ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 26, NO. 4, 2009, 717–726

# Contribution of the Sea Surface Temperature over the Mediterranean-Black Sea to the Decadal Shift of the Summer North Atlantic Oscillation

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(Received 19 December 2008; revised 2 March 2009)

**ABSTRACT**

Recent observational study has shown that the southern center of the summer North Atlantic Oscillation (SNAO) was located farther eastward after the late 1970s compared to before. In this study, the cause for this phenomenon is explored. The result shows that the eastward shift of the SNAO southern center after the late 1970s is related to the variability of the Mediterranean-Black Sea (MBS) SST. A warm MBS SST can heat and moisten its overlying atmosphere, consequently producing a negative sea level pressure (SLP) departure over the MBS region. Because the MBS SST is negatively correlated with the SNAO, the negative SLP departure can enhance the eastern part of the negative-phase of the SNAO southern center, consequently producing an eastward SNAO southern center shift. Similarly, a cold MBS SST produces an eastward positive-phase SNAO southern center shift.

The reason for why the MBS SST has an impact on the SNAO after the late 1970s but why it is not the case beforehand is also discussed. It is found that this instable relationship is likely to be attributed to the change of the variability of the MBS SST on the decadal time-scale. In 1951–1975, the variability of the MBS SST is quite weak, but in 1978–2002, it becomes more active. The active SST can enhance the interaction between the sea and its overlying atmosphere, thus strengthening the connection between the MBS SST and the SNAO after the late 1970s. The above observational analysis results are further confirmed by sensitivity experiments.

**Key words**: summer North Atlantic Oscillation, Mediterranean-Black Sea, sea surface temperature, decadal variability

**Citation**: Sun, J. Q., and W. Yuan, 2009: Contribution of the sea surface temperature over the Mediterranean-Black Sea to the decadal shift of the summer North Atlantic Oscillation. *Adv. Atmos. Sci.*, **26**(4), 717–726, doi: 10.1007/s00376-009-8210-8.

## 1. Introduction

The North Atlantic Oscillation (NAO), known as the most important and typical teleconnection pattern in the Northern Hemisphere, has been well studied for many decades (e.g., Walker and Bliss, 1932; van Loon, and Rogers; Wallace and Gutzler, 1981; Barnston and Livezey, 1987; Hurrell, 1995; Hurrell and van Loon, 1997; Chang et al., 2001; Li et al., 2003; Li, 2004; Yang et al., 2004; Yu and Zhou, 2004). These studies showed that the NAO is most active in the winter season. The winter NAO (WNAO) exhibits a strong interannual and decadal variability, which induces simultaneous and delay climate anomalies over the North Atlantic and surrounding continents and even over Asia and the North Pacific.

In recent years, one new characteristic of the WNAO has been fueled. That is, there is a spatial

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shift of the WNAO pattern around the late 1970s. The centers of action of the WNAO variability were located farther eastward after the late 1970s compared to before. Such an eastward shift of the WNAO pattern alters its relationship with some climate variables, such as surface air temperature, sea ice export, cyclone activity, heat flux, etc., over the North Atlantic and surrounding regions (Hilmer and Jung, 2000; Jung et al., 2003). This finding indicates that it should be very cautious when any conclusions of long-term WNAO-related climate variability are being drawn from relatively short recent observational data (Jung et al., 2003). Because of the importance of the WNAO pattern shift, some studies started to examine its causes. Lu and Greatbatch (2002) argued that this shift may be related to the change of the North Atlantic storm activity. Peterson et al. (2003) addressed that the spatial shift of the NAO pattern may be related to the trend towards a higher WNAO index during the last several decades of the 20th century. Luo and Gong (2006) pointed out that the eastward shift of the NAO centers is probably due to an increase in the strength of the zonal mean westerly winds in the North Atlantic region. Ulbrich and Christoph (1999) performed an integration of the coupled ECHAM/OPYC3 model under increasing greenhouse gas concentrations, and found an eastward shift of the WNAO centers of action in the simulation, which closely resembles the observed shift, thus implying that the anthropogenic climate change may be an important external forcing for the WNAO pattern shift.

The NAO is also one of the teleconnection patterns that have a year-round presence, although it is most active during the winter. It had been claimed that the summer NAO (SNAO) also explains a large portion of the total variance in the atmospheric circulation over the North Atlantic and has an important influence on the Northern Hemispheric climate (Hurrell and Folland, 2002; Hurrell et al., 2003; Linderholm et al., 2007). In addition, similar to the WNAO variation, the summer NAO (SNAO) pattern also showed a spatial shift around the late 1970s. In investigating the relationship between the SNAO and the simultaneous middle East Asian surface air temperature, Sun et al. (2008) found that the correlation between these two climate systems switched from being uncorrelated before the late 1970s to being strongly correlated after the late 1970s. Further analysis indicated that such an instable relationship had resulted from the eastward shift of the southern center of action of the SNAO variability. The southern center of the SNAO action is enhanced and moves from the North Atlantic to dominate the Mediterranean Sea region after the late 1970s, as shown in Fig. 1. The enhancement of the atmospheric circulation over the Mediterranean-Black Sea (MBS) region produces a strong upper level divergence over the Asian jet entrance region, then stimulates a zonal oriented wave train pattern trapped in the Asian upper level jet, and finally impacts the middle East Asian atmospheric circulation and surface air temperature (Sun et al., 2008). But why is there an eastward shift in the southern center of action of the SNAO after the late 1970s? This is an open question and has not been explored up to now.

