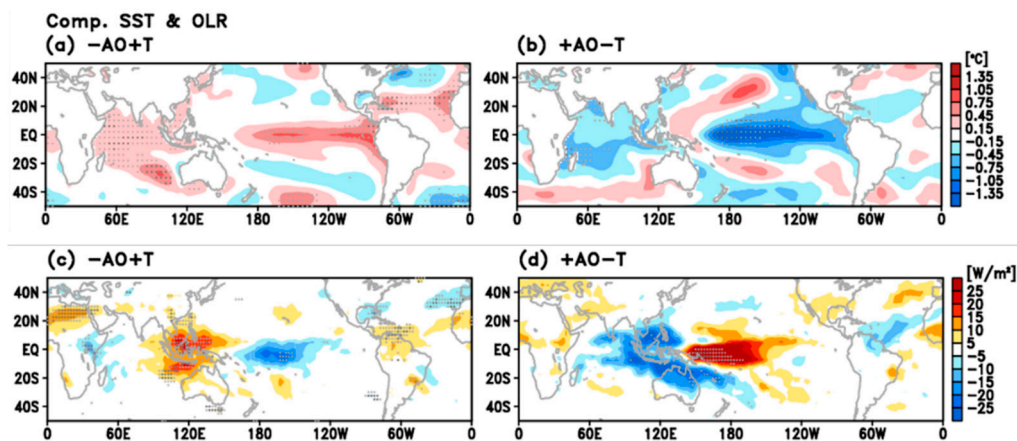


Figure 5. Composite maps of sea surface temperature (SST) anomalies in winter season for in (a) $-AO+T$ and (b) $+AO-T$ group. (c) and (d) are same as (a) and (b) but for outgoing longwave radiation (OLR) anomalies. Light (dark) gray dots denote grid points which satisfy 90% (95%) confidence level through the two-tailed Student's T -test.

3.3. Modulation of Relationship between AO and SAT by ENSO Teleconnection

To examine the modulation effect of ENSO on the relationship between AO and SAT in South Korea, upper and lower-tropospheric circulation anomalies over East Asia were examined with respect to the ENSO phases shown in Figure 6. In the case of a positive ENSO, the wave-like disturbance emanating from the Maritime continent to East Asia in the upper-troposphere is distinct, consisting of anticyclonic anomalies over the Maritime continent and the eastern part of Japan, and cyclonic anomalies in South China. Upper-tropospheric circulation can be understood as the result of Rossby wave propagation by suppressed convection linked to the positive ENSO that exists over the western Pacific to the Maritime continent [29,31]. East Asia, from South Korea to Japan, is under the influence of anticyclonic anomalies. Additionally, the negative anomalies of zonal wind are seen clearly over the middle of China, near the entrance of the East Asian jet. These upper-tropospheric conditions correspond to the flattening of the East Asian climatological trough, bringing warm SAT over South Korea. Moreover, the lower-tropospheric circulation anomalies linked to positive ENSO conditions also show favorable circulation for the warm conditions in South Korea. There is a wide range of anticyclonic circulation from the Philippine Sea to the Northwest Pacific; the anomalous Philippine Sea anticyclone is the response of suppressed convective heating induced by both ocean surface cooling and subsidence over the western Pacific as a result of the positive ENSO [26]. Along the northwestern margin of the Philippine Sea anticyclone, the southerly anomalies prevail, implying warmer conditions than normal over South Korea in the winter season. These ENSO-related circulations in the upper- and lower-troposphere over East Asia resemble those in the $-AO+T$ group. Specifically, the wave-like pattern represented by the cyclonic anomaly over southern China and the anticyclonic anomaly centered over Japan in the $-AO+T$ group (Figure 3b) are consistent with the circulation anomalies in the positive ENSO (Figure 6a). Moreover, the position of the weakened East Asian jet also coincides with the positive ENSO (Figure 6a) and $-AO+T$ group (Figure 3b). In the lower-troposphere, the prominent southerly wind along the East Asian coast from the subtropics toward South Korea in the $-AO+T$ group (Figure 4b) is also relatively similar to the northwestern pattern of the Philippine sea anticyclone in positive ENSO conditions (Figure 6c). The similarities between the ENSO teleconnection pattern and the circulation anomalies in the out-of-phase groups indicate that a positive (negative) ENSO-related teleconnection over East Asia contributes to a circulation pattern that favors a warm anomaly in South Korea, despite the negative phase of AO.

