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Possible impact of the autumnal North Pacific SST and November AO on the East Asian winter temperature

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[1] This study investigates the effects of the North Pacific sea surface temperature (NP SST) anomalies on the East Asian winter temperature (T_{EA}), and the relationship between the Arctic Oscillation (AO) and NP SST anomalies in association with T_{EA}. Time-lagged correlation analysis revealed that the third mode of the September–October–November (SON) mean NP SST ("SON SST 3rd mode") and the AO index for November ("Nov AO") are closely related to T_{EA}, and further that the first and second modes of NP SST are associated with the Pacific Decadal Oscillation (PDO) and Pacific North America (PNA) patterns, respectively. This study reveals that when the SON SST 3rd mode and Nov AO have a positive (negative) phase, the intensity of the Siberian High weakens (strengthens), which in turn weakens (strengthens) the East Asian winter monsoon (EAWM), resulting in a warm (cold) winter in East Asia. Our results suggest that the North Pacific Ocean signals influence the AO, which is one of the most pronounced Northern Hemispheric atmospheric global patterns. Such an influence in turn governs the continental-scale circulation over Siberia and affects the subsequent local climate variation over the East Asia regions.

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1. Introduction

[2] The East Asian winter temperature (T_{EA}) is influenced by the East Asian winter monsoon (EAWM), which is one of the most active synoptic systems in the Northern hemisphere winter. The EAWM is closely related to the expansion and shrinkage of the Siberian high. The variability of the Siberian high is known to be affected by the Arctic Oscillation (AO), the dominant pattern of extratropical atmospheric variability in the Northern hemisphere [*Thompson and Wallace*, 1998]. The relation between the AO and the Siberian high and their impact on T_{EA} are well known [*Gong and Ho*, 2002; *Gong et al.*, 2001; *Shin et al.*, 2006]. According to previous studies, when the AO is in a positive phase in winter, the Siberian high and EAWM are weaker than normal. Correspondingly, air temperature from surface to the middle troposphere is higher than normal in the East Asian region. When the AO reaches its negative phase, an opposite phenomenon is observed. *Im and Ahn* [2004] also documented the relationship between the variability of winter temperature over Korea, located in Far East Asia, and the AO. They found that the winter minimum, maximum, and mean temperature anomalies had significant positive correlations with the AO index at the 99% confidence level, and suggested that the AO could be an appropriate index to explain the T_{EA} variations.

[3] Several studies on the ocean-atmosphere interaction have pointed out the atmospheric impact on SST at the middle and high latitudes [e.g., *Seager et al.*, 2001; *Sun and Wang*, 2006; *Alexander*, 2010]. Whereas, many studies have also tried to determine the role of extratropical SST variability on the midlatitude climate anomalies through the air-sea interaction [e.g., *Liu et al.*, 2006; *Kushnir et al.*, 2002; *Liu and Wu*, 2004; *Czaja and Frankignoul*, 2002; *Sen Gupta and England*, 2007]. The response of the atmosphere to North Pacific SST (NP SST) anomalies, in particular, has been recognized as one of the important issues to be resolved. Since the 1960s, many studies have investigated the ocean-atmosphere interaction over the North Pacific [e.g., *Namias*, 1969]. Recently, *Wu and Li* [2007] suggested that the North Pacific Ocean can play an active role in affecting both local and remote climate changes through coupled ocean-atmosphere model experiments. They found that the warming of the North Pacific forces a quasi-barotropic warm ridge and warm trough in early and late winter, respectively, and then alters summer global precipitation and the surface air temperature. *Liu et al.* [2006] found the local atmospheric response to winter NP SST, which is similar to the Pacific Decadal Oscillation (PDO). This pattern persists into spring and summer and leads to the summer atmospheric response with a wave train over the midlatitude North Pacific. *Frankignoul and Sennechael* [2007] suggested that the tropospheric signal associated with NP SST anomalies in late fall-early winter resembles the Pacific North America (PNA) pattern. This is consistent with *Zhang et al.*'s [1998] findings

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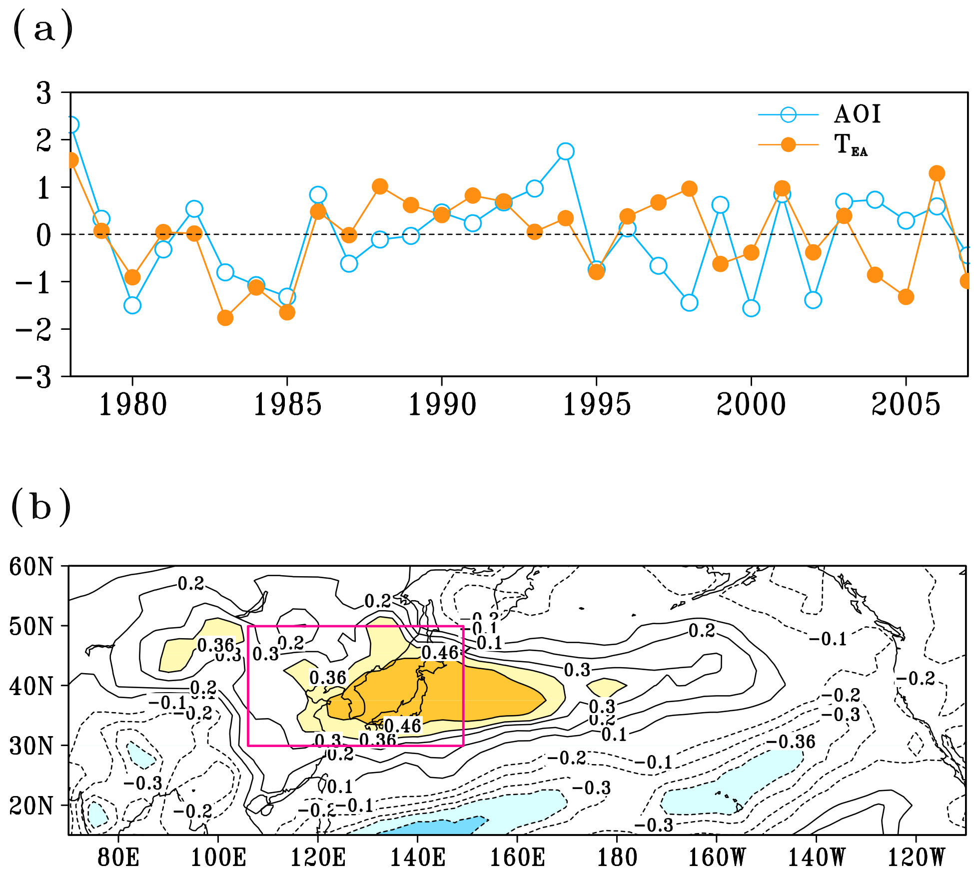

