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The long-term variability of sea surface temperature in the seas east of China in the past 40 a

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Abstract

The global surface temperature change since the mid-19th century has caused general concern and intensive study. However, long-term changes in the marginal seas, including the seas east of China, are not well understood because long-term observations are sparse and, even when they exist, they are over limited areas. Preliminary results on the long-term variability of sea surface temperature (SST) in summer and winter in the seas east of China during the period of 1957–2001 are reported using the Ocean Science Database of Institute of Oceanology, Chinese Academy of Sciences, the coastal hydrological station in situ and satellite data. The results show well-defined warming trends in the study area. However warming and cooling trends vary from decade to decade, with steady and rapid warming trends after the 1980s and complicated spatial patterns. The distribution of SST variation is intricate and more blurred in the areas far away from the Kuroshio system. Both historical and satellite data sets show significant warming trends after 1985. The warming trends are larger and spread to wider areas in winter than in summer, which means decrease in the seasonal cycle of SST probably linked with recently observed increase of the tropical zooplankton species in the region. Spatial structures of the SST trends are roughly consistent with the circulation pattern especially in winter when the meridional SST gradients are larger, suggesting that a horizontal advection may play an important role in the long-term SST variability in winter.

Key words: sea surface temperature, long-term variability, East China Sea, winter circulation

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1 Introduction

The recent studies show that the global surface temperature increased 0.74 (0.56 to 0.92)°C during the last century, with the most rapid warming (about 0.2°C to 0.3°C) occurring in the last two decades of the 20th century (IPCC, 2007). Because the vast earth surface is covered by the oceans, the strong interannual and interdecadal variabilities in the sea surface temperature (SST) contribute significantly to the observed global warming signal. Many studies have focused on the low-frequency variations of SST in the Pacific, Indian and Atlantic Oceans (Folland et al., 1984; Cane et al., 1997; Lau and Weng, 1999; Levitus et al., 2000; Solomon and Jin, 2005; Latif et al., 2007; Chen and Li, 2008). Study of warming in the marginal seas, however, is lacking, due to the limited long-term observation data sets.

The seas east of China are defined including the Bohai Sea (BS), the Huanghai Sea (HS) and the East China Sea (ECS) and lie on one of the largest continental shelves of the world. Climate and general circulation in the area are strongly influenced by external and internal forcings, i.e., the East Asian monsoon, the Kuroshio, the coastal currents along China, and river discharge. Several studies have investigated climate variability in these seas. Zhang et al. (2005) detected a warming trend over the past 100 a in several regions in these seas based on the Hadley centre's SST (HadISST) data. Huang et al. (2007) confirmed the strengthening of relationship between the East Asia coastal regions SST and the East Asian summer monsoon since the mid-1970s using numerical simulations. Jin and Wang (2011) discussed the interdecadal, interannual and seasonal variations of SST in China offshore area using HadISST. Yan and Li (1997) pointed out that the air temperature in the ECS presented a similar tendency with the SST variations during the period of 1900–1987 using comprehensive ocean-atmosphere data set (COADS) data. Bao et al. (2002) analyzed the seasonal variations of SST using advanced very high resolution radiometer (AVHRR) satellite data. Yu and Xu (2003) showed a 41-month variation cycle of the SST in the ECS using the AVHRR data. Chen et al. (2004) analyzed the same hydrographic data and found that the cold eddy in the ECS in summer has been strengthened since 1977. Tang et al. (2009) documented significant warming trends in the northern ECS based on the hydrographic observation data of 1957–1996. Feng and Lin (2009) discussed the long-term trend of SST variations in the

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East China offshore during 1945–2006 based on the HadISST1 data and showed warming at 0.015±°C/a with most obvious change occurring in the ECS. Fang et al. (2002) and Wu et al. (2005) also showed an increase of SST in the BS during the past decades.

This paper is focused on the long-term linear trend of SST in the seas east of China based on a few available data sets, including the historical field data, coastal hydrological station data, and satellite remote sensing data. Attempts are made to provide an integrated spatial trend pattern and reasons of SST variations in the whole region during the past four decades.

