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Research papers

# Climatological characteristics and long-term change of SST over the marginal seas of China

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ABSTRACT

Based on monthly mean HadISST data, climatological characteristics and long-term changes of sea surface temperature (SST) over marginal seas of China are analyzed for the time period 1870–2011. The results show that (1) The smallest and largest spatial SST differences among various areas are seen in August and January respectively, with the coolest month occurring in February for all of the seas and the warmest month occurring in August for all but South China Sea (SCS); (2) The warming trends of the marginal seas of China during the time periods analyzed are generally larger than the global and hemispheric averages, with the East China Sea seeing the largest warming of all seas; (3) All of the sea areas see significant rising trends of annual mean SST in the last 140 years and the last 50 years, with larger and more significant warming generally occurs in autumn and winter; (4) The last 30 years especially the last 14 years undergo a slowdown of warming in the marginal seas of China, and the slowdown in the last 14 years is more evident than the global and northern hemispheric averages; (5) A weak upwelling current exists in western SCS, and the upwelling intensity has a significant positive correlation with the SCS summer monsoon index, with both seeing a decreasing trend in the last 64 years.



## 1. Introduction

Ocean and atmosphere are important components of climate system. Sea–air interaction, especially that occurring between tropical oceans and global atmosphere has been a hot topic in climatology nowadays. There are many studies on global and basin scale SST climatology using different datasets (Reynolds, 1988; Reynolds and Marsico, 1993; Reynolds and Smith, 1995; Smith and Reynolds, 1998). IPCC AR4 showed that global SST exhibits significant increasing trend in recent 100 years, especially in recent 30 years (Trenberth et al., 2007). SST at gulf area and continental shelf area are also studied and dataset is optimized for these areas (Shea and Trenberth, 1992) and relation with large scale change is also analyzed (Belkin, 2009; Takeshige et al., 2013).

The marginal seas of China span tropical, subtropical and temperate zone and exhibit significant geographical diversities. There are many studies about SST change and variability of the region during different time periods (Tang et al., 2009; Huang et al., 2012; Wang et al., 2013). Different datasets are used to study the SST change and variability (Yan and Li, 1997; Hickox et al., 2000; Wu et al., 2005; Song et al., 2007; Jin and Wang, 2011; Liu and Zhang, 2013). It has been shown that the 1990s is the warmest decade of the past 100 years in the marginal seas of China (X.Z. Zhang et al., 2005; Feng and Lin, 2009), and water masses, currents and ENSO might have been the main factors for different modes of SST variability for the East China Sea (ECS) (Song et al., 2007). The SST variability might in turn affect other system, such as East Asian monsoon (Li et al., 2010). Xie et al. (2002) and Yeh and Kim (2010) examined winter SST variability of Yellow/East China Sea in recent years and explained it in terms of the associated atmospheric circulation anomalies and Bathymetric effect.

The previous studies are important for understanding climatological characteristics and change of SST on varied spatial and temporal scales. Most of the previous studies, however, have been limited to given areas or specific time periods. For the marginal seas of China on a whole, the general features of normal climate and climate change of SST over the past more than 100 years have not been well understood, in spite of the fact that a few studies examined the long-term trends of the SST for varied time periods and areas.

In this paper, we use the updated HadISST data to reveal the climatological characteristics and long-term change of SST over the marginal seas of China. Our analysis shows the distinct characteristics of SST climatology and rapid warming of the last 140 years in the region.

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## 2. Study region, data and methods

### 2.1. Study region

In this paper, marginal seas of China are defined as the offshore region of 5–41°N and 105–130°E. The region is further divided into three sub-regions: Bohai Sea and Yellow Sea (BYS, 117–127°E and 35–41°N), East China Sea (ECS, 120–130°E and 22–35°N) and South China Sea (SCS, 105–120°E and 5–22°N) (Fig. 1).