Figure 1. Nov AO index and following winter temperature of East Asia (T_{EA}) during 1978–2007. (a) Detrended time series of the Nov AO index and DJF T_{EA} and (b) the correlation map between Nov. AO index and NCEP/NCAR reanalysis of DJF air temperatures across East Asia and the North Pacific. The shaded areas indicate the 95% and 99% levels of confidence.

that the NP SST anomaly at the onset of the winter season could trigger a PNA response. These aforementioned studies were all focused on the PDO and PNA as examples of large-scale atmospheric circulation connected with NP SST.

[4] A few studies, however, have examined the impact of NP SST on the AO, although the North Pacific is one of the midlatitude centers of the AO. Instead, *Liu and Wu* [2004] suggested that the atmospheric response to NP SST forcing induces an image of an AO-like pattern. Nevertheless, the region where *Liu and Wu* [2004] are concerned is limited in the western North Pacific area of the Kuroshio extension.

[5] In this study we examined the effects of the NP SST on T_{EA} by analyzing the relationship between the AO and the NP SST. Based on the study results, we claim that ocean signals influence atmospheric global circulation and local climate change in terms of T_{EA}.

2. Data

2.1. NCEP/NCAR Reanalysis Data

[6] For analysis of large-scale circulation, we used the National Centers for Environment Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis monthly mean data with a resolution of latitude and longitude 2.5°. The variables were sea level pressure, 300 hPa zonal wind, and air temperature.

[7] T_{EA} is defined as the area-averaged air temperature from NCEP/NCAR reanalysis over the (30°∼45°N, 105°∼150°E) region and is boxed in Figure 1b. The T_{EA} (DJF) used in this study refers to three-month mean temperature for December of the year, and January and February of the next year for 30 years from 1978 to 2007.

2.2. HadSST1

[8] Monthly mean SST data were HadSST1 from Hadley Center, Met Office. The SST is available on a 1° × 1° latitude-longitude grid from 1978 to 2007. Focusing on the atmospheric response to SSTA over the extratropics, we confined the domain of analysis to the North Pacific area (20°∼50°N, 110°∼250°E).

2.3. Indices

[9] Monthly mean AO indices for 30 years from 1978 to 2007 were obtained from the Climate Prediction Center (CPC). Here, the AO index was defined as the first principal component of the monthly mean 1000 hPa geopotential height anomalies for the Northern hemisphere north of 20°N from the NCEP/NCAR reanalysis data.

[10] For correlation analysis related to the leading mode of NP SST, we used various indices influencing the North Pacific region such as PDO, North Pacific Index (NPI), and PNA. PDO was obtained from Nate Mantua's anonymous

Table 1. Time-Lagged Correlation Coefficients (C.C.) Between East Asia Winter Temperature (T_{EA}) and the AO Index (AOI)[a]

	1-Month Averaged		2-Month Averaged		3-Month Averaged	
Beginning Month	AOI	C.C.	AOI	C.C.	AOI	C.C.
Mar.	Mar.	0.17	MA	0.14	MAM	0.21
Apr.	Apr.	0.02	AM	0.17	AMJ	0.22
May	May	0.25	MJ	0.26	MJJ	0.26
Jun.	Jun.	0.12	JJ	0.15	JJA	0.12
Jul.	Jul.	0.12	JA	0.06	JAS	−0.06
Aug.	Aug.	−0.00	AS	−0.14	ASO	−0.14
Sep.	Sep.	−0.17	SO	−0.16	SON	0.23
Oct.	Oct.	−0.08	ON	0.33		
Nov.	Nov.	0.50**				

[a]Here a double asterisk denotes 99% level of confidence.

ftp directory (http://jisao.washington.edu/pdo/PDO.latest), and the NPI and PNA indices from the CPC.

3. Time-Lagged Correlations

[11] To determine which indices affect T_{EA} (DJF), we first examined the time-lagged correlation with the AO and NP SST. The 1-, 2-, 3- and 5-month averaged indices were used for correlation analysis and the relations were calculated with a lead-time up to 9 months. For example, 1-month averaged indices were calculated from March to November, 2-month averaged indices from March–April (MA) to October–November (ON), 3-month averaged indices from March–April–May (MAM) to September–October–November (SON), and so on. Linear trends were removed from all the indices.