2 Data

The historical temperature data used in the present study are from the Ocean Science Data-base of Institute of Oceanology, Chinese Academy of Sciences (OSD-IOCAS), which includes the hydrographic observational data from 1930 through 2001 collected by Chinese investigations and various international data sets including the World Ocean Database (WOD) 1998 and 2001 of the National Ocean Data Center (Levitus et al., 2002). The primary quality control of these data is done following the methods outlined by Boyer and Levitus (1994). Other quality control methods are developed and applied to ruling out the duplicate, wrong and false data from the data-base (Wang et al., 2004). Several steps of the computer-manpower integrated quality control procedure are performed, including inspections and selections of duplicate profiles, inversed and duplicated depths and densities in individual profiles, and statistically based criteria range and standard deviation checks. The data (319029 profiles) cover more coastal regions (Fig. 1a) than the WOD01 (221269 profiles). More detail about the data set was described by Hao et al. (2010). The temperature data mainly

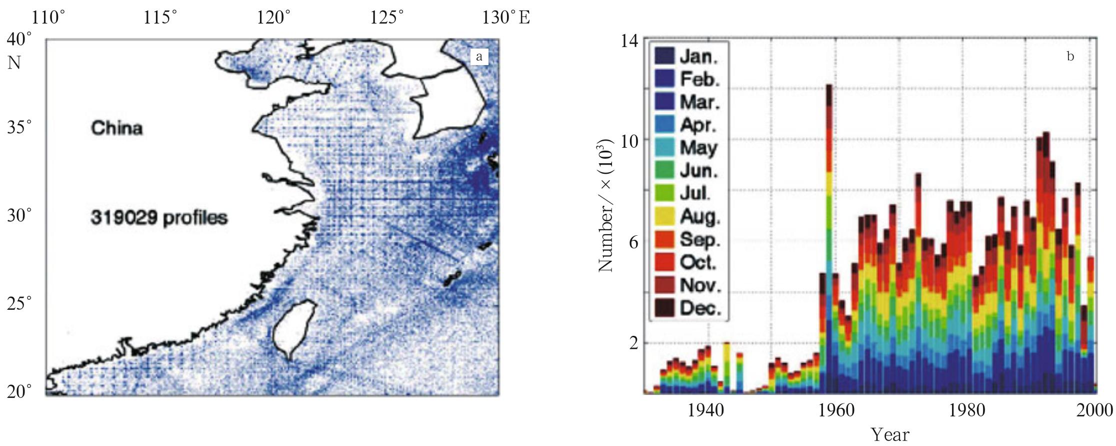

Fig.1. Spatial (a) and temporal (b) distributions of temperature data in the China's seas and adjacent areas (from Hao et al., 2010).