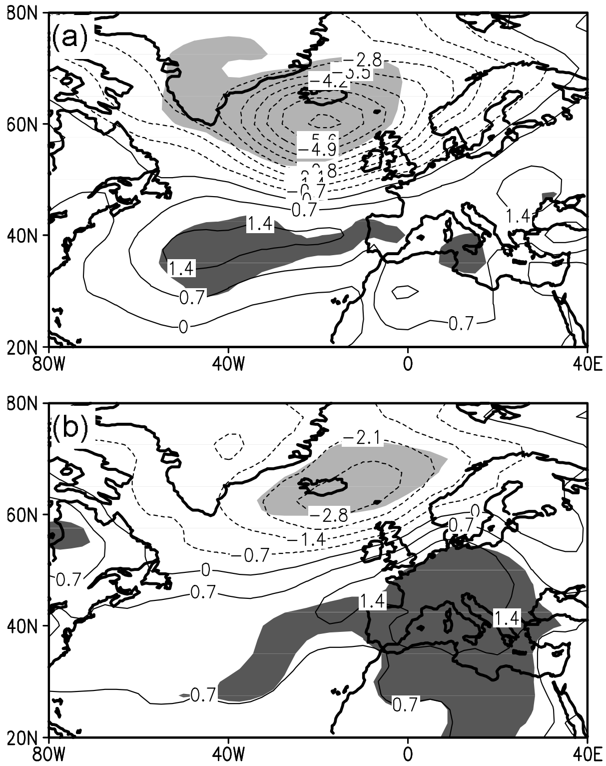


**Fig. 1.** Composite differences of the SLP (in hPa) between the positive-phase and negative-phase SNAO years over the periods of (a) 1951–1975 and (b) 1978–2002. The contour interval is 0.7 hPa while the positive (negative) composite differences significant at the 0.02 level are shaded dark (light). The positive-phase (negative-phase) SNAO years are selected based on the criterion with the SNAO index larger than 0.5 (less than −0.5) standard deviation.

Considering that the most significant change of the SNAO pattern before and after the late 1970s is over the MBS region and some previous studies indicated that the MBS plays important roles in the summer climate over northern Africa and Europe (Li, 2006; Feudale and Shukla, 2007), in this study we try to examine the relationship between the SNAO and the MBS SST to see if this relationship can shed any light on the eastward shift of the SNAO southern center.

## 2. Data description

The atmospheric data applied are the reanalysis data produced by the National Centers for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) (Kalnay et al., 1996). The variables analyzed include winds, geopotential heights, sea level pressure (SLP), and air temperature. All of these variables are gridded at a $2.5° \times 2.5°$ resolution.

The needed SST data are the extended reconstruction of the global SST (NOAA_ERSST_V3) data, which are provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA. The SST data are gridded at a $2° \times 2°$ resolution.

The NAO index used is the difference between the normalized SLPs over Gibraltar and over Reykjavik, Iceland (http://www.cgd.ucar.edu/cas/jhurrell/indices.html).

Considering there is a change of the SNAO pattern around the late 1970s (Sun et al., 2008), the following analysis is performed in two sub-periods: 1951–1975 and 1978–2002.

## 3. Relationship between the SNAO and the MBS SST

Figure 2 shows the correlation maps between the SNAO index and the MBS SST in 1951–1975 and 1978–2002, respectively. It displays that in 1951–1975, there are quite weak correlations distributed over the MBS. There are no significant correlations. However, in 1978–2002, the situation is changed. The whole Black Sea and middle-to-eastern Mediterranean Sea are both covered by significant negative correlations. It implies that there is an instable relationship between the SNAO and the MBS SST on a decadal time scale.

A similar result is also found in an additional index analysis. The mean SST over the whole Black Sea and middle-to-eastern Mediterranean Sea (west of 15°E) is chosen to represent the SST variability of the MBS region. The running correlation with a 25-year window width for the period of 1951–2002 between these two indices is shown in Fig. 3. It exhibits that the correlations between the SNAO and the MBS SST indices show a rapid rise from near zero before the 1970s to a much higher correlation that jumps above the 1% significant level around 1976. This further confirms that the relationship between the SNAO and the SST over the MBS varies with time.

## 4. Mechanism for the impact of the MBS SST on the SNAO

In general, a warm SST can heat and moisten its overlying atmosphere via transferring heat flux and mass (water vapor) from the ocean to the atmosphere. By doing so, the warm SST can induce an anomalous atmospheric variability. In this section, we try to explore the influence of the MBS SST on the SNAO from both the observations and numerical simulations.