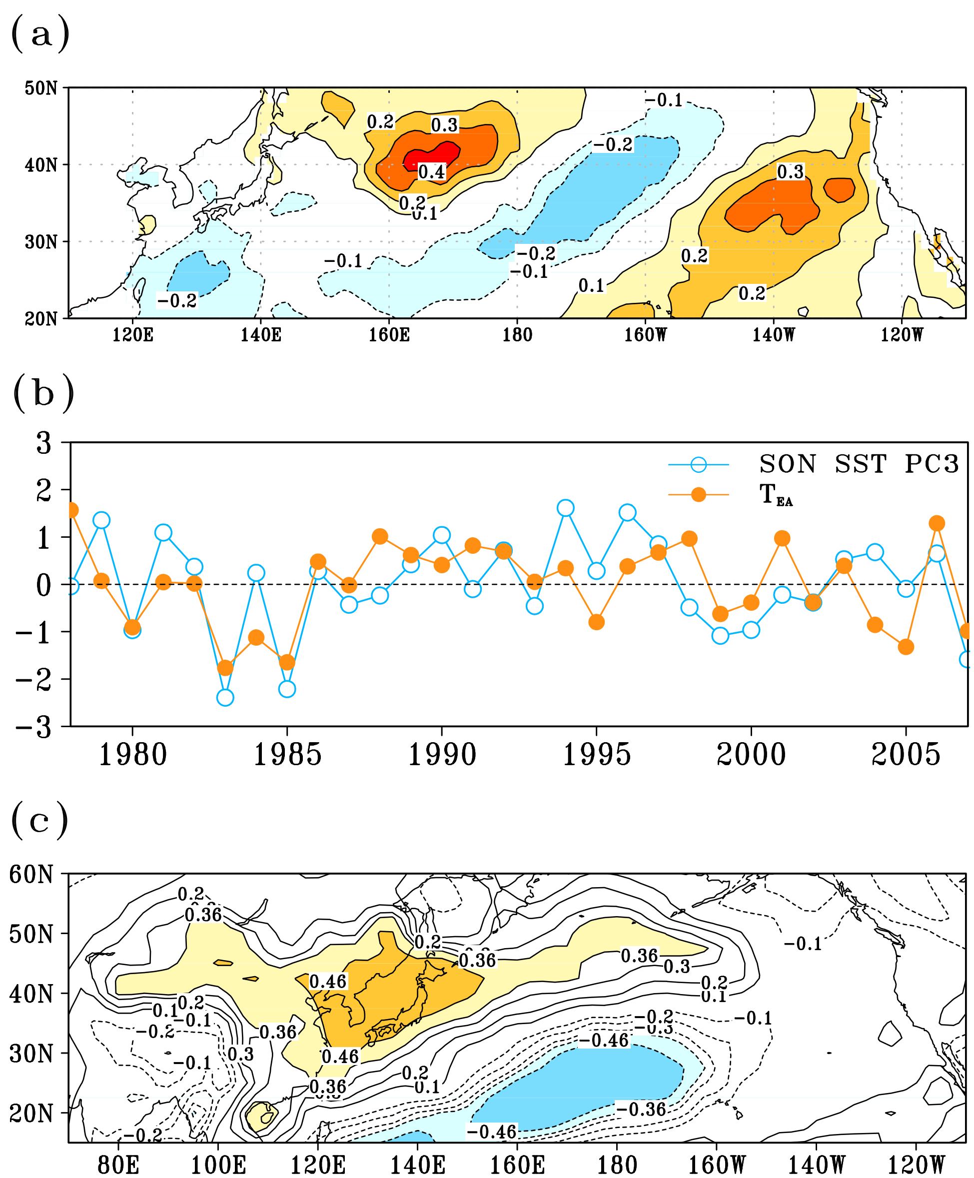

Figure 2. East Asian winter temperature (T_{EA}) and prior SON NP SST during 1978–2007. (a) EOF3 of SON SSTs (explaining 13.0% of the total variance), (b) detrended time series of the SON SST PC3 and DJF T_{EA}, and (c) the correlation pattern between SON SST PC3 and NCEP/NCAR DJF air temperatures. The shaded areas indicate the 95% and 99% levels of confidence.

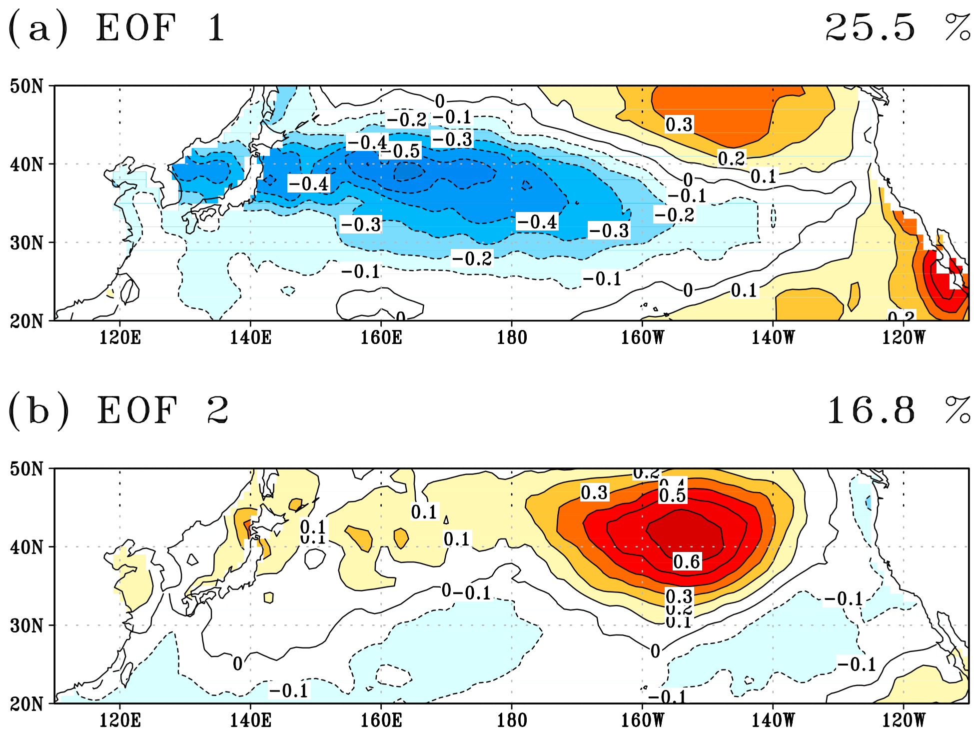

Figure 3. (a) The first and (b) second EOF eigenvectors of SON SST during 1978–2007.