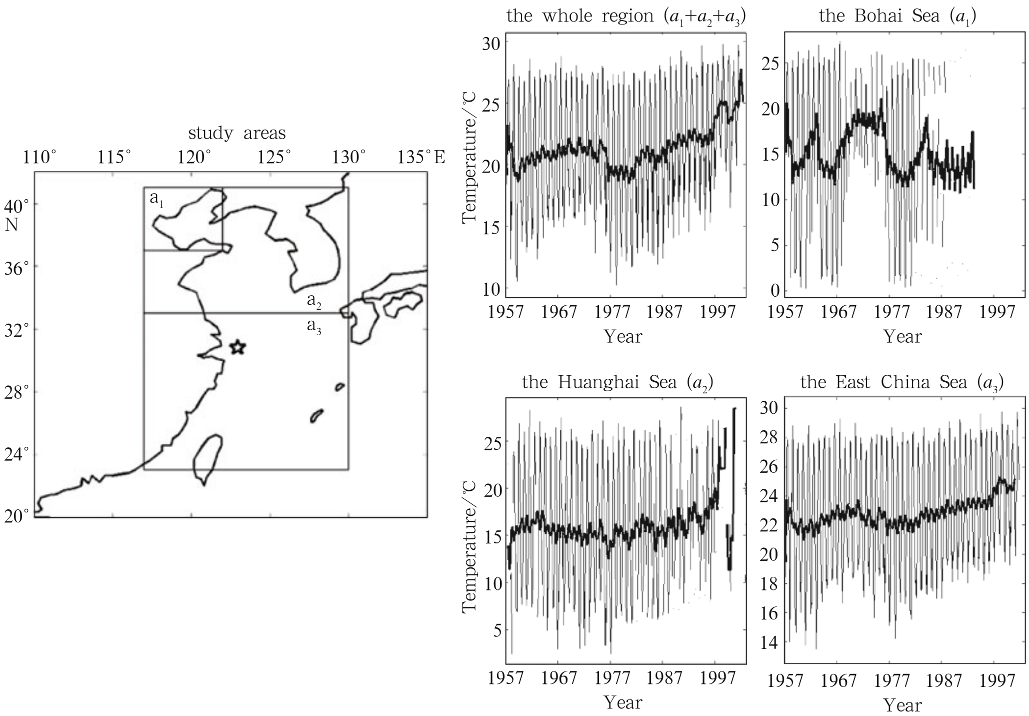

Fig.2. Time series of SST variations in the seas east of China from OSD-IOCAS data set. Thin lines are for monthly-mean SST, and thick lines, for eleven-month running mean. The black pentagram in the left panel indicates Shengshan Station.

during 1957 and 2001 (Fig. 1b) were used to calculate the long-term variation of SST. The data set has already been used for the study of the thermodynamic structures (Chen et al., 2004) and warming trend (Tang et al., 2009) in the northern ECS and temperature inversion (Hao et al., 2010) in China's seas.

The study areas include the seas off China in an area of 23°–41°N, 117°–130°E (Fig. 2, left). The historical data include temperature and salinity data at 28 standard depths (which are 0, 5, 10, 15, 20, 25, 30, 50, 75, 100, 125, 150 and 200 m in the upper water column) and at bottom. The data at 0 m are spatially averaged on 2°×2° grids for statistics of monthly-mean time series in the period from 1957 to 2001.

For comparison, we also utilize the AVHRR pathfinder satellite daytime data, which provide monthly-mean SST during the period from 1985 to 2002 on 9.25 km×9.25 km resulotion, and linearly interpolated into 0.5°×0.5° grids in this study, from NOAA/NASA (Vazquez et al., 1998), and the monthly-mean SST at a coastal station named Shengshan (30.8°N, 123.0°E; the black pentagram in the left panel of Fig. 2) from 1960 to 1999. In this study, based on the least square method, we computed the linear trend of SST in February and August as representative of the summer and winter variations with the units of °C/a. We did not use the mean value of December–January–February and June–July–August for winter and summer due to the lack of historical data in time and space. Meanwhile, the standard deviation in February and August are relatively low.

3 Results

The warming trends can be seen clearly from the monthly-mean SST time series spatially averaged over the BS, the HS, and the ECS (Fig. 2). The whole region shows moderate warming trends from the late 1950s till the mid 1960s, cooling during the 1970s, and significant warming after the early 1980s. The HS and the ECS exhibit the same variation phases, while trends in the BS are quite different. The fast drop of SST in the HS in the late 1990s may be related to the lack of data, which is obviously discontinued. It could be deduced that the HS and the ECS are a major part of the SST variation depending on their trend magnitudes and area coverages.

Owing to the lack of observations in the HS after 1995, we compute the linear trends of SST of February, August and annual mean in the ECS for different periods with 95% confidence bounds (Table 1). It shows decadal variability with cold periods at the end of the 1950s and the 1970s but with too much uncertainty. The annual-mean SST shows significant warming trend with a larger value of (0.136±0.038) °C/a from 1985 to 2001, and a smaller value of (0.050±0.014) °C/a from 1957 to 2001. They are both dominated by warming in winter, with linear trends at (0.196±0.077) °C/a and (0.067±0.030) °C/a, respectively.