### 4.1 *Observational results*

In order to investigate the influence of the MBS SST on its overlying atmosphere, the correlations be-

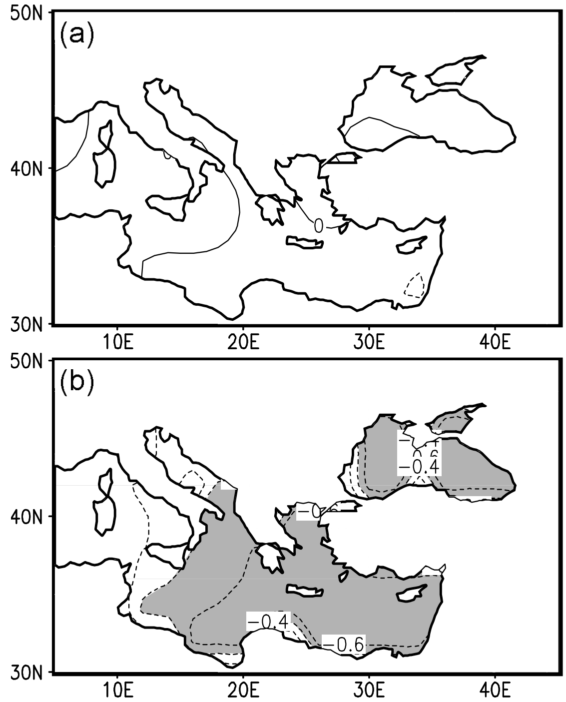


**Fig. 2.** Geographical distributions of the correlation coefficients between the SNAO and MBS SST over the periods of (a) 1951–1975 and (b) 1978–2002. Light shading shows areas where the SST correlates negatively with the SNAO index at the 0.05 significance level.

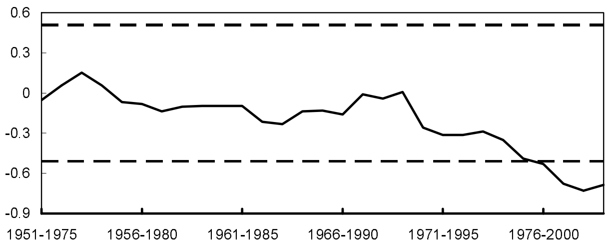


**Fig. 3.** Running correlations between the SNAO index and MBS SST index with a 25-year window width for the period of 1951–2002. Dashed line indicates the 0.01 significance level.

**Table 1.** Correlation coefficients between the MBS SST index and five atmospheric indices over the MBS region. The bold means that the correlation coefficient is significant at the 0.05 level.

| Atmospheric indices | Correlation coefficient | |
|---|---|---|
| | 1978–2002 | 1951–1975 |
| 925 hPa air temperature (°C) | **0.74** | 0.39 |
| 925 hPa specific humidity (g kg$^{-1}$) | **0.53** | 0.18 |
| 850 hPa divergence (s$^{-1}$) | **−0.74** | 0.00 |
| 200 hPa divergence (s$^{-1}$) | **0.63** | 0.38 |
| 500 hPa vertical velocity (Pa s$^{-1}$) | **−0.61** | −0.30 |

tween the MBS SST index and the indices of the 925 hPa air temperature and specific humidity, 850 hPa divergence, 500 hPa vertical velocity, and the 200 hPa divergence over the MBS region spanning 30°–50°N, 0°–40°E are calculated. As shown in Table 1, these five atmospheric indices are all significantly correlated with the SST index over the period 1978–2002. The positive correlations between the SST index and the 925 hPa air temperature and specific humidity indicate a warm MBS SST heats and moistens its overlying lower level atmosphere. This heated and moistened lower level air can enhance the atmospheric instability, thus favoring to stimulate an upward motion over the region. This point is well reflected in the significant negative correlation between the SST index and the 500 hPa vertical velocity. The upward motion then demands an anomalous lower level convergence (negative correlation between the SST and the 850 hPa divergence indices) and upper level divergence (positive correlation between the SST and the 200 hPa divergence indices) based on the mass continuity. Thus, a significant negative SLP departure over the MBS region is induced corresponding to a warm SST (Fig. 4). Because there is a negative correlation between the MBS SST and SNAO indices, the SNAO is in the negative-phase when the MBS is warm. The middle

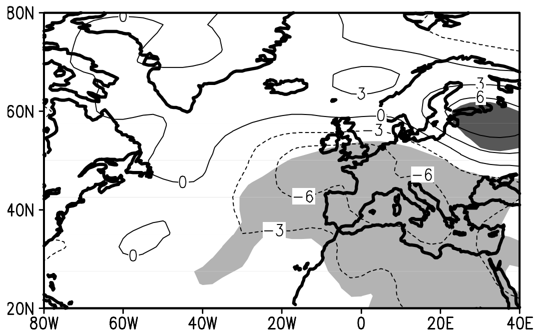


**Fig. 4.** Regression pattern of the summer 1000 hPa geopotential height (in gpm) based on the normalized MBS SST index in the period of 1978–2002. The contour interval is 3 gpm while the positive (negative) correlations significant at the 0.05 level are shaded dark (light).

latitude of the North Atlantic region is therefore covered by a negative SLP departure at this time. The aforementioned warm MBS SST-related negative SLP departure can strengthen the eastern part of the negative SLP departure of the negative-phase of the SNAO southern center over the MBS region, thus resulting in an enhanced and eastward shifted SNAO southern center.