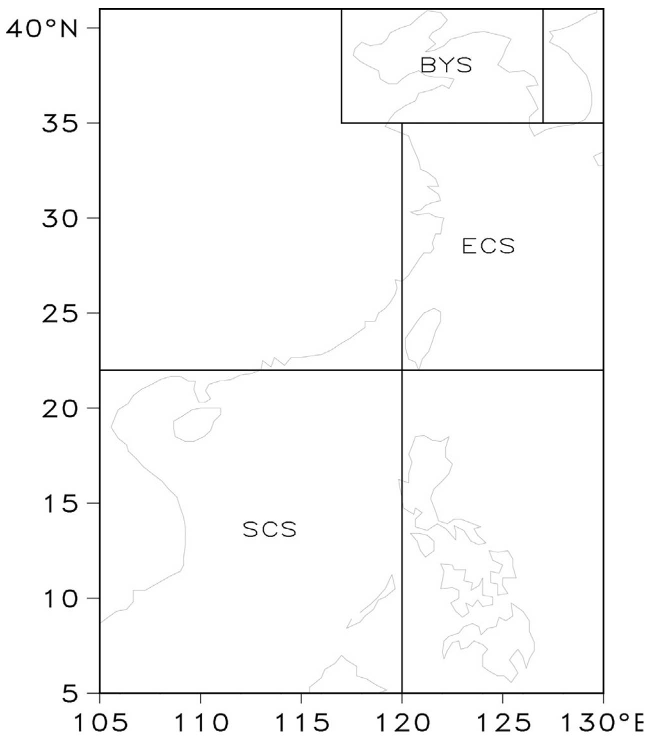


**Fig. 1.** Study regions defined in this paper. BYS: Bohai Sea and Yellow Sea; ECS: East China Sea; SCS: South China Sea.

### 2.2. Data and methods

Monthly SST data and SCS Summer Monsoon index series are used. $1 \times 1$ monthly HadISST (Rayner et al., 2003) data during 1870–2011 are from Hadley Centre, UK (http://www.metoffice.gov.uk/hadobs/hadisst/data/download.html). This dataset is the longest global historical and real time SST observations with the highest spatial resolution and coverage, and it has been widely used in studies of climate change and variability. In order to examine the relationship between the western SCS upwelling intensity and SCS Summer Monsoon (SCSSM), the SCSSM index data developed by Li et al. (http://ljp.lasg.ac.cn/dct/page/1) from the Institute of Atmospheric Physics, Chinese Academy of Sciences (Li and Zeng, 2002, 2003, 2005) is utilized in this paper. Monthly reanalysis data of 850 hPa zonal wind ($u$), 500 hPa geopotential height (hgt) and sea level pressure (slp) from the National Centers for Environmental Prediction (NCEP) during 1948–2012 are used for calculating the monsoon index series.

We made a quality check of the HadISST data, and found a few quality problems with the data in the Bohai Sea and the Yellow Sea. The absolute values of SST anomalies are larger than 2 times the standard deviation for a few months of 1977, 1980 and 1981 for the grids. These are proved to be wrong records by comparing them to the neighboring grid data. We replace these records with climatological average of the latest climate reference period (1981–2010).

Regional average is calculated by area-weighted averaging the grid data using latitude cosine as weights (Jones and Hulme, 1996). The reference time period 1981–2010 is applied to calculate mean SST values for analyzing climatological characteristics and the time period 1961–1990 as recommended by World Meteorological Organization (WMO) is used as reference time period for calculating SST anomalies for analyzing climate change. We use May, August, November and February as the representative months for spring, summer, autumn and winter respectively as sea water temperature change generally lags by a month or two behind land air temperature. The method of least-squares is used to calculate the linear trends of the SST anomalies series for given time periods, and student $t$-test is used to examine the significance of the linear trends of the time series (Hu, 1996; Von and Francis,