We analyze the spatial patterns of the linear trend of SST in February and August during 1957–2001 from the OSD-IOCAS data set (Fig. 3). It shows that the seas are warming up significantly in winter especially in the central HS and the central ECS,

Table 1. Linear trends (°C/a) of SST in the seas east of China in different periods with 95% confidence bounds

	Time period			
	1957–1967	1972–1982	1985–2001	1957–2001
February	0.075±0.347	−0.141±0.290	0.196±0.077	0.067±0.030
August	0.080±0.134	−0.038±0.096	0.031±0.059	0.008±0.013
Annual mean	0.033±0.104	−0.037±0.073	0.136±0.038	0.050±0.014

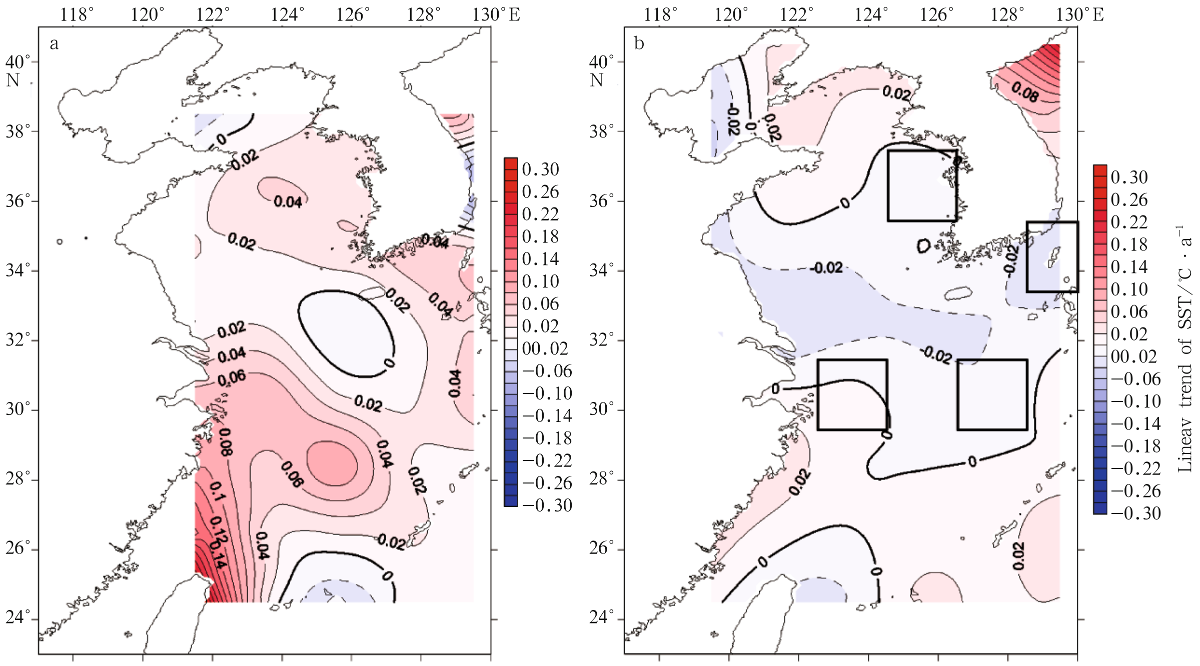

Fig.3. Linear trend of SST (contours) in the seas east of China during the period of 1957–2001 in February (a) and August (b) from the OSD-IOCAS data set. Boxes are the representative areas, namely, the eastern southern HS, the Tsushima Strait, the Changjiang Estuary and the Kuroshio region from top left to bottom right.

with a linear trend larger than 0.04 °C/a and 0.08 °C/a, respectively (Fig. 3a). Most part of the ECS is warmed up by at least 0.02 °C/a, in the northeastern ECS where the cyclonical ECS cold eddy is located; the SST is lightly cooled down at –0.02 °C/a. The largest linear trend in the study area, which is about 0.17 °C/a with a large standard deviation, is located to the northeast of Taiwan Island, where the Kuroshio and the Taiwan Warm Current enter the ECS. It is different in summer, with more cooling areas and much weaker linear trend of SST (Fig. 3b). The strong warming areas with a 0.02 °C/a rate in summer are mostly located to the north HS and the coastal area of the ECS. The main cooling areas include part of the BS at a rate of –0.04°C/a, and the south HS and northern ECS at a rate of –0.02 °C/a.