To further investigate the role of the MBS SST in the SNAO variability after the late 1970s, the authors compare the SNAO pattern in anomalous MBS SST years to that in normal MBS SST years. Here the composite analysis is used. The positive-phase (negative-phase) SNAO and warm (cold) MBS SST are tagged as their normalized indices larger than 0.5 (less than −0.5) standard deviation. Based on this criterion, ten positive-phase SNAO years (1978, 1979, 1981, 1982, 1985, 1988, 1990, 1991, 1992, and 1997) and nine negative-phase SNAO years (1986, 1987, 1994, 1995, 1998, 1999, 2000, 2001, and 2002) are identified respectively over the period 1978–2002. In these ten positive-phase (nine negative-phase) SNAO years, there are eight (seven) years with cold (warm) MBS SST and two years of 1982 and 1988 (1987 and 1995) with normal MBS SST. Figure 5a shows the composite difference of the 1000 hPa geopotential height between the positive-phase SNAO years with a cold MBS SST and the negative-phase SNAO years with a warm MBS SST. It shows a significant negative center over the high latitude North Atlantic and a significant positive center over the MBS region, which is consistent with the SLP pattern in Fig. 1b. When the MBS SST is normal, the SNAO pattern shows a different scenario. Figure 5b shows the composite difference of the 1000 geopotential height between the positive-phase SNAO and the negative-phase SNAO with a normal MBS SST. It displays that the significant negative center is still over the high latitudes of the North Atlantic, but the significant positive center is now located over the middle North Atlantic. Over the MBS region, there is no large scale significant anomalous signal. This implies that if the MBS SST is normal, it is likely that the SNAO pattern would not shift eastward. The dif-

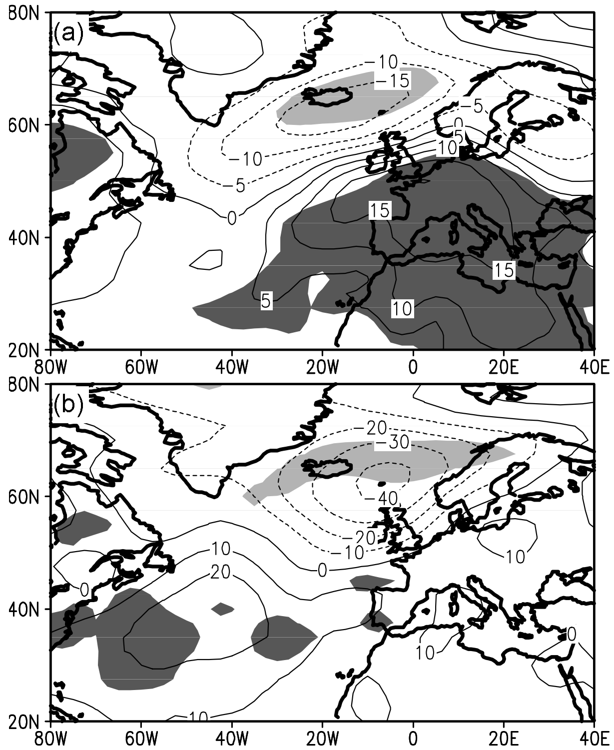


**Fig. 5.** Composite differences of the 1000 hPa geopotential height (in gpm) (a) between the positive-phase SNAO years with a cold MBS SST and the negative-phase SNAO years with a warm MBS SST and (b) between the positive-phase SNAO and the negative-phase SNAO with normal MBS SST in the period 1978–2002. Dark (light) shading shows areas where the composite difference is positively (negatively) significant at the 0.05 level.

ferent behavior of the SNAO in anomalous and normal MBS SST years indicates that the MBS SST may play an important role in the eastward shift of the SNAO southern center after the late 1970s.

### 4.2 *Modeling results*

The above subsection examines the role of the MBS SST from observations. In this subsection, the authors further examine its role via numerical simulations. The numerical model used is the Atmospheric General Circulation Model (AGCM) developed at the Institute of Atmospheric Physics (IAP) under the Chinese Academy of Sciences. The IAP-AGCM is a global grid point model with 5° (lon)×4° (lat) horizontal resolution. The model has nine levels unevenly spaced in the vertical direction with the upper model boundary at 10 hPa. A brief description on the IAP-AGCM dynamical framework, physical processes, and land surface process schemes was presented by Zeng et al. (1987), Zhang (1990), Bi (1993), and Liang (1996), respectively. It is a state-of-the-art climate model, already used in a series of climatic studies, for example in studying the interannual variability and predictability of the global climate (Wang et al., 1997), the global monsoon (Xue et al., 2001), the African climate (Chineke et al., 1997), paleoclimate questions (Wang, 2002; Jiang et al., 2003; Zhang et al., 2007), East Asian climate variability and predictability (Lang et al., 2003; Wang et al., 2003; Wang et al., 2006), and so on.