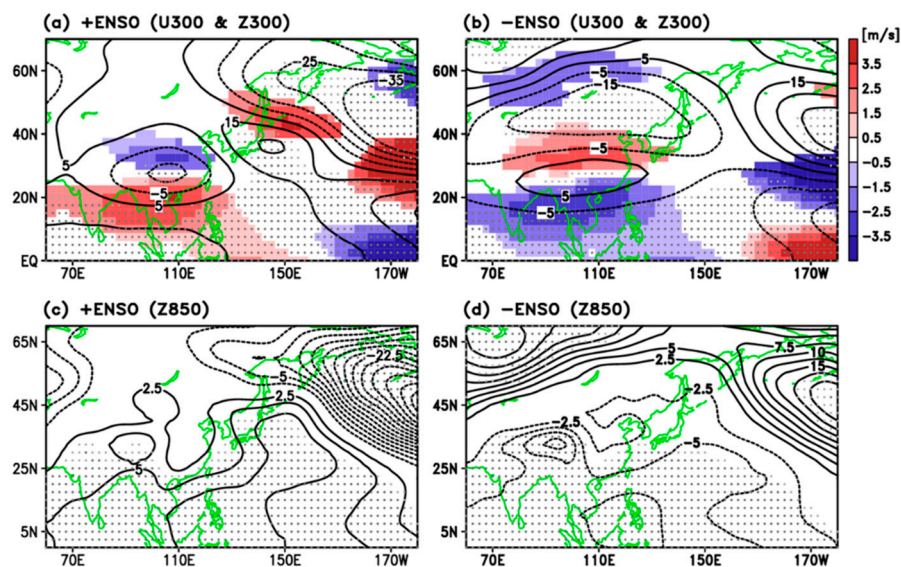


Figure 6. Composite maps of zonal wind (shading) and geopotential height (contours with interval 10m) anomalies at 300hPa in winter season for (a) +ENSO and (b) −ENSO. (c) and (d) are same as (a) and (b) but for geopotential height anomalies at 850hPa. Light (dark) gray dots denote grid points which satisfy 90% (95%) confidence level through the two-tailed Student's *T*-test. Zonal wind in (a) and (b) is shaded only for the grids which satisfy 90% confidence level.

In the case of a negative ENSO (Figure 6b), anticyclonic anomalies in South China and cyclonic anomalies over northern China are evident. The East Asian jet is enhanced over China to Japan, opposite to that observed in the positive ENSO phase. In the lower-troposphere (Figure 6d), the cyclonic circulation centered in the Philippine region extends to East Asia, and thus, South Korea is likely to be under the influence of the associated northerly wind. These circulation patterns reinforce the East Asian winter monsoon and are in favor of cold conditions over South Korea. Furthermore, these upper and lower-tropospheric circulations are relatively similar to the circulations observed in the +AO−T group (Figures 3c and 4c). In particular, the enhancement of the East Asian jet over central China to Japan and of the lower-tropospheric northerly wind over East Asia in the −AO+T group is likely to be the considerable influence by the ENSO teleconnection. These results indicate that the ENSO may contribute to the manifestation of the out-of-phase case between AO and SAT over South Korea, significantly modulating the conventional relationship between AO and SAT.

The ENSO index (Niño 3.4) shows a negligible correlation with SAT in South Korea for the winter season (Figure 1b), but this should not be interpreted that ENSO has little impact on South Korea. Since the wintertime SAT in South Korea is affected by various other climate factors such as AO [17,19], West Pacific pattern [23], and Eurasian pattern [39,40], the effect of ENSO is often not noticeable. For example, 82/83 shows that the Eurasian wave pattern propagating from the Atlantic and negative AO are likely to contribute to the negative SAT anomalies (DJF mean) in South Korea, even though it was a strong El Niño. ENSO is closely linked with the variability of convection over the western Pacific. The convection over the western Pacific plays a crucial role as an atmospheric force on the teleconnection toward East Asia, as seen in Figure 6 [28,29]. Our results (Figures 3, 5, and 6) show that ENSO-related convection in the Western Pacific affects the atmospheric circulation over East Asia, particularly the contribution to modulating the relationship between AO and SAT in South Korea.