3.1. Arctic Oscillation (AO)

[12] The time-lagged correlations between the AO index and T_{EA} were obtained first. The AO index that had the highest correlation coefficient with T_{EA} appeared in November; the coefficient value of 0.50 was statistically significant at the 99% confidence level (Table 1). The time series of these two variables are shown in Figure 1a. These time variations showed similar fluctuations. The spatial distribution of T_{EA} from the NCEP/NCAR reanalysis data correlated with the Nov AO index also indicated the highly positively correlated area over South Korea and Japan and negative signals in the southern central part of the North Pacific (Figure 1b).

3.2. North Pacific Sea Surface Temperature (NP SST)

[13] To find the NP SST related to T_{EA}, the SST anomalies from 1978 to 2007 were used for EOF analysis. The North Pacific domain applied in this study was almost identical to that of *Frankignoul and Sennechael* [2007], but the region north of 50°N was excluded from the analysis because the sea surface was covered with sea ice in wintertime. For each time-lag, 10 major principal components (PCs) of SST were extracted and their correlations with T_{EA} were estimated. As a result, the third PC of SST averaged for three months from SON (SON SST PC3) was closely associated with T_{EA} with a correlation coefficient of 0.54 (99% level of confidence). The spatial structure of the SON SST 3rd mode showed a tripole pattern with a cold anomaly in the central North Pacific region, and a warm anomaly in the western North Pacific and eastern North Pacific, tilting toward the northeast (Figure 2a).

[14] Figure 2b confirms the similar variations of the time series of SON SST PC3 and T_{EA}. The spatial pattern of NCEP/NCAR reanalysis air temperature corresponding to SON SST PC3 (Figure 2c) had a high positive correlation around South Korea and considerable negative signals in the Pacific region south of there, which strongly resembled the relationship between the AO and temperature (Figure 1b). This similarity of pattern was verified from the high pattern correlation coefficient (0.76) between Figures 1b and 2c.

4. The Atmospheric Response to SON SST 3rd Mode and Nov AO

[15] An understanding of the SON SST 3rd mode first requires an understanding of the first and second modes. The first mode (Figure 3a) had a similar structure to that of PDO, which is the decadal oscillation of NP SST anomalies [*Mantua et al.*, 1997]. The high correlation coefficient of 0.86 between the first PC and the PDO index confirmed that the first mode of SON SST was a PDO-related mode (Table 2).

[16] The strong positive area in the second mode (Figure 3b) was nearly coincident with the domain of NPI (30°N–65°N, 160°E–140°W), which denotes the Aleutian Low intensity [*Trenberth and Hurrell*, 1994]. The correlation coefficient between the second PC and NPI was 0.48, and was significant at the 99% confidence level. According

Table 2. Correlation Coefficients (C.C.) Between SON SST PC1 and PC2 and Global Indices[a]

C.C.	SON SST PC1	SON SST PC2
PDO	0.86**	−0.36*
PNA	−0.19	−0.59**

[a]Here single and double asterisks denote 95% and 99% levels of confidence, respectively.

Table 3. Correlation Coefficients Between SON SST PC1 and PC2 and Global Indices[a]

	SON SST PC1	SON SST PC2	SON SST PC3
Nov AOI	−0.17	0.24	0.47**

[a]Here a double asterisk denotes 99% level of confidence.

to *Coleman and Rogers* [2003], NPI and PNA have a remarkable negative correlation characterized by the strengthening (weakening) of the Aleutian Low and the positive (negative) PNA pattern. We also found a strongly significant negative correlation coefficient of −0.68 between NPI and the PNA index, and the second PC showed a high negative correlation with the PNA index. Therefore, the second mode of SON SST can be regarded as an NP pattern or PNA pattern (Table 2).

[17] Because the Nov AO was correlated with T_{EA} and SON SST PC3 was also associated with it, we examined whether these two indices were related to each other. As shown in Table 3, their correlation coefficient was also as high as 0.47. Furthermore, the SON SST pattern related to the Nov AO index was similar to the SON SST 3rd mode (Figures 2a and 4a) and the sea level pressure pattern in November regressed onto SON SST PC3 was also in good agreement with the AO pattern (Figure 4b).

[18] The influences of the SON SST 3rd mode and Nov AO on T_{EA} were investigated in terms of the atmospheric circulation connected with the AO. Figure 5 shows the correlation maps between sea level pressure and SON SST PC3 (Figures 5a–5d), and the Nov AO index (Figures 5e–5h). The positive signals for both cases centered at 45°N in SON gradually moved southwestward over time from fall to winter. In DJF, the positive signal weakened and expanded toward the southwest. Furthermore, the negative correlation located in the central area of the Siberian High (the boxes in Figures 5c, 5d, 5g, and 5h) began to prevail in NDJ and was further reinforced during DJF. The resemblance of these two maps can be seen from the spatial correlation coefficient between the two (Table 4).

