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Warming trend in northern East China Sea in recent four decades*

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Abstract Global warming has become a notable trend especially since an abrupt climate change in 1976. Response of the East China Sea (ECS) to the global warming trend, however, is not well understood because of sparse long-term observation. In this paper, hydrographic observation data of 1957–1996 are collected and reviewed to study climatological variability in northern ECS. Significant warming trends are found in both summer and winter. In summer, the average SST is about 0.46°C higher during the period of 1977−1996 than that of 1957−1976, and the Taiwan Warm Current Water (TWCW) was strengthened. In winter, despite of the cooling effect in the coastal areas adjacent to the Changjiang (Yangtze) River Estuary (CRE), the average SST increase was about 0.53°C during the same period. The causes of this SST warming up in summer are different from in winter. The warming trend and intensification of the TWCW in summer were primarily influenced by the strengthening of the Kuroshio transport, while the warming in winter was mainly induced by the variability of the climate system.

Keyword: global warming; climate change; East China Sea; sea surface temperature; long-term variability

1 INTRODUCTION

Global warming is a serious reality that has received much attention since last decades. It is believed that an abrupt climate change in the global atmosphere-ocean system around 1976 promoted the global warming trends, and caused many impacts such as the increase of the sea temperature in the tropical Pacific (Graham, 1995; Gu and Philander, 1997), temperature decrease in northern Pacific (Trenberth, 1990; Latif and Barnett, 1994; Kawamura, 1994), intensification and extended duration of the ENSO events (Trenberth and Hoar, 1996), weakening of the East-Asian summer and winter monsoons (Guo et al., 2003; Yan et al., 2003), warming in the northern part of China (Yu et al., 2003b), and enhancement of heat transport of the Kuroshio in winter (Weng et al., 1996; Ni et al., 2003).

The East China Sea (ECS) is a marginal sea and it has strong connection with human environments and plays an important role in economy. Being relatively shallow water depth and interaction with outer ocean, its response to the global warming is very sensitive. Yan and Li (1997) used ship observation data during 1900−1987 in the ECS to study the variations of regional-averaged temperature in the period, and found the warmest period in the 1950s. Yu and Xu (2003a) and Li et al. (2007) analyzed the AVHRR sea surface temperature (SST) data recorded since 1990 and 1980s, respectively, and discussed their relationships with ENSO and other influence factors in the region. Zhang et al. (2005) studied SST data of 1901−2004 from Hadley Center, and found significant warming trend in the coastal China Seas since the 1980s. Cai et al. (2006) used the HadISST and SODA data to investigate the response of coastal waters of China to the global climate change during 1958−2000, and showed strong weakening of wind stress and increased SST in the ECS since 1976. Although these previous studies provide some important information for our understanding of the

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temperature variability in the ECS, detailed studies on this subject are still very limited, especially due to the lack of the available long-term and direct observation data, which makes it difficult to obtain a reliable and sensitive temperature variability pattern in the ECS. Moreover, our knowledge on how the ECS respond to the global climate change is even more limited.

In this paper, we use historical hydrographic data to examine the warming-up trend in the northern part of the ECS in summer and winter, and discuss the possible causes. As the thermohaline structure and circulation in northwestern ECS are mainly controlled by the distribution, variation and interaction of the Changjiang (Yangtze) Diluted Water (CDW) and the Taiwan Warm Current Water (TWCW), i.e. the northward branch of the Kuroshio, causes of the termohaline variability by these major environmental factors are also discussed.

2 DATA AND METHODS

Data used in this study are historical hydrographic observations from the Marine Science Dataset of the Chinese Academy of Sciences (CAS) developed by the Institute of Oceanology, CAS. The data sets are not limited to SST, but also include temperature and salinity data at standard depths (5 m, 10 m, 15 m, 20 m etc.) and bottom. Fig.1 shows total data distribution and locations of the studied area (28° to 32°N, coast of China to 128°E). The data are seasonally averaged in the summers (June to August) and the winters (December to February) from 1957 to 1996, and spatially averaged on 0.5°×0.5° grids for statistics of multi-year mean hydrographic fields, and on 0.5°×1° grids for Empirical Orthogonal Function (EOF) decomposition.