3.4. ENSO Modulation Features in Climate Model

The ENSO modulation effect on the relationship between AO and SAT in South Korea was suggested by the observational analysis. To support this suggestion, we investigated the modulation effect in the CCSM4 historical simulation of CMIP5. Analogous with the observational analysis, the four groups of +AO+T, +AO−T, −AO−T, and −AO+T were categorized according to the SAT averaged over the Korean Peninsula (125° E–130° E and 32.5° N–40° N), and the AO index was calculated by the same method used in the observational analysis. The number of cases for the four groups detected in the model simulation were 62, 34, 48, and 32, respectively. As shown in the observations, the in-phase condition occurs more frequently than that of the out-of-phase. Figure 7 represents the SST and upper-tropospheric circulation anomalies in the −AO+T and +AO−T groups of the CCSM4 historical run. The results of this simulation support the observational analysis. As in the results of the observational analysis (Figure 5a), in the −AO+T group of CCSM4, the tropical SST evidently demonstrates a positive ENSO (Figure 7a), which is characterized by a positive SST anomaly from the central Pacific to the eastern Pacific and a negative SST anomaly over the western Pacific. Contrastingly, the negative ENSO characteristics are clearly seen in the +AO−T group (Figure 7b). Furthermore, the upper-tropospheric circulation anomalies (Figure 7c,d) exhibit similar features to those found in the observational analysis in the East Asian region (Figure 3b,c). In the −AO+T group (Figure 7c), there is a negative geopotential height anomaly in southern China and a positive anomaly stretching from northern China to Japan, with weakened zonal wind over central China. This circulation pattern favors warmer than normal conditions in South Korea. In the +AO−T group (Figure 7d), an upper-tropospheric circulation pattern opposite to that in the −AO+T group is shown. The anticyclonic anomaly in South China and cyclonic circulation elongated from northern China to Japan is similar with the observational +AO−T group (Figure 3c). Since the results can be model-dependent, the same analysis with CCSM4 was carried out using two other models, GFDL-CM3 (Figure S3) and MIROC5 (Figure S4), from the CMIP dataset. Both models simulated the overall features of ENSO modulation in the out-of-phase group, similar to observation (Figures 3 and 5) and CCSM4 (Figure 7). However, the upper-tropospheric circulations in the −AO+T and +AO−T groups shown in the observations (Figure 3b,c) are not symmetric like those in the CCSM4 simulation; in particular, simulations of the −AO+T group show an anticyclone centered on Japan, whereas in observations, it was shifted to northern China. This symmetric feature is likely a reflection of a common problem (systematic bias) in CMIP5 coupled models: an underestimation of the ENSO asymmetry [41]. In other words, models are not able to accurately simulate the asymmetry of the ENSO teleconnection found in observations. Nevertheless, the CCSM4 simulation of the circulation over East Asia in the out-of-phase group is overall similar to observations. These evident ENSO-like SST anomalies and the related atmospheric circulation patterns over East Asia, shown in the out-of-phase groups of the CCSM4 simulation, support the ENSO modulation effect on the relationship between AO and SAT in South Korea.

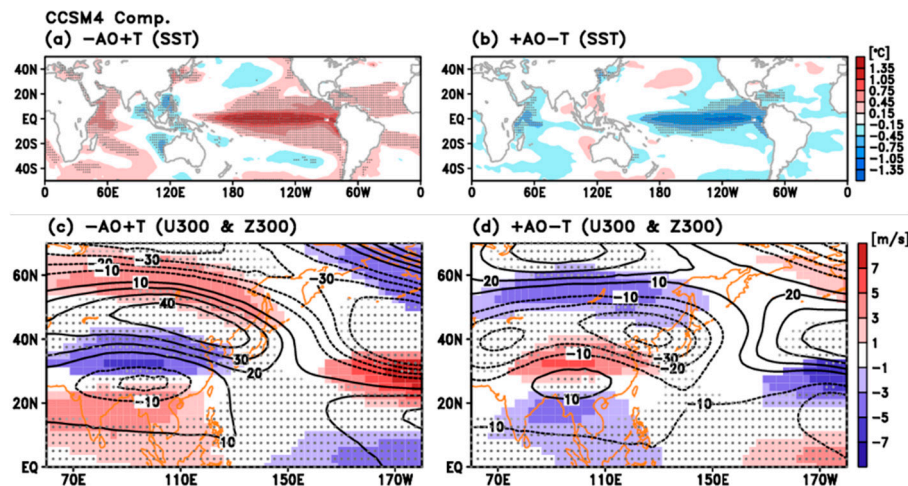


Figure 7. Composite maps of SST anomalies for (a) $-AO+T$ and (b) $+AO-T$ group in CCSM4 historical simulation. (c) and (d) are same as (a) and (b) but for zonal wind (shading) and geopotential (contours with interval 10m) anomalies at 300hPa. Gray dots denote grid points which satisfy 95% confidence level through the two-tailed Student's *T*-test. Zonal wind in (c) and (d) is shaded only for the grids which satisfy 95% confidence level.