[19] Figure 6 illustrates the correlation maps between the 300 hPa zonal wind and SON SST PC3 (Figures 6a–6d), and the Nov AO index (Figures 6e–6h). The zonal negative signals appeared between 25°N and 45°N from SON to DJF. Positive areas were shown over the north and south of the negative correlation part. This structure further extended in both east and west directions over time, and a coherent pattern was found in both variables. The spatial correlation coefficient of these two maps was high through OND to DJF (Table 4). The area around the core of the negative signals was the center of the winter jet stream. The decrease (increase) of zonal wind in this area corresponded to the weakening (strengthening) of the EAWM. The correlation between the EAWM index [*Jhun and Lee*, 2004] and SON SST PC3 was significant at 95% or 99% level from OND to DJF (Table 5). The significant value appeared in the third mode not in the first and second modes. Figure 7 confirms that this weakening of jet flow occurred only in the

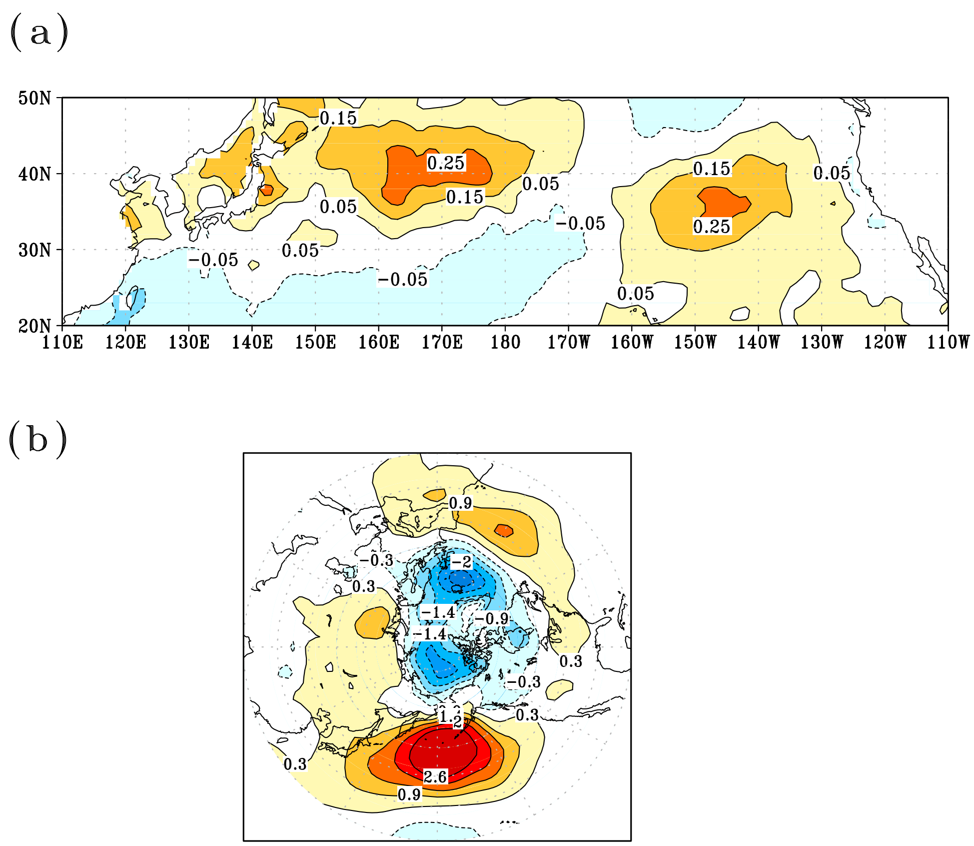

Figure 4. Regression maps between (a) SON SSTs and the Nov AO index, and (b) sea level pressure for Nov. and SON SST PC3 during 1978–2007.