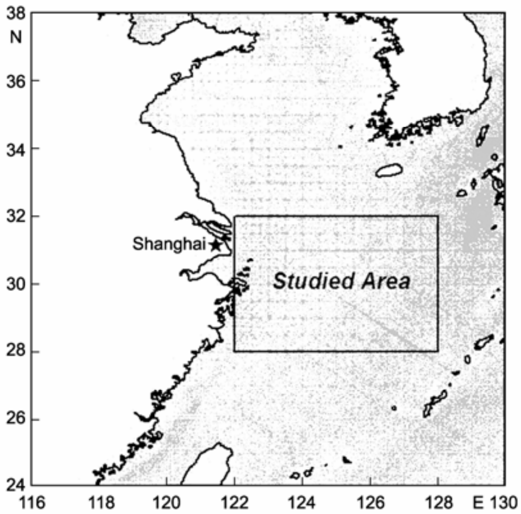

Fig.1 Data distribution (gray dots) and locations of the studied area (tangle)

Time series data of other environmental factors are also applied to investigate their influence on the thermohaline variations with correlation analyses, namely seasonal mean air temperature in Shanghai (1951−1998), Changjiang River run-off discharge at Datong (1950−1999), and transport of the Kuroshio through PN section by the Japanese Meteorology Agency (1955−2001).

3 EVIDENCE IN OBSERVATION

Multi-year mean temperature and salinity are calculated for the periods of 1957−1976 and 1977−1996, respectively, and differences between the two periods are presented to study the response of northern ECS to the abrupt climate change in 1976.

In summers of 1977−1996, the average thermohaline pattern in northern ECS shows that the SST was cooler along the shore than in the other areas (Fig.2a1), and the saline TWCW extended northwards beneath the thermocline to the latitude of Changjiang River Estuary (CRE) (Fig.2a2) (Detailed hydrographic features of the TWCW are referred to Mao et al., 1965a, b; Tang and Wang, 2004). Compared with the previous 20 years, most areas became warmer after 1976 (Fig.2b1), indicating that the ECS did respond to the global warming tendency in the recent decades. The average increase of SST in the studied area was 0.46°C. Large SST increment was mainly located at south of 31°N (shaded area in Fig.2b1), especially near the path of northward intrusion of the TWCW (as seen from the position of saline tongue in Fig.2a2, with salinity greater than 34). Bottom salinity also increased in most areas of northern ECS, and the increment was the largest along the path of TWCW between 30°N and 31°N (Fig.2b2). It is known that the warm, saline TWCW is a branch of the Kuroshio, and the extent to which it reaches northwards has strong interannual-to-interdecadal variations (Tang and Wang, 2004). The notable warming and increase of salinity at its northern edge (about 30−31.5°N, 122.5–124°E) reveals the strengthening of northward extension of the TWCW after 1976.

In winters of 1977–1996, the thermohaline structure became vertically homogeneous; the average SST shows the warm TWCW intruded northwards into the cold coastal water, and reached the north of 31°N (Fig.3a). Shown by the temperature difference between the two periods, the warming trend can also be seen in vast areas (Fig.3b). The average increase of SST in winter in the studied area was 0.24°C. Water temperature adjacent to the CRE decreased dramatically, yet this phenomenon is uncertain because the data are sparse in coastal areas in winter. Despite of this, other areas were warmed up with an average temperature of 0.53°C after 1976. Temperature at bottom was very similar to that of surface because of the strong mixing in winter in the coastal seas.

4 CAUSES AND INFLUENCE FACTORS

The main controlling factors of the climatological change in the thermohaline structure are studied through EOF decomposition and correlation analysis. Some EOF modes of temperature and salinity anomaly at surface and 20 m depth (subsurface layer beneath the thermocline) are found helpful for understanding the warming phenomena mentioned above. Discontinuity in the EOF time sequences is due to insufficient data in some years, which has no significant effect to the results.