Recently, Lin et al. (2011) and Lin and Yang (2011) presented the existence of the Huanghai Sea Warm Current (HSWC) from the observation, and analyzed the mechanism of westward shift. It is important for the structure of winter circulation, which is roughly consistent with the spatial pattern of SST linear trend in winter in the present study. It shows strong warming trends along the paths of the Taiwan Warm Current, the Kuroshio and the HSWC and cooling near the area of the cept for the warming along the paths of the Taiwan Warm Current and the Kuroshio, which affect the SST variation in the seas all the year round.

The rate of SST linear trend in winter has been enhanced since 1985, though the warming/cooling pattern is similar with that of 40 a, and the rate in summer is less increased as compared with that in winter (not shown). The strong warming trend in winter since 1985 has been consistent with the IPCC report (Su et al., 2007), which found most rapid warming occurring in the last two decades.

Based on the historical field data, the coastal station data, and the satellite remote sensing data, we further compute the time series of SST indices in some selected areas indicated by boxes in Fig. 3b (Fig. 4). The Kuroshio, a warm current, is a great impact on the climate of ECS with high salinity and temperature. The Kuroshio bifurcates two parts as northwestward and northeastward after intrusion ECS. According to that, we selected four areas, namely, the Kuroshio region (29.5°–31.5°N, 126.5°–128.5°E), which is linked to the Kuroshio; the eastern south HS (35.5°–37.5°N, 124.5°–126.5°E), as it is related to the northwestward part after the Kuroshio bifurcated; the Tsushima Strait (33.5°–35.5°N, 128.5°–130°E), which is related to the