3.5. Combined Effect of AO and ENSO on Wintertime SAT and Extreme Cold Days in South Korea

The results may suggest that AO and ENSO modulation effects on East Asian climate better explain the SAT variability in South Korea compared to individual variability. To address this issue, a multiple linear regression (MLR) was carried out based on both AO and ENSO indices to SAT and the results were compared with those from an individual regression of AO and ENSO. Figure 8 shows the correlation coefficient maps between observational SAT anomalies over East Asia in wintertime and SAT reconstructed from a regression on AO-only, ENSO-only, and on multiple regression based on both variables. During the winter season, the SAT variabilities explained by AO are distributed mainly in Siberia and northeastern China (Figure 8, center column). The SAT variability in South Korea shows a statistically significant correlation with AO in January. On the other hand, the SAT variability associated with ENSO (Figure 8, right column) appears mainly in the oceanic regions, including the western Pacific and Indian Ocean, excluding the continent. In December only, a significant correlation is limited to areas near South Korea and Japan. However, the multiple regression SAT using both AO and ENSO shows a higher correlation to observational SAT variability in South Korea and its surrounding regions (Figure 8, left column). The correlation between the multiple regression SAT and observational SAT averaged over South Korea (hereafter, correlation skill) was considerably improved in all winter months than that of the individual variables (Figure 9), especially in December, which demonstrates an improvement in correlation skill of 1.5 or more. This indicates that South Korea's SAT variability can be better explained by considering ENSO, which modulates the conventional positive correlation between AO and SAT.