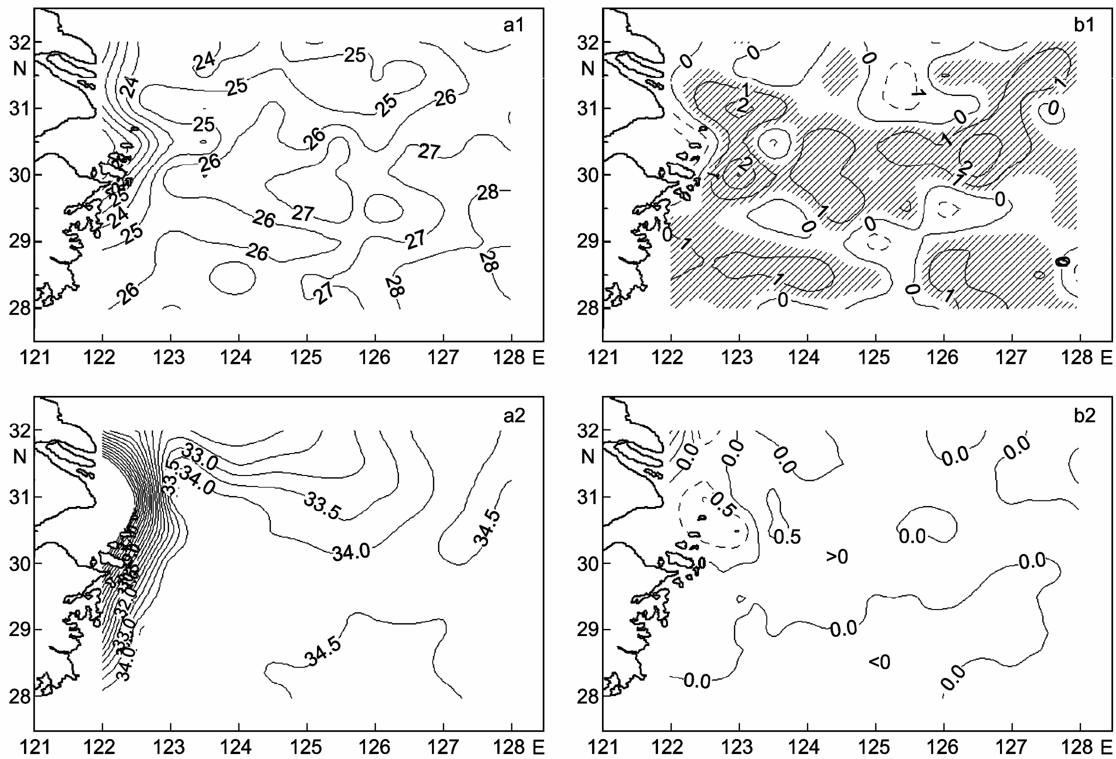

Fig.2 Multi-year mean (a1) SST, (a2) bottom salinity in summer of 1977–1996, and difference of (b1) SST, (b2) bottom salinity in summer between 1957–1976 mean and 1977–1996 mean

Positive in (b) denotes increment in temperature or salinity; Shaded area in (b1) shows temperature increments greater than 0.5°C