To simplify the experimental design, the authors introduce an idealized situation by imposing a homogeneous warming of 1.2°C for the eastern Mediterranean sea and the whole Black Sea surface (east of 15°E; 13 model points for the current resolution). The reason for choosing such a warming anomaly is because the largest departure of the MBS index over the period 1978–2002 is 1.2°C. In order to eliminate the strong SST gradient around 15°E, the western Mediterranean SST is linearly decreased westward, as shown in Fig. 6a.

We perform a 22-year run with the model's climatological SST and sea ice boundary conditions, and the average for the last 20-year are defined as the control run (EXP0). For the sensitivity experiment (EXP1), an ensemble of 20 members, each starting from different initial fields and integrated for 3 months from 1 July to 30 September, is performed with a combined SST boundary condition: the idealized MBS warming

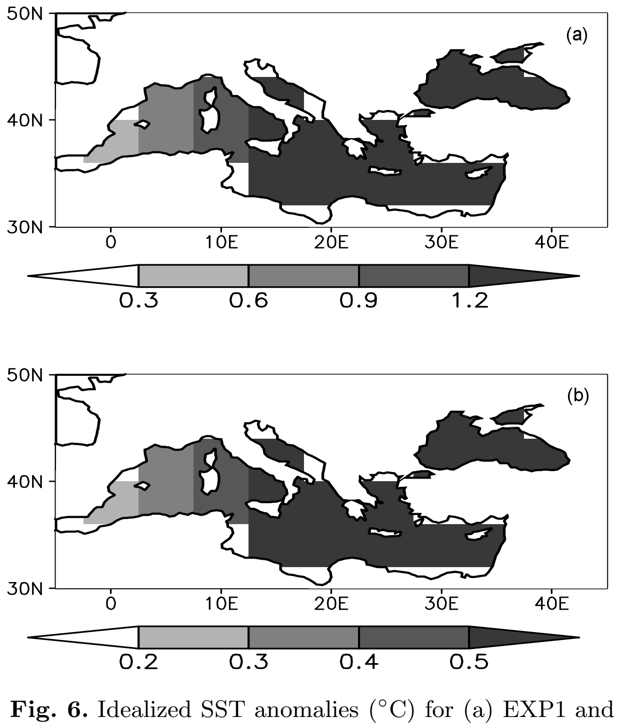


**Fig. 6.** Idealized SST anomalies (°C) for (a) EXP1 and (b) EXP2.

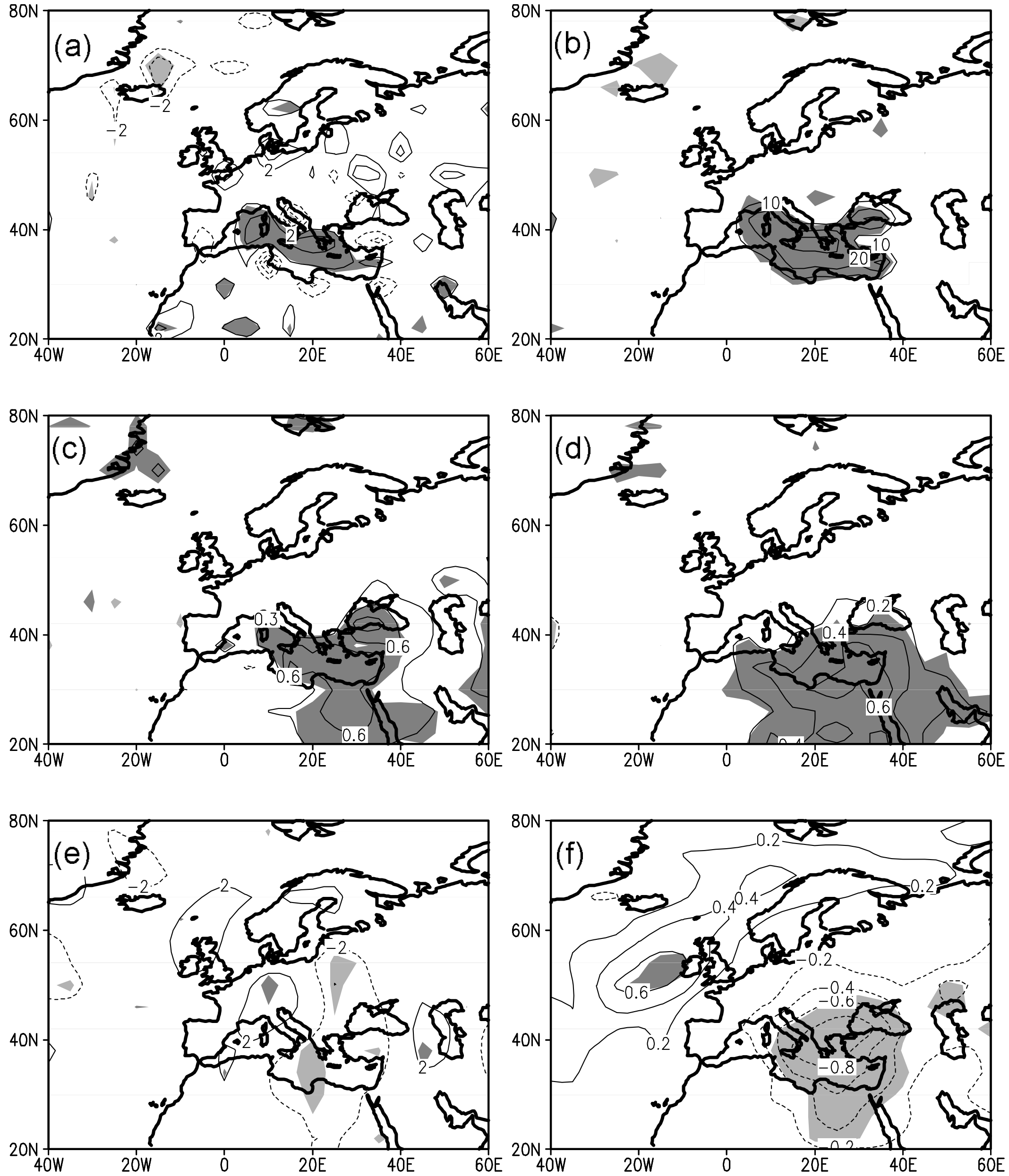

**Fig. 7.** Anomalies (EXP1-EXP0) of the (a) sensible heat flux (W m$^{-2}$), (b) latent heat flux (W m$^{-2}$), (c) surface air temperature (°C), (d) 925 hPa specific humidity (g kg$^{-1}$), (e) 475 hPa vertical velocity ($10^{-3}$ Pa s$^{-1}$), and (f) sea level pressure (hPa). Dark (light) shading shows areas where the composite difference is positively (negatively) significant at the 0.05 level.

(Fig. 6a) superimposed on the model's climatological monthly SST. These 20 initial fields are taken from the restart files of the control run (every 1 July of the 20-year control run). Differences between EXP1 and EXP0 thus reveal the influences of the imposed boundary forcing—a MBS SST warm anomaly after the late 1970s.

As shown in Fig. 7, the model simulation displays a quite similar result with the above observational analysis. With a warming over the MBS, there is significant turbulent heat flux (latent and sensible heat flux) transferred from the sea to its overlying atmosphere. Thus, the overlying lower level atmosphere is heated and moistened. The heated and moistened atmosphere then produces a