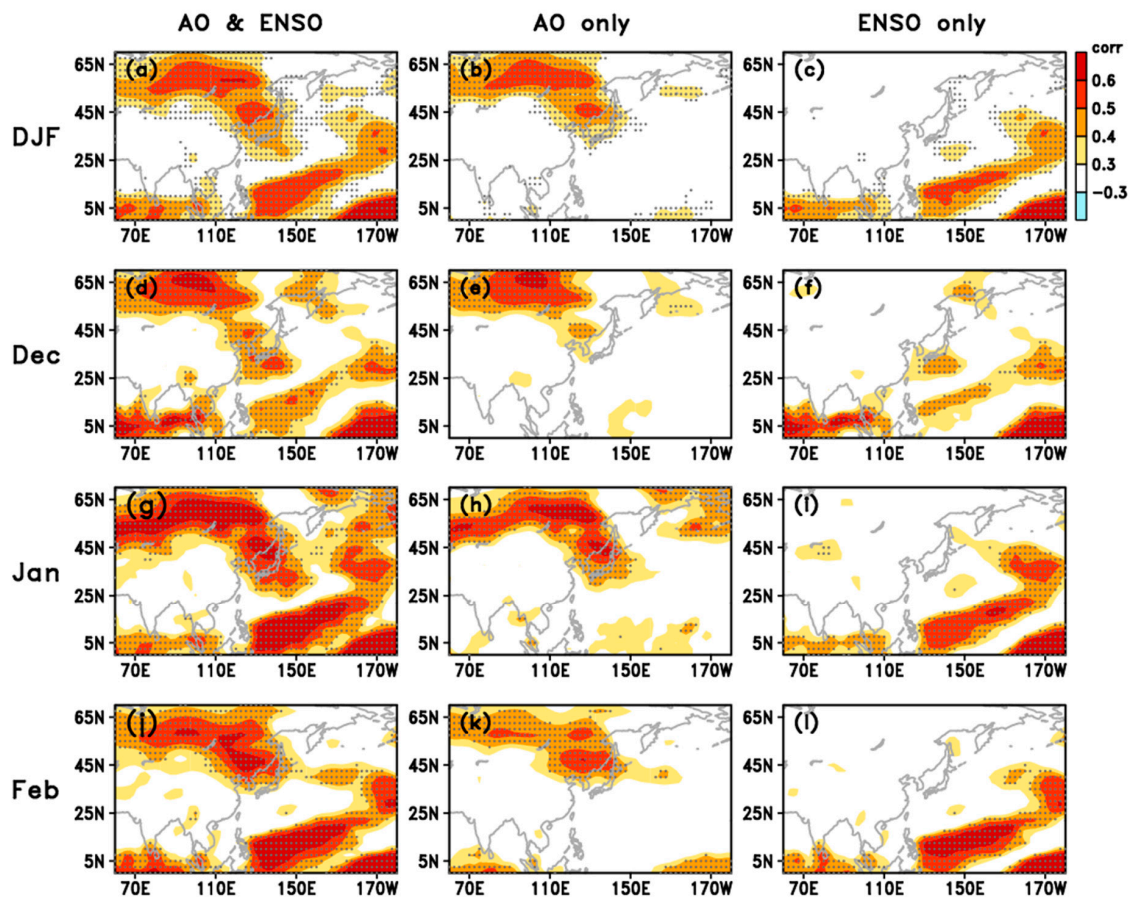


Figure 8. Correlation maps between observational SAT and SAT reconstructed from multiple regression based on (left column) AO and ENSO in (a) DJF mean, (d) December, (g), January, and (j) February. Center columns are the same as left column, but for SAT regressed on AO-only in (b) DJF mean, (e) December, (h), January, and (k) February. Right columns are the same as left column, but for SAT regression on ENSO-only in (c) DJF mean, (f) December, (i), January, and (l) February. Gray dots denote grid points which satisfy 95% confidence level through the two-tailed Student's *T*-test.

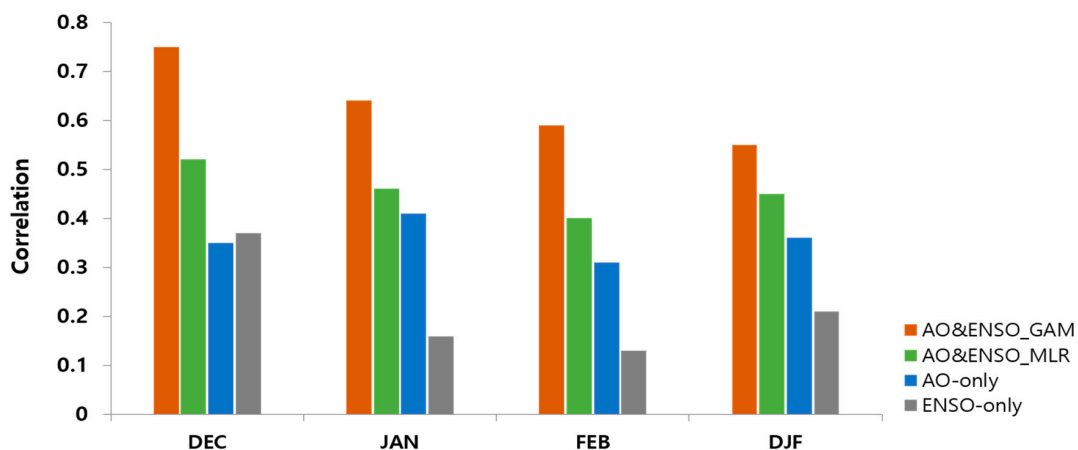


Figure 9. Correlations between observational SAT in South Korea and reconstruction of GAM (orange bar) and MLR (green bar) based on both AO and ENSO (blue bar) for the winter season. Correlation skill of SAT regressed on AO-only (blue bar) and ENSO-only (gray bar).

Moreover, in Figure 9, we can find that the consideration of both AO and ENSO better explains the SAT variability in South Korea than simply adding the influence of two climate modes. However, the influence of AO and ENSO over East Asia could be not purely linear additive, and nonlinear interaction between them could have a large influence. Some previous studies also argued that ENSO contributes substantially to AO-related circulation over the North Pacific in particular [33,34]. We examined the contribution of nonlinearity to SAT variability in South Korea using the general additive model (GAM), which can capture the nonlinearity in the data [42]. Comparing the correlation skill of GAM based on both climate factors and that of MLR (Figure 9), GAMs better explain the SAT variability than MLMs in all winter months. These results imply that the nonlinearity of the relationship between the SAT and both climate factors can contribute to SAT variability in South Korea considerably.