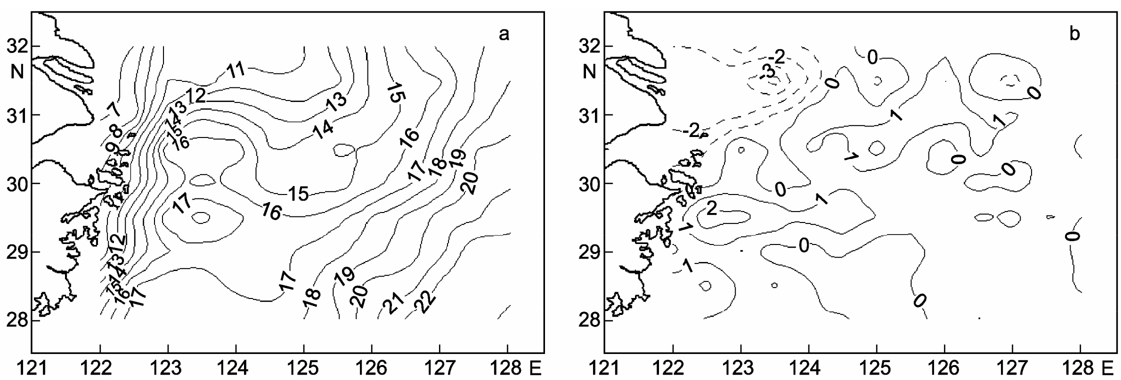

Fig.3 (a) Multi-year mean SST in winter of 1977–1996, and (b) difference of SST in winter between 1957–1976 mean and 1977–1996 mean

Positive in (b) denotes increment in temperature

First, the EOF modes of temperature and salinity in summer are analyzed. Spatial patterns and time coefficients of the first EOF mode of SST show in-phase distribution with 20–30 years period (Fig.4a1, b1), and has positive correlation of 0.51 (confidence level greater than 99%) with air temperature in Shanghai. Accounting for 38.5% of the total SST variance, this mode reflects the primary influence of climate system on variability of SST. Characteristics of the first mode of temperature at 20 m are similar to that of SST (not shown), and also has a positive correlation of 0.336 (90% confidence level) with air temperature in Shanghai. Therefore variability of the sea temperature responds to the atmospheric forcing in the first modes, and the response decreases with depth. Air temperatures of Shanghai in summer do not show obvious warming trend or interdecadal fluctuation periods; accordingly, the first modes of sea temperature do not reflect the warming trends.

The second SST mode shows out-of-phase change along the two sides of 31°N (Fig.4a2), and its time coefficients show an increasing tendency since the 1960’s (Fig.4b2), which is accordant with the previous result showing that SST in summer raised mainly in the south of 31°N. Although not dominant (accounting for 14.01% of the total variance), the second SST mode reveals the long-term part of SST variations. Characteristics of the second mode of temperature at 20 m is similar to that of SST, except for the coastal positive areas expanded to the north of the CRE (Fig.4a3). The first mode of salinity at 20 m in summer shows positive anomalies in the most regions with large values between 30°N and 31°N, the north edge of the TWCW (Fig.4a4). All these three modes have increasing time coefficients, which can be interpreted as warming trend to the south of 31°N, and the increases of temperature and salinity in the north part of the TWCW, all have high correlations (0.55, 0.487 and 0.405, respectively, 99% and 95% confidence level) with summer Kuroshio transport (Fig.5). It can be safely inferred that the warming of SST and strengthening of the TWCW in summer after 1976 were principally influenced by the variability of the Kuroshio. The TWCW is a crucial influence factor to the thermohaline structure of ECS. As transport of the Kuroshio was apparently stronger after the 1970s (Fig.5), it is not surprising that its northward branch TWC strengthened meanwhile and brought more heat to warm up the ECS. It should be pointed out that, as seen from the time coefficients in Fig.4b2, b3, b4, the changes of SST and TWCW associated with climate change as discussed above seem to be gradual trends rather than abrupt shifts. Comparison between the two periods before and after 1976 can only reveal changes of the mean states. Details of the temporal variations still need to be further studied.

Then the EOF modes of temperature and salinity in winter are investigated. The first EOF mode of SST in winter (Fig.6a) shows out-of-phase variation of temperature near the CRE and in the other areas, which resembles the cooling and warming patterns depicted in Fig.3b. Its time coefficients, in general, are greater after the 1970s than before the time period (Fig.6b). The coefficients of this mode have evident correlation (0.649, 99% confidence level) with the mean air temperature in Shanghai in winter, which itself has obvious warming trend (Fig.7). Therefore, different from the mechanisms in summer, the temperature increment in the northern ECS in winter was primarily induced by the variability of the climate system. The first SST mode of temperature at 20 m has very similar pattern to the SST, and also has very high correlation (0.735, 99% confidence level) to the air temperature in Shanghai, which reveals the same mechanisms as the first mode of SST. It is possible that with the weakening of the winter monsoon since the 1970s, air temperature over the continent and coastal areas became warmer and wind became weaker, thus caused the warming up of sea temperature. The Kuroshio transport in winter also has a trend of strengthening, but does not have discernable correlation with the sea temperature modes. Hence the Kuroshio is not a major influence factor to the warming trend of northern ECS in winter.