significant baroclinic structure circulation over the MBS region, with an upward motion at the middle level and a negative SLP departure at the lower level. The negative SLP departure over the MBS can enhance the eastern part of the negative-phase of the SNAO southern center, consequently producing an eastward shifted SNAO southern center. The similarity between the modeling and observational results reconfirms the impact of the MBS SST on its overlying atmosphere and further on the SNAO.

## 5. Discusses

### 5.1 *Instable relationship between the MBS SST and the SNAO*

This study also raises another question as to why there is a change of relationship between the SNAO and the MBS SST. In other words, why does the MBS SST have an impact on the SNAO after the late 1970s but not before? In order to answer this question, we compare here the variability of the MBS SST between these two sub-periods.

Figure 8 shows the running standard deviations of the MBS SST index for 1951–2002. It displays that, before the late 1970s the standard deviation of the MBS SST is low, implying that the variability of the MBS SST is weak over the former period; while after the late 1970s the standard deviation of the MBS SST is increased remarkably, indicating that the variability of the MBS SST becomes more active over the latter period. For the spatial distribution, the significantly increased region of the standard deviation of the SST is mainly located over eastern Mediterranean Sea and the whole Black Sea (Fig. 9), which is quite consistent with the correlation distribution between the SST and SNAO index (Fig. 2b). Such an increase in the MBS SST variability after the late 1970s enhances the air-sea interaction of the region, thus favoring the occurrence of strong atmospheric circulation departures over the MBS region. Such atmospheric circulation departures can enhance the eastern part of the SNAO southern center and consequently produce an eastward shift of the SNAO southern center. While in the period before the late 1970s, the variability of the SST over the MBS is quite weak. This limits the air-sea interaction; there is therefore not a significant correlation between the SNAO and MBS SST.