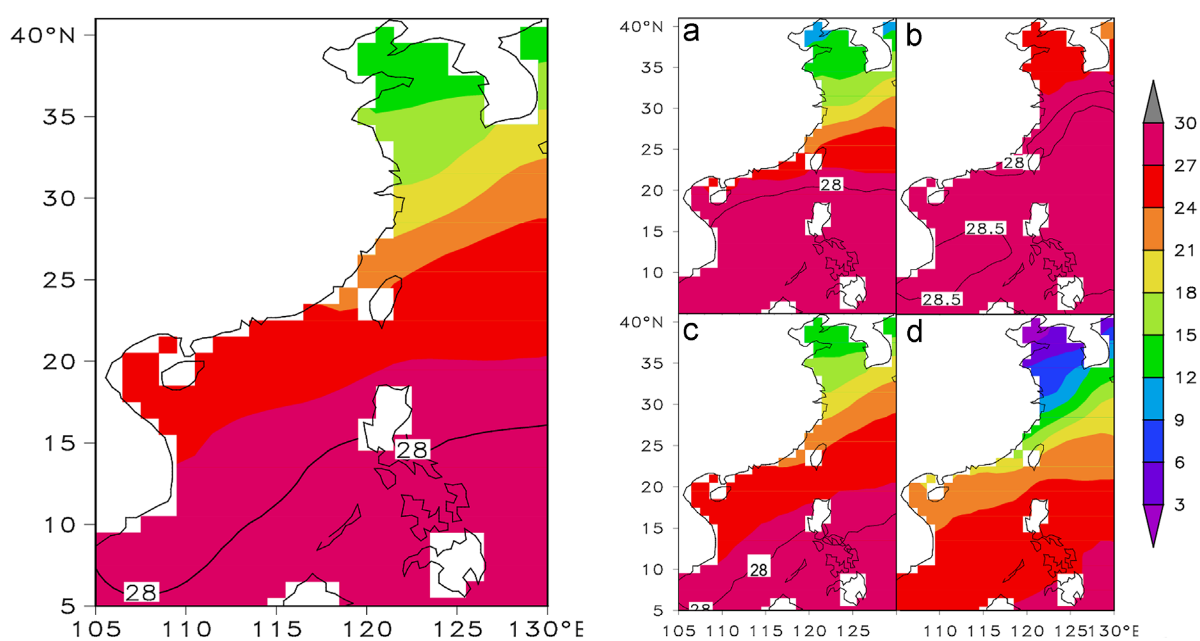


**Fig. 2.** Annual (left) and seasonal (right) mean SST distribution during 1981–2010 in the marginal seas of China. (a): Spring; (b): Summer; (c): Autumn; (d): Winter (Unit: °C).

2003; Wei, 2007). Regime shift analysis is based on the method developed by Rodionov (2004) and Rodionov and Overland (2005), in our regime shift analysis, parameters are assigned as: cut-off length equals 10 and probability level is 0.01.

## 3. Results

### 3.1. Spatial and seasonal characteristics

Fig. 2 shows spatial distribution of annual and seasonal mean SST for time period 1981–2010. Annual mean SST decreases with increasing latitude, with high temperature ranging from 24 °C to 28 °C in the south and low temperature ranging from 12 °C to 20 °C in the north. This pattern is closely related to the solar radiation distribution in the offshore region. The isotherm is northeast–southwest oriented and the SST gradient increases as getting closer to the mainland coastal line. It is obvious that the landmass effect in wintertime has contributed to the tilting of the isotherms, which was pointed out by Bao et al. (2002). The ECS exhibits the largest temperature gradient, and the SCS in the tropical zone the lowest temperature gradient.

As a transition season from winter to summer, spring has its unique character (Fig. 2a). Winter northerly wind begins to weaken and the southward coastal current along the coast of the Yellow Sea is not as apparent as in winter. The Yellow Sea SST is latitudinally distributed with smaller gradient. The largest SST gradient occurs in the north, and the SST in the BYS is evidently lower. The SCS SST to the south of the Taiwan Channel is uniformly distributed. The most uniform spatial distribution of SST and the highest seasonal mean temperature appears in most parts of the marginal seas of China during summertime (Fig. 2b). Apparent gradient appears in the joint area of the Yellow Sea and the ECS. The autumn (Fig. 2c) bears a similar spatial distribution of seasonal mean SST to that of annual mean SST (Fig. 2 left). In winter, the temperature gradient largely increases, as a result of the tremendous drop of temperature in the BYS (Fig. 2d). As semi-closed sea, the BYS winter temperature is deeply influenced by the land. The lowest SST, ranging from 0 °C to 3 °C, occurs in the Bohai Sea, and the 27 °C SST isotherm can still be seen in the south of the SCS during wintertime.

There is a unique phenomenon in summer SST of the south-western SCS, characterized by a large area of relative cooler surface water centered to the southeast of the Indochina Peninsula (Fig. 3a, b). This phenomenon was reported in Cai et al. (2001) and Li et al. (2011). The interpretation for its formation is summer southwesterly wind which causes offshore upwelling current. Deep cold water is transported upward and cool the surface water (Cai et al., 2001; Li et al., 2011). In autumn, the cold water area disappears. Weaker upwelling phenomena also appear in the Taiwan Strait and northeast of the Hainan Island in summertime, but they need further investigation by using high-resolution observational data. Under the background of warming during 1981–2010, the upwelling in western SCS still exists in spite of the fact that the SST increases almost everywhere in the SCS (Fig. 3b).