Time coefficients of this mode also have considerable correlation (0.426, 95% confidence level) with the Changjiang run-off discharge in winter, implying that the decrease of temperature in coastal waters adjacent to the CRE is likely affected by the Changjiang River run-off.

The different causes of the warming trends in summer and winter are discussed above, but the processes how the Kuroshio and climate system influence the thermohaline structure still need further discussion. In fact, the mechanisms could be very complicate. Yan and Li (1997) discussed the influencing factors for the temperature variability in the ECS by correlation analyses on air temperature and SST in the ECS and air temperature of the coastal stations. They found that there was a time delay between the SST and the air temperature over the

ECS, and the latter had high correlation with the air temperature of the western continent (Shanghai) in winter, while SST of the ECS in summer had high correlation with the air temperature of the eastern islands (Kagoshima of Japan). This could suggest that in winter, the Asian continent is cooled down rapidly by the winter monsoon and thus influences the air temperature over the ECS,

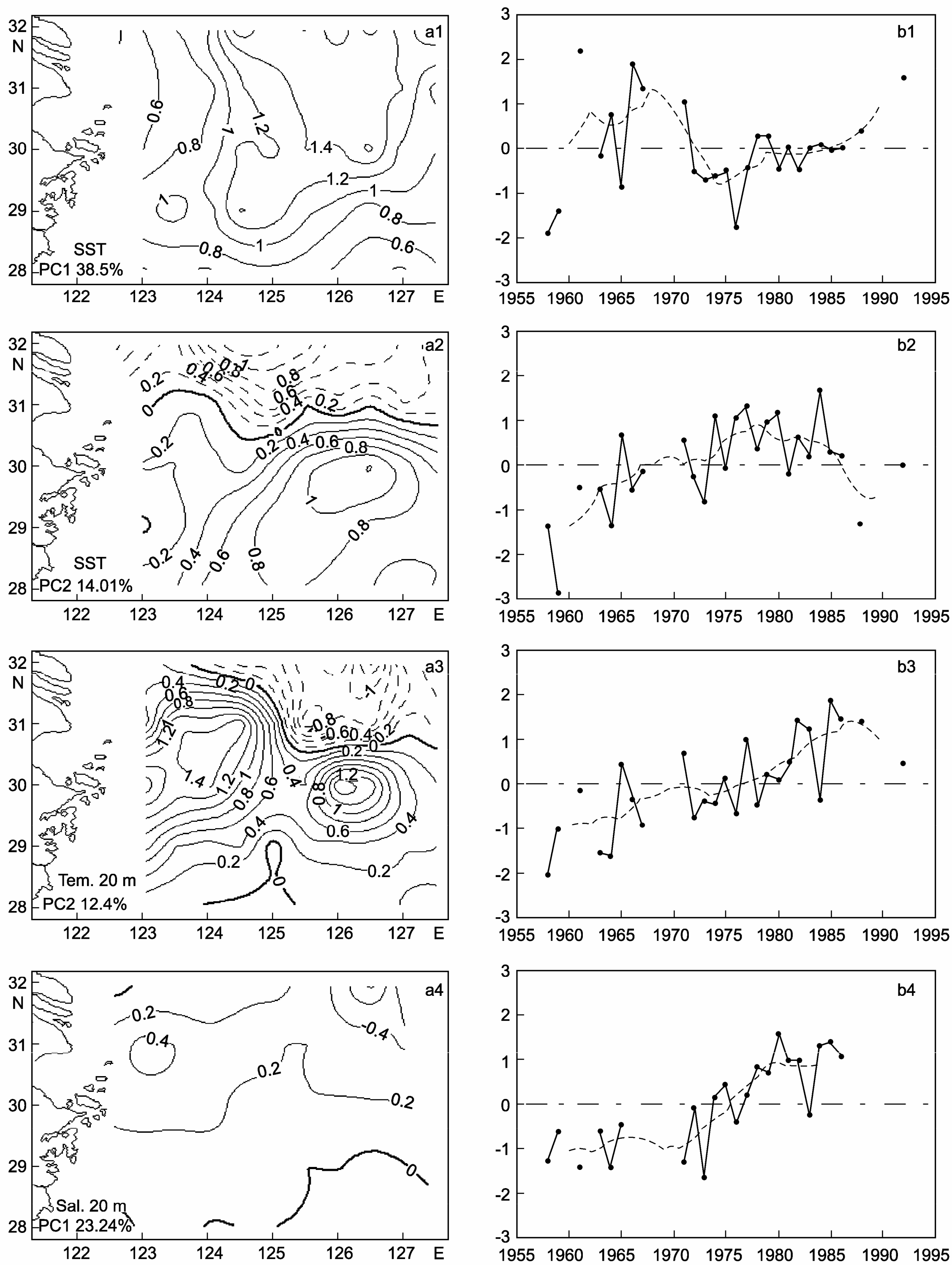

Fig.4 (a) EOF modes and (b) respective time coefficients in summer

a1, b1. 1st mode of SST; a2, b2. 2nd mode of SST; a3, b3. 2nd mode of temperature at 20 m; a4, b4. 1st mode of salinity at 20 m; dashed lines in (b) denote 5-year running mean; PC. principal component

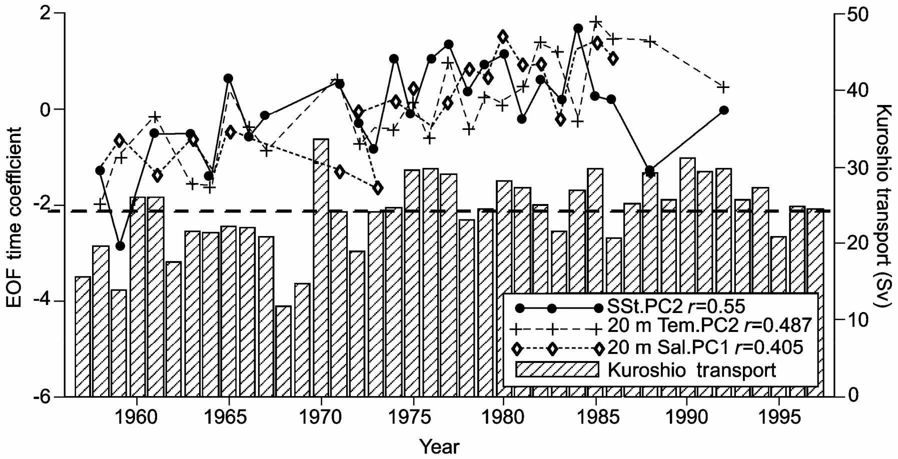

Fig.5 Correlation between summer Kuroshio transport and time coefficients of the EOF modes in summer (curves)