We also further investigated whether the impact of AO and ENSO on the SAT variability in South Korea is revealed in the features of extreme cold days (ECDs) (Table 1). ECD is defined by the day that is colder than the 10th percentile of SAT anomalies during the analysis period. The four groups were classified by the combination of AO and ENSO indices with the criteria of their ± 0.5 standard deviation (+AO+ENSO: 12 cases; +AO−ENSO: 16 cases; −AO+ENSO: 12 cases; and −AO−ENSO: 12 cases). Comparing the features of ECDs between the four groups, the ECDs occur more frequently in the −AO group (−AO+ENSO and −AO−ENSO) than in the +AO group (+AO+ENSO and +AO−ENSO). In particular, the ECDs occur most frequently in −AO−ENSO group. On the other hand, in the case of the mean SAT anomalies during ECDs, ENSO had little effect. Specifically, the mean SAT anomalies of ECDs in the −AO groups tend to be lower SAT anomalies (about -1°C) than in the +AO groups. However, there was no distinct difference depending on the ENSO phases. Whereas, comparing monthly mean anomalies with respect to ENSO phases when AO has the same phase, +ENSO(−ENSO) contributes to increasing (decreasing) the monthly mean SAT anomaly in South Korea. These results seem to be related to the mechanism of ECDs occurrence over East Asia. The ECDs in East Asia are caused by the cold surge (with a synoptic time scale) related to the strengthening of the Siberian high and its expansion toward East Asia, so the occurrence of ECDs is closely related to AO variability. ENSO seems to provide favorable conditions for negative SAT anomalies over East Asia in the background by modulating East Asian circulation at a monthly or seasonal time scale.

Table 1. Extreme cold days frequency, mean of sea surface temperature (SAT) during cold days, and monthly SAT anomalies according to a combination of Arctic Oscillation (AO) and El Niño Southern Oscillation (ENSO) phases.

Groups	+AO+ENSO	+AO−ENSO	−AO+ENSO	−AO−ENSO
Freq. of cold days (days/month)	1.27	1.94	4.25	5.72
Mean SAT ano. of cold days ($^{\circ}\text{C}$)	−5.31	−5.32	−6.32	−6.13
Monthly SAT ano. ($^{\circ}\text{C}$)	+1.01	+0.26	−0.22	−1.31

4. Conclusions and Discussion

In this study, it was suggested that the ENSO teleconnection significantly modulates the relationship between AO and SAT in South Korea. In the out-of-phase groups, including +AO−T and −AO+T, the ENSO-like SST anomaly pattern is significant, and its related convection anomalies over the western Pacific results in the teleconnection toward East Asia, which influences the circulation over this region. Despite the negative (positive) phase of AO, the positive (negative) ENSO-related teleconnection toward East Asia results in a weakening (strengthening) of the East Asian jet over central China to Japan and the development of anticyclonic (cyclonic) anomalies over East Asia. This corresponds to a flattening (deepening) of the East Asian climatological trough, which favors cold winter conditions over East Asia, including South Korea.

There are certain limitations present in this analysis. Our analyses of the ENSO teleconnection were based on a linear concept. However, recent research has suggested that ENSO teleconnections are

inherently nonlinear and are sensitive to the patterns and amplitudes of ENSO-related SST anomalies, implying ENSO diversity [43–45]. In addition, certain studies emphasize that the relative roles of ENSO-related convection anomalies in the western North Pacific and equatorial central Pacific determine the features of the ENSO teleconnection over East Asia [31,38,46]. As the ENSO diversity or the relative role of regional convections were not considered in our analysis of the ENSO teleconnection, this study cannot accurately quantitate the impact of ENSO on the East Asian climate.

As discussed in Section 3.5, it is important to understand the interaction between AO and ENSO over East Asia. We discussed the contribution of nonlinear interaction between AO and ENSO to SAT variability in South Korea, based on comparing the SAT correlation skills between GAM and MLR. However, since this approach only considers the interaction statistically, there is a limitation on dynamical interpretation. To understand the interaction more dynamically and quantitatively, a sensitivity experiment using the global climate model is likely to be necessary. Nevertheless, our results are likely to be adequate enough to reveal that ENSO partly contributes to the modulation of the relationship between AO and SAT in South Korea, and the wintertime SAT in South Korea could be better explained by considering both AO and ENSO.

East Asian countries, including South Korea, have experienced an increase in extremely cold winters associated with an increase in the SAT variability, despite progressing global warming. Expanding our understanding of how climatic factors affect regional SAT variabilities, such as AO and ENSO, will aid our comprehension of this paradoxical situation. The results of this study will additionally be useful for seasonal predictions of wintertime climate.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-4433/11/9/950/s1>, Figure S1: Composite maps of SST anomalies in winter season for in-phase groups; Figure S2: SST anomalies in individual case of the out-of-phase groups; Figure S3: Composite maps of SST, U300 and Z300 anomalies in GFDL-CM3 historical simulation.; Figure S4: Same as Figure S4 but for MIROC5.

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