Monthly mean SST generally shows cosine seasonal pattern for the marginal seas, and the range increases with latitude, with the BYS witnessing the largest seasonal variation (Fig. 4). The highest (lowest) SST occurs in August (February) for the BYS and the ECS, and in less extent for the whole region (Fig. 4b). For the SCS, however, the highest SST appears in May and June, about 2–3 months earlier than in the north of the study region, but the lowest SST appears in the same month (February) as other areas. The earlier peak and the flattening pattern of the SCS SST are in large extent related to the northern position of the ITCZ (Inter-Tropical Convergence Zone) and the SCS monsoon in this area during summer (R.H. Zhang et al., 2005; Ding et al., 2008), leading to more cloudy and rainy days, less solar radiation absorbed by the sea surface (Feng et al., 1999) and the upwelling in the off-shore area of the western SCS as described below.

The average annual temperature range is 7.08 °C for the study region, and it is 20.58 °C for the BYS, 11.26 °C for the ECS and 4.03 °C for the SCS. The fastest warming stages within a year occur in different months for different areas, with the whole region in May, the BYS in June, the ECS in May, and the SCS in April. The fastest cooling stage within a year occurs in December for all areas of the region.

### 3.2. Temporal variations in SST

In recent 150 years, all the four areas show increasing trends of annual mean SST anomalies (Fig. 5). The highest annual mean SST anomaly appears in 1998, and the temperature undergoes a decreasing trend since then, in spite of the fact that all of the

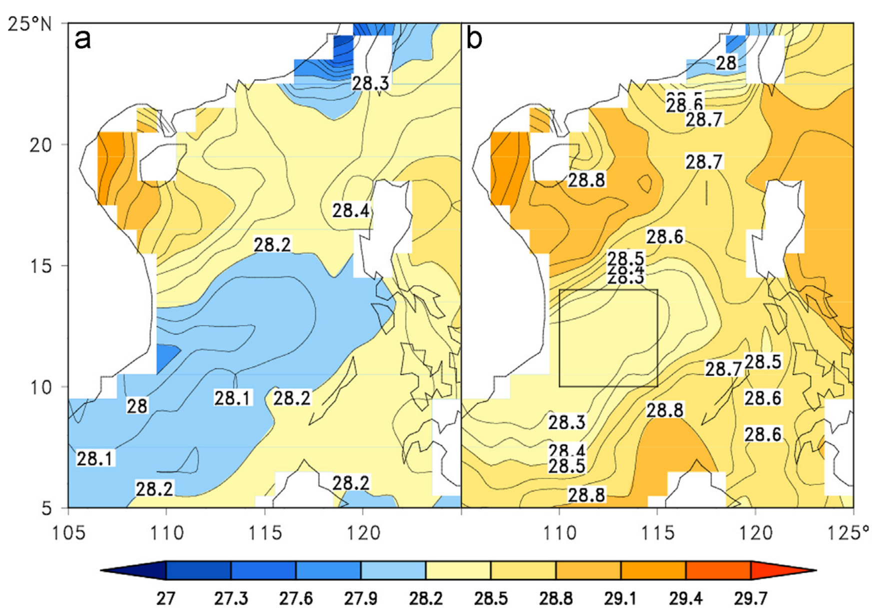


**Fig. 3.** Summer mean SST distribution of the SCS during 1961–1990 (a) and 1981–2010 (b) (Unit: °C).

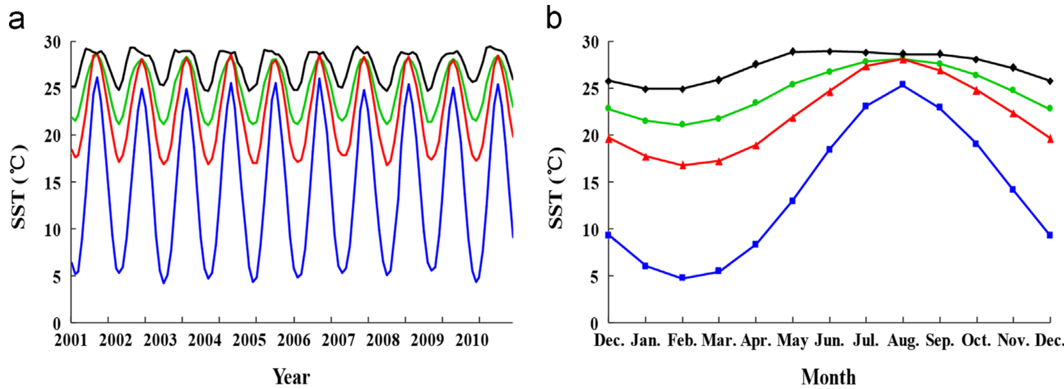


**Fig. 4.** Long term monthly mean SST of the marginal seas of China during 2001–2010 (a) and 1982–2011 (b) for different study areas. Blue: BYS; red: ECS; green: Whole region; black: SCS.