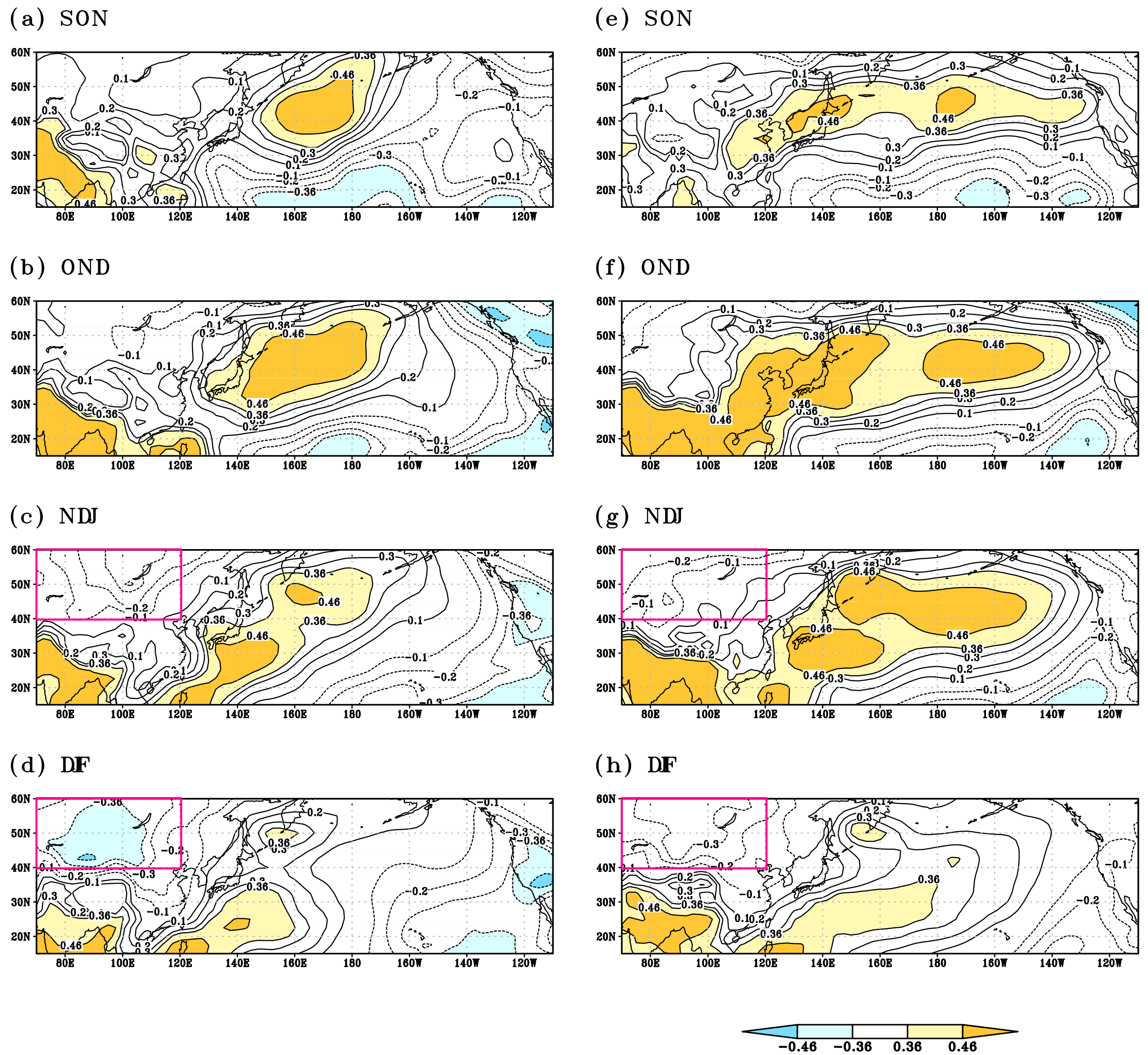

Figure 5. Correlation maps between sea level pressure and (a–d) SON SST PC3 and (e–h) the Nov AO index from SON to DJF. The shaded areas represent the 95% and 99% levels of confidence. The boxes in Figures 5c, 5d, 5g and 5h show the Siberian High area.

correlation map with SON SST PC3 but not with PC1 or PC2. In other words, the SON SST 3rd mode was independent from the first and second modes of SST and was related to the variation of the AO in November.

[20] Figure 8 reveals the air temperature field connected with SON SST PC3 and the Nov AO index. The temperature structure (Figure 8a) related to SON SST PC3 was positive in the west North Pacific region north of 40°N and the east Pacific near 20°N, but negative between these two warm places along the southwest to northeast. This tripole pattern resembled the SON SST 3rd mode (Figure 2a). The pattern developed and moved southwestward over time, so that the center of the positive area was located in East Asia in NDJ and DJF. This feature was also exhibited in the temperature field associated with the Nov AO index, and the spatial correlation coefficient of these two maps was above 0.7 (Table 4).

[21] Consequently, the large-scale atmospheric circulation patterns related to SON SST PC3 were consistent with those related to the Nov AO index. This suggests that the migration of atmospheric circulation pattern associated with the

Table 4. Spatial Correlation Coefficients (C.C.) Between Correlation Patterns Related to SON SST PC3 and the Nov AO Index

Spatial C.C.	SLP	U300	Tair
SON	0.73	0.62	0.65
OND	0.83	0.78	0.67
NDJ	0.89	0.85	0.72
DJF	0.86	0.76	0.76