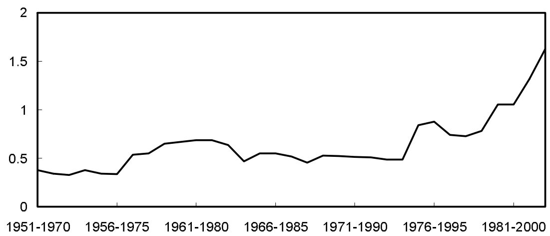


**Fig. 8.** Running standard deviations of the MBS SST with a 20-year window width for the period of 1951–2002.

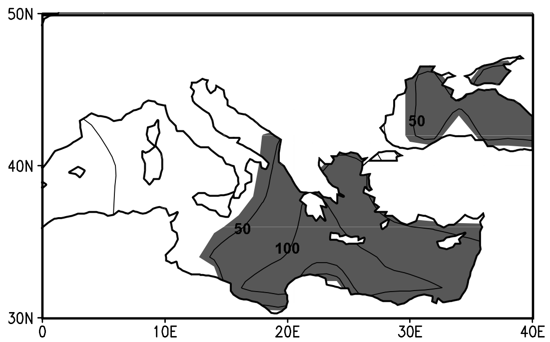


**Fig. 9.** Increased percent of the standard deviation of MBS SST in 1978–2002 relative to 1951–1975. Dark shading shows areas where the increase is significant at the 0.05 level.

The above deduction is well confirmed by another sensitivity experiment (EXP2). In this experiment (EXP2), the initial fields and the integrated period are the same as EXP1. The only difference is that the idealized SST anomaly over the eastern Mediterranean Sea and the whole Black Sea surface (east of 15°E; 13 model points) is 0.5°C. That is because the largest departure of the MBS index over the period 1951–1875 is 0.5°C. Similar to EXP1, the western Mediterranean SST is also linearly decreased westward in order to eliminate the strong SST gradient around 15°E. The distribution of such an idealized SST anomaly is shown in Fig. 6b. Relative to a strong warming over the MBS (EXP1), the anomalous of the turbulent heat flux transferred from the sea is quite weak in a weak warming (EXP2). There are not significant latent and sensible heat flux anomalies located over the MBS region (Figs. 10a and 10b). It implies that the air-sea connection in EXP2 is weak. Thus, the associated changes of the overlying atmosphere are smaller in EXP2 relative to EXP1 (Figs. 10c–f). So, it can be concluded that the decadal change of the MBS SST variability around the late 1970s is likely to contribute to the instable relationship between the MBS SST and SNAO.

### 5.2 *Decadal change of SST over the MBS*

The above analysis indicates that the decadal change of the MBS SST plays an important role in the decadal shift of the SNAO pattern, which further raises a question: what is the feature of the MBS SST variability, especially its decadal variability? About this question, there are some studies that have focused on it recently. For example, Moron (2003) investigated the long-term variability of the Mediterranean Sea SST for the period 1856–2000 based on two different datasets: the Global Ocean Sea Temperature Atlas elaborated