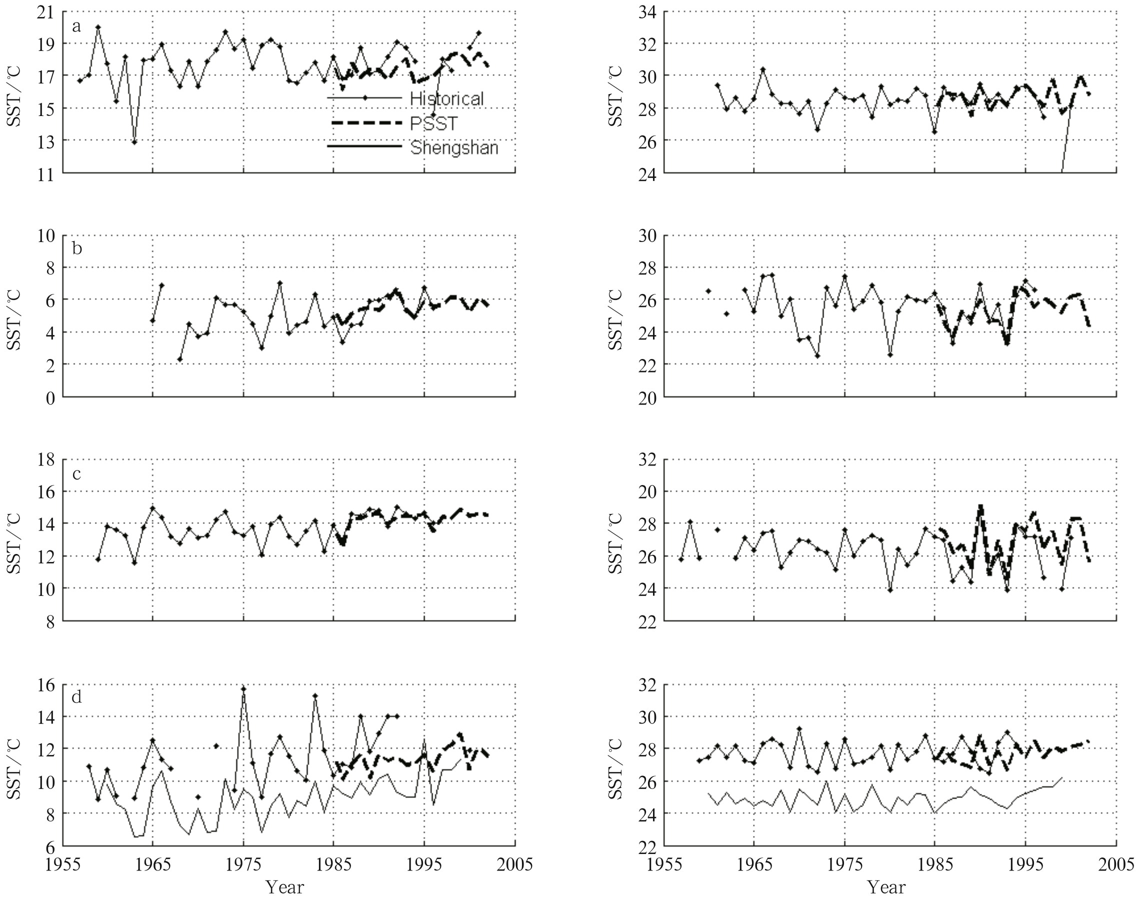

Fig.4. SST time series averaged in the representative regions shown in Fig. 2, namely, the Kuroshio region (29.5°–31.5°N, 126.5°–128.5°E) (a), the eastern south HS (35.5°–37.5°N, 124.5°–126.5°E) (b), the Tsushima Strait (33.5°–35.5°N, 128.5°–130°E) (c), and the Changjiang Estuary (29.5°–31.5°N, 122.5°–124.5°E) (d), in February (left panel) and August (right panel). Blue line denotes historical in situ SST from OSD-IOCAS, red line denotes SST at Shengshan Station, and dark line denotes *Pathfinder* satellite SST data.

122.5°–124.5°E), where is the Changjiang Disputed Water located in, which plays important role in the local climate and ecology.

The Kuroshio region shows a moderate warming trend in winter and slightly cooling trend in summer (Fig. 4a). The correlation between the historical in situ data and the satellite data after 1985 is 0.67 in summer surpassing the 95% confidential level, a convincing consistency. It is less correlated in winter but they both show warming trends. The indices of the eastern southern HS and the Tsushima Strait both display exactly the same interannual variations and warming trends with a correlation over 0.8 between the in situ and satellite data (Figs 4b and c). The SST time series of the Changjiang Estuary agree well among the three data sets (Fig. 4d), although the coastal station shows a systematical lower temperature than the other two data sets, which is mainly due to the cold southward coastal current in winter and the coastal upwelling in summer near the Changjiang Estuary (Hu et al., 1984; Su and Lobanov, 1998). The warming trend in the whole region, especially in winter, seems to be robust, with high correlations among the three data sets.

4 Discussion and conclusions

In this study, we investigate the long-term linear trends of SST, their interdecadal variations and spatial structures in the seas east of China during 1957–2001 based on reconstruction of time series from the historical field data, the coastal station data and the satellite remote sensing data. It shows a warming trend as a whole, and complicated spatial patterns and decade-to-decade differences of not only warming trends but also cooling trends. Warming trends are larger and spread to wider areas in winter than in summer. Both historical and satellite data show a significant warming trend after 1985 in most of the study area, which agrees well with Jin and Wang (2011). The SST trend in the Kuroshio region is weaker than that in the shelf waters.