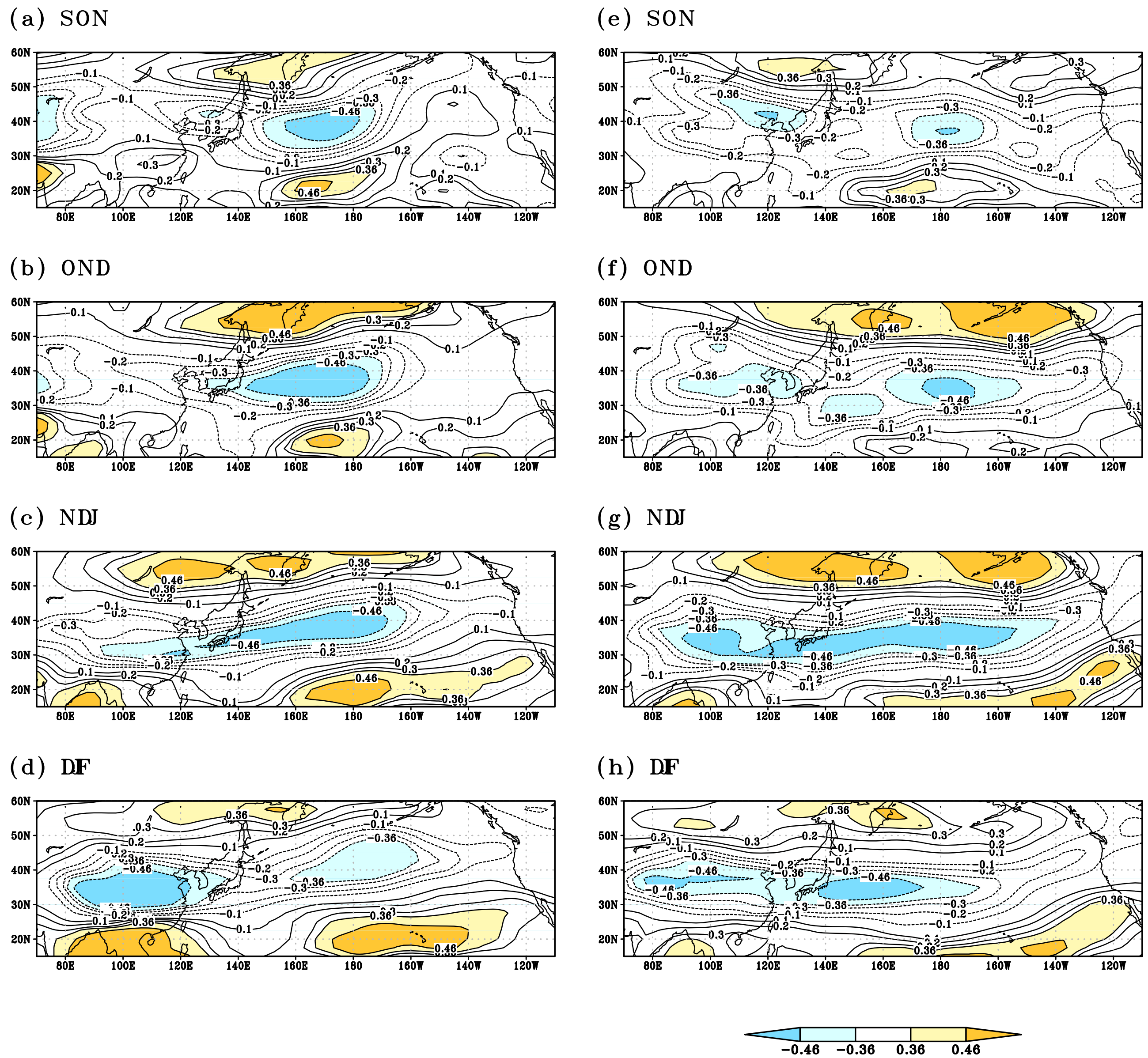

Figure 6. Same as Figure 5 but for 300 hPa zonal wind.

SON SST 3rd mode corresponds to the dynamics of the AO. When they are in positive phase, the intensity of the Siberian High weakens, and consequently so does EAWM, resulting in a warm winter in East Asia, and vice versa in the negative phase.

5. Discussion Summary

[22] This study has investigated the effects of NP SST on T_{EA} and also the relationship between the AO and NP SST. According to the time-lagged correlation analysis, both Nov AO and the SON SST 3rd mode characterized by tripole pattern were closely related to T_{EA}. The key study finding is that these two indices associated with T_{EA} were also highly correlated at the 99% level (0.47). On the other hand, PDO and PNA, the first and second modes of SON SST, respectively, were not closely related to Nov AO and EAWMI. This indicated that the SON SST 3rd mode over the North Pacific is a unique mode in determining the AO, EAWM and their associated winter climate over the East Asian region.

[23] We also compared the correlation maps between large-scale variables, such as SLP and 300 hPa zonal wind and SON SST PC3, and the Nov AO index. These two corresponding time-evolving correlations were very similar

Table 5. Correlation Coefficients Between East Asia Winter Monsoon (EAWM) Indices and SON SST PCs[a]

	SON SST PC1	SON SST PC2	SON SST PC3
EAWMI (OND)	0.02	−0.02	−0.39*
EAWMI (NDJ)	−0.07	0.00	−0.54**
EAWMI (DJF)	−0.13	−0.10	−0.39*

[a]Here single and double asterisks denote 95% and 99% levels of confidence, respectively.