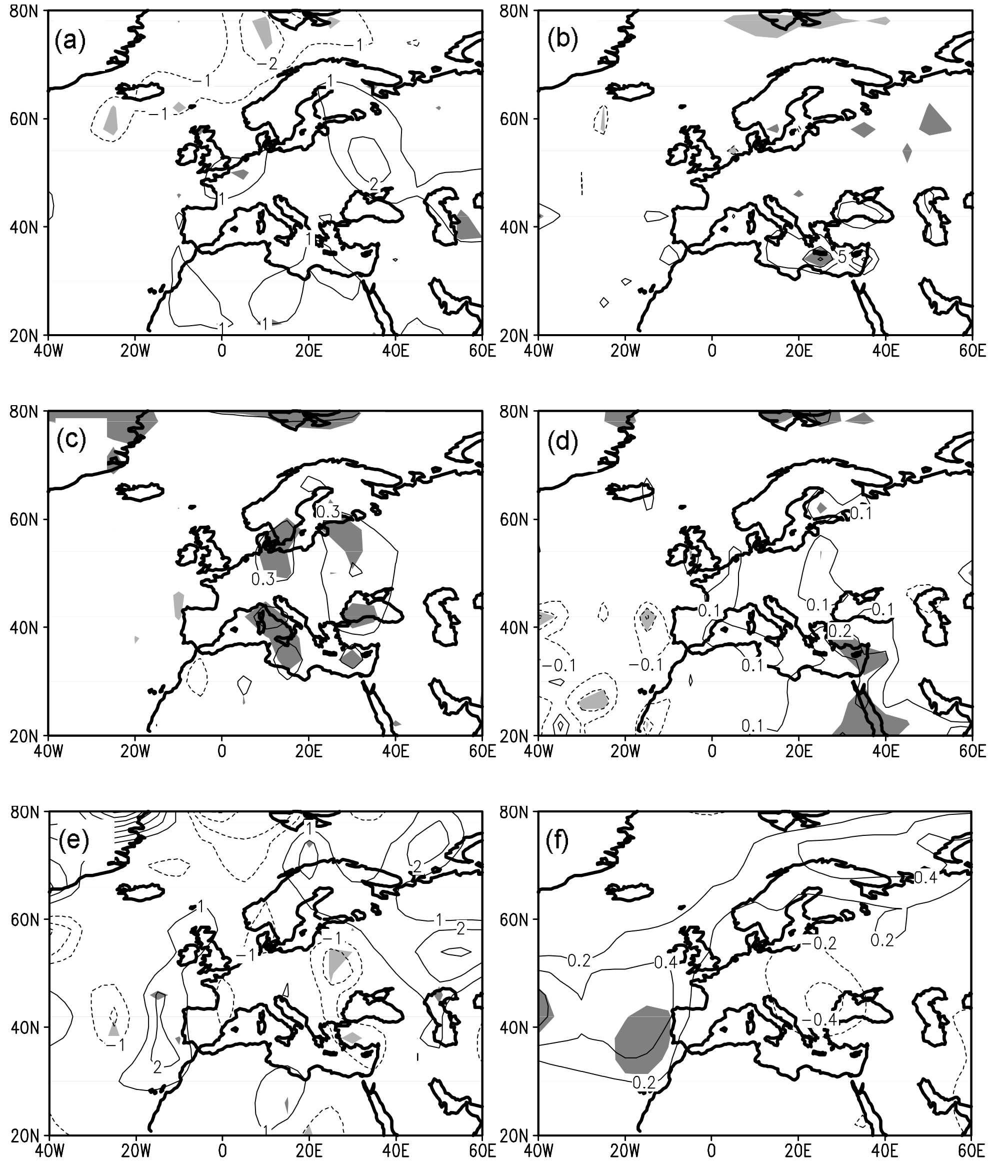

**Fig. 10.** Anomalies (EXP2-EXP0) of the (a) sensible heat flux (W m$^{-1}$), (b) latent heat flux (W m$^{-1}$), (c) surface air temperature (°C), (d) 925 hPa specific humidity (g kg$^{-1}$), (e) 475 hPa vertical velocity ($10^{-3}$ Pa s$^{-1}$), and (f) sea level pressure (hPa). Dark (light) shading shows areas where the composite difference is positively (negatively) significant at the 0.05 level.

by the Hadley Centre and the "optimal" dataset of Kaplan et al. (1998). He found that the major mode of the SST shows the same sign across the Mediterranean Sea and it exhibits a remarkable decadal variation. Later, Zveryaev and Arkhipkin (2008) obtained a similar result using the modern SST dataset in the second half of the 20th century (The Global Sea-Ice and SST dataset, version 2.3b), and they further addressed that the character of interdecadal SST changes is common for all seasons. So it can be concluded that the decadal variability is one major feature of the MBS SST variability.

But what is the possible mechanism for the formation of the decadal variability of the MBS SST? There has been insufficient attention paid to this question. Pisacane et al. (2006) proposed that the decadal variability in the Mediterranean Sea may result from the overturning circulation variability in the eastern basin. Zveryaev and Arkhipkin (2008) supposed that the variability of deep temperature characteristics and its relation to the surface processes may have an impact on the decadal variability of the MBS SST. So up to now, the possible formation mechanism of the MBS SST decadal variability is still an open question, which needs further exploration.

## 6. Conclusion

This study is performed to explore why there is a spatial shift of the SNAO southern center in the late 1970s. Here, the role of the MBS SST is focused on. It is found that the variability of the MBS SST contributes mainly to the eastward shift of the SNAO pattern over the period after the late 1970s. The possible process responsible for the influence of the SST on the SNAO pattern can be described simply as follows. When the MBS is warmer than usual, it can heat and moisten its overlying atmosphere via modulating the latent heat flux out of the sea. The heated and moistened atmosphere then leads to an upward motion and a negative SLP departure over the MBS region. For there is a negative correlation between the MBS SST and SNAO, and this warm SST-related negative SLP departure enhances the eastern part of the negative-phase of the SNAO southern center, consequently producing the eastward shifted southern center of the SNAO pattern. Correspondingly, the cold MBS SST produces an eastward shifted southern center of the positive-phase of the SNAO pattern.

The authors also tried to discuss the possible reason for why the MBS SST is highly correlated with the SNAO in 1978–2002 but not in 1951–1975. It is found that the decadal change of the MBS SST variability in these two sub-periods is likely to contribute to the above instable relationship. In the first sub-period, the variability of the MBS SST is quite weak, and the exchange of the air-sea heat flux is also weak. Thus, the connection of the MBS and its overlying atmosphere is loose and there is not a significant correlation between the MBS SST and the SNAO. However, in 1978–2002, the situation is changed. The MBS in this period becomes more active. It transfers sufficient heat and moisture to the atmosphere. Thus, the MBS SST has a significant impact on its overlying atmosphere and further on the SNAO.

Considering the local scale of the MBS SST variability, the decadal change of the MBS SST might not be the primary cause for the decadal shift of the SNAO, such a large-scale atmospheric circulation change. But our study indicates that, at least, the variability of the MBS SST could enhance the decadal shift of the SNAO.

***Acknowledgements.*** The authors are grateful to the two anonymous reviewers for their valuable comments and helpful advice. This research was jointly supported by National Basic Research Program of China (Grant No. 2009CB421406), the Chinese Academy of Sciences (Grant Nos. KZCX2-YW-Q1-02 and KZCX2-YW-BR-14), and the National Natural Science Foundation of China (Grant Nos. 40631005 and 90711004).

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