The long-term variability of SST in the study area does not seem to have a close relationship with that of the North Pacific, especially for the coastal areas, which may be mainly linked to local forcing and response. The local air-sea heat flux and heat advection by the oceanic circulation seem to play different roles in the SST trend's spatial pattern in different seasons. Although it is difficult to quantitatively assess their relative importance, it seems that the winter pattern is highly linked to the circulation (Fig. 3a). We calculated the meridional SST gradient in each grid. It could be inferred from Fig. 5 that there is a closer relationship between the meridional SST gradient and trend in winter than in summer, suggesting again that the horizontal advection by circulation is more important in winter (Fig. 5). In contrast, it would be more complicated in summer owing to the weak meridional SST gradient and strong stratification, which weaken the effects of circulation on the SST trend. It implies that the shelf circulations, including the Kuroshio and its branches, coastal currents and the cyclonical eddy, became stronger in the past 40 a. The Kuroshio transport across the pollution Nagasaki (PN) line observed by the Japan Meteorological Agency is increased indeed (not shown), which provides a good support to our conclusion. However, in the recent studies, Lin et al. (2011) analyzed the mechanism of the westward shift of the HSWC using a linear, barotropic and wind stress driven model. They said that the HSWC was actually arrested topographic waves in response to local wind stress forcing. This indicates that the increase of Kuroshio transports, the SST gradients and the local atmospheric forcing may be all involved in the spatial pattern of SST liner trend in winter. It needs further studies in detail in the future.

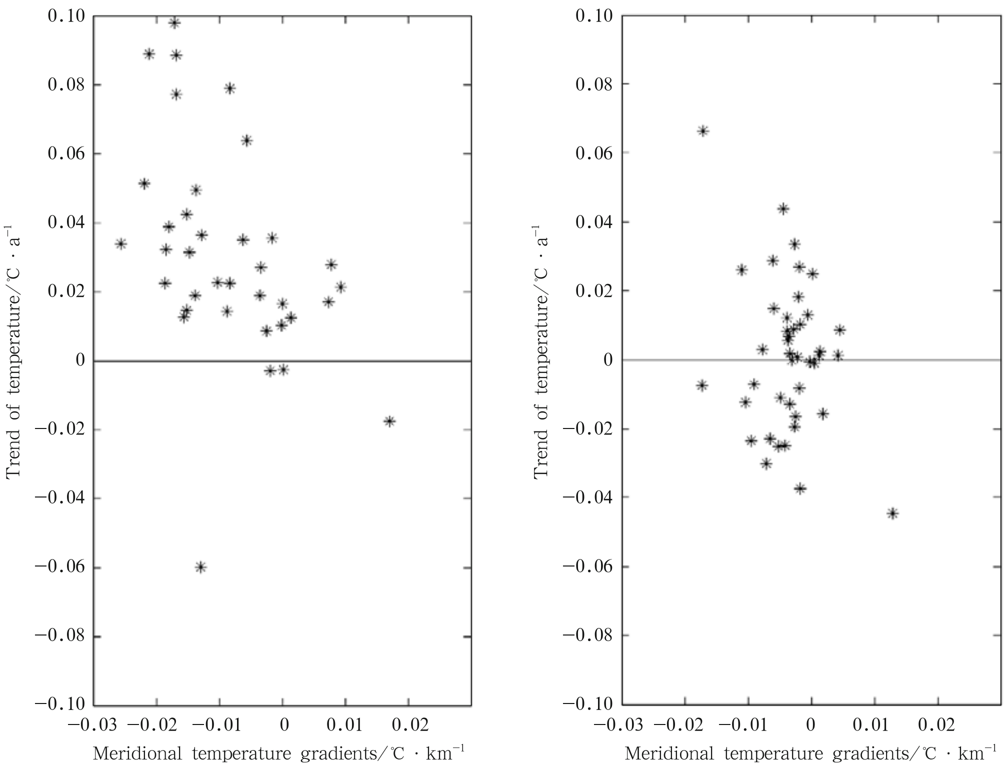

Fig.5. Scatter graph of the linear trend of the SST and the meridional SST gradients in the seas east of China in February (a) and August (b).

Faster warming in winter than in summer would decrease the amplitude of seasonal cycle, which is highly relavant to the ecosystem and environmental evolution. It is found that the giant jellyfish and salps have increased greatly in the HS in recent years (Sun et al., 2010) and more tropical-subtropical species survive in the temperate Changjiang Estuary (Zhang et al., 2010). These may provide evidence to support the results on the long-term trend of SST reported here. In addition, good agreement among the three data sets in some representative regions supports the reliability of the OSD-IOCAS historical data, although uncertainty is inevitable.

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