Thick dashed (bar chart) line is averaged Kuroshio transport

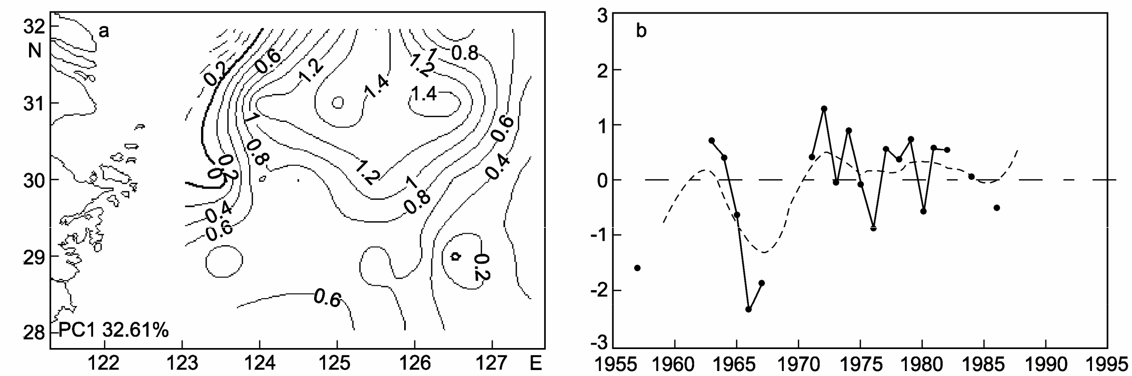

Fig.6 (a) 1st EOF mode of SST and (b) its time coefficients in winter

Dashed line in (b) denotes 5-year running mean

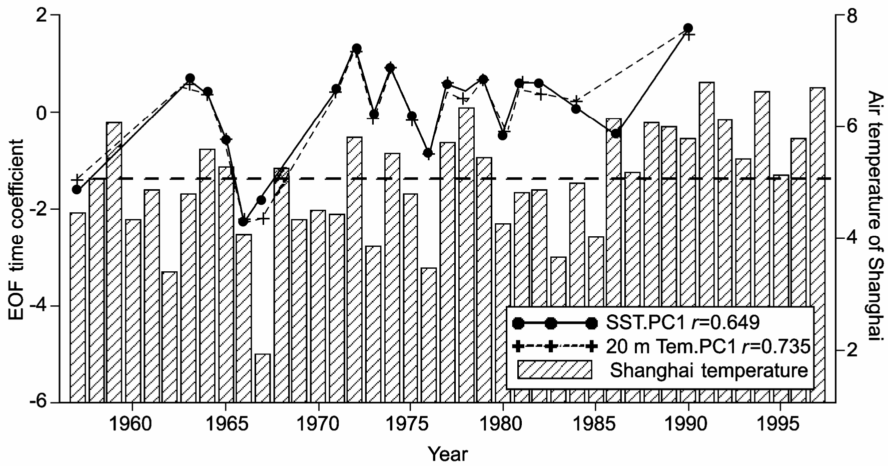

Fig.7 Correlation between air temperature of Shanghai in winter (bar chart) and time coefficients of the EOF modes in winter (curves)

Thick dashed line is averaged air temperature of Shanghai

which in turn cools down the SST. Heat transport of the Kuroshio to the ECS can only neutralize a fraction of the cooling effect. Therefore, variability of SST in winter is primarily controlled by the air temperature on the continent. In summer, on the contrary, heat is brought to the ECS mainly by the northward transport of the Kuroshio additional to the solar radiation, analogous with the warming signals brought to the continent by summer monsoon generated over the sea. As a result, although variability of SST in summer is related to the air temperature in the first mode, its interdecadal part mainly follows the warm trend of Kuroshio. Therefore, we believe that the interdecadal warming trend in summer came from the ocean processes, while warming in winter was influenced by the atmosphere.

5 CONCLUSIONS

Statistics and EOF analyses of historical hydrographic data for the northern ECS lead to the following conclusions:

(1) Significant warming trends were found in northern ECS after a climate shift in 1976. In summer, the average increase of SST in 1977–1996 is 0.46°C higher than that during 1957–1976, with large increment mainly at the south of 31°N, and the TWCW was strengthened. In comparison, in winter, the average increase of SST during the same period is 0.24°C. Despite of cooling in the coastal waters adjacent to the CRE, SST increased on an average of 0.53°C.

(2) The causes of warming up are different in summer and winter. The climatological shifts of temperature in northern ECS and the TWCW in summer were primarily influenced by the variability of the Kuroshio, while the warming in winter was primarily induced by variability of the climate system and the decrease of temperature in coastal waters adjacent to the CRE was probably influenced by the Changjiang River run-off.

Response of the coastal seas of China to the global climate change is very complicate processes in both spatial and temporal patterns. The dynamical mechanisms of the warming processes in the ECS need to be further studied.

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