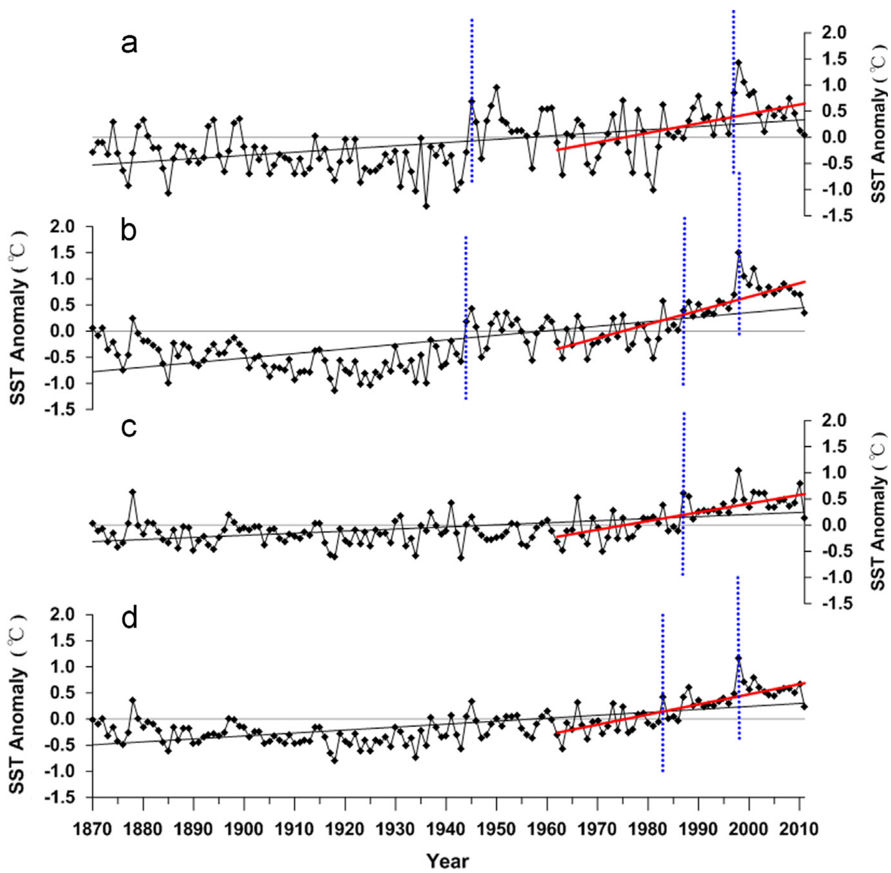


**Fig. 5.** Regional mean annual SST anomalies for marginal seas of China during 1870–2011. Black (red) lines indicate the latest 140 (50) years linear trends; blue dashed lines indicate regime shift years. (a) BYS; (b) ECS; (c) SCS; (d) Whole region. All of the linear trends passed 99% significance test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

areas exhibit positive SST anomalies for continuous 14 years. Averaged annual mean SST anomalies in 1998 are 1.16 °C for the whole region, 1.43 °C for the BYS, 1.51 °C for the ECS and 1.04 °C for the SCS respectively. The increasing trends during 1870–2011 reaches 0.06 °C/10 yr for the whole region, 0.09 °C/10 yr for the ECS, 0.06 °C/10 yr for the BYS, 0.04 °C/10 yr for the SCS, and all of the trends are significant at the 99% confidence level. Fig. 5 also indicates the linear trends of annual mean SST anomalies for the last 50 years, and shows the generally larger warming than for the last 140 years for all the seas.

The marked warming begins in 1940s for the BYS and the ECS, but in 1980s for the SCS as indicated in Fig. 5. There exist decadal to multi-decadal variations in the SST anomalies series, with a general cool period from 1870s to 1930s, a weak warm period from 