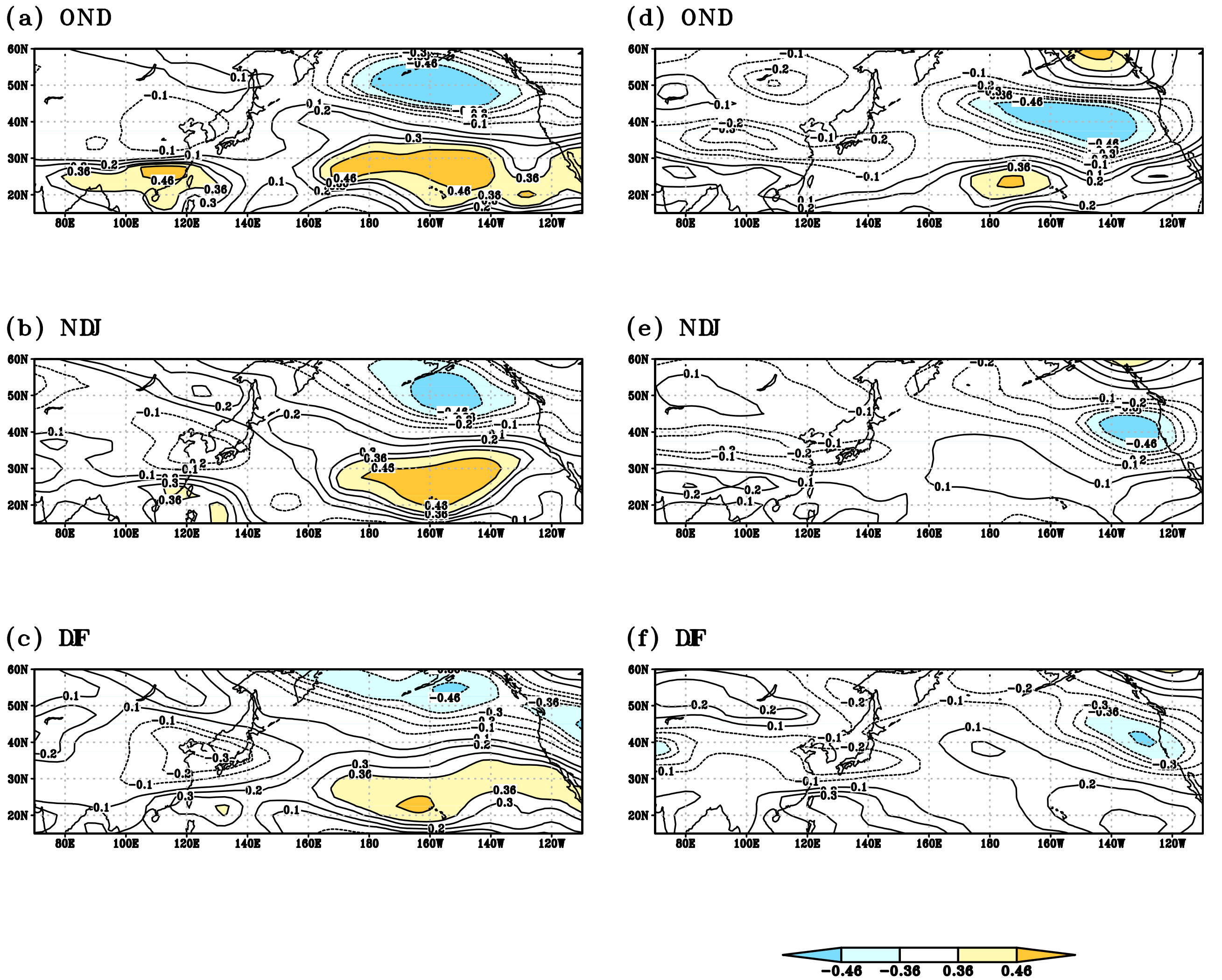

Figure 7. Correlation maps between 300 hPa zonal wind and (a–c) SON SST PC1 and (d–f) PC2, from OND to DJF. The shaded areas represent the 95% and 99% levels of confidence.

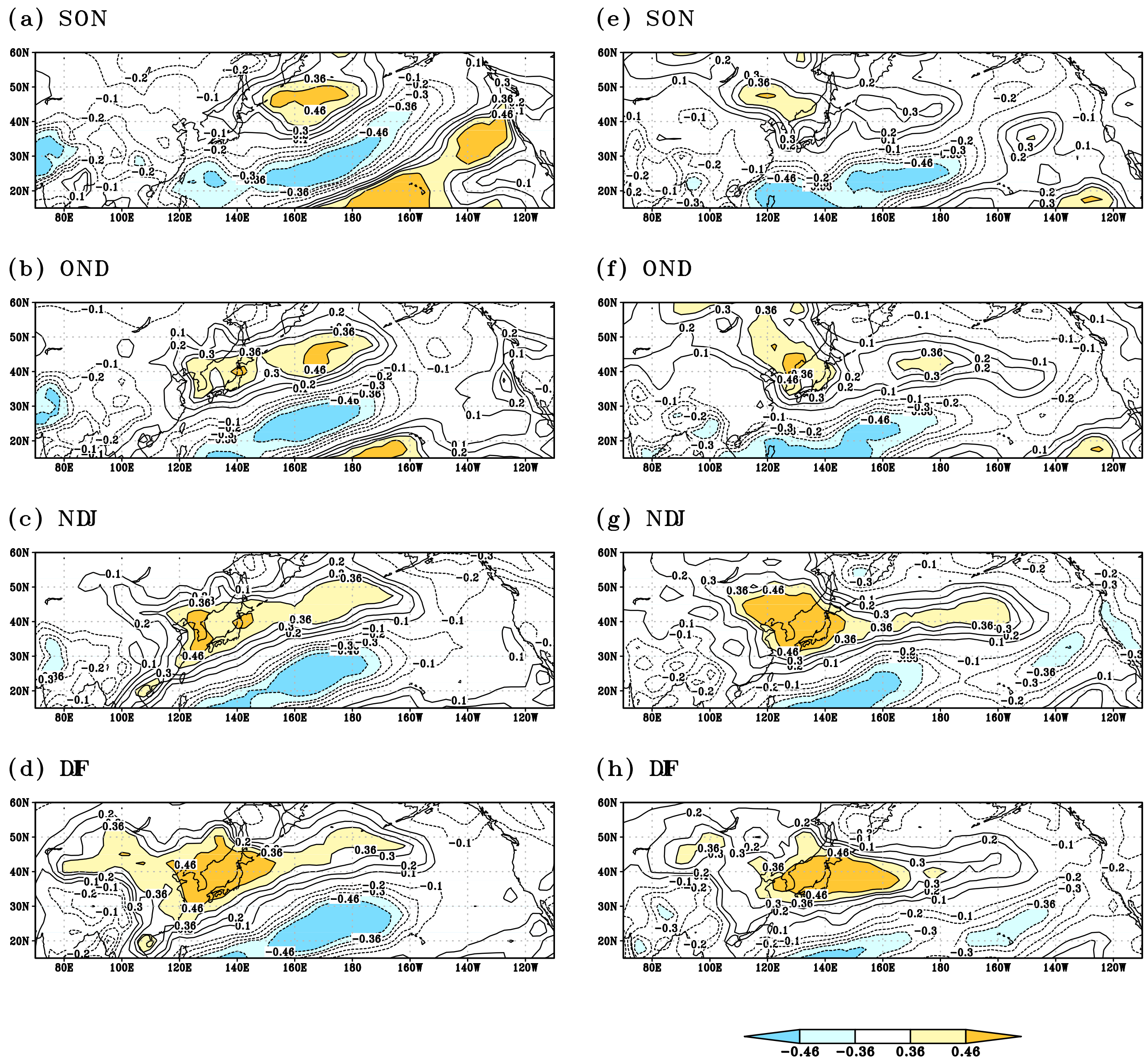

Figure 8. Same as in Figure 5 but for air temperature.

in their pattern changes from fall to winter. That is, the migration of the atmospheric circulation related to the SON SST 3rd mode was consistent with the variation of the AO. This implied that when the SON SST 3rd mode and Nov AO have a positive (negative) phase, the Siberian High and EAWM both weaken (strengthen), resulting in a warm (cold) winter in East Asia.

[24] Our results also imply a possibility that the ocean signal may be a trigger for the atmospheric global pattern, which, in turn, influences the local climate in the East Asia region. We found that SON SST influences the AO in November, which suggests that SON SST can be used in forecasting the AO and winter climate over East Asia. Although our study provides evidence for the NP SST influences on the AO, further observational and/or modeling studies are required to fully elucidate the dynamic mechanism by which NP SST affects the AO, and the relationship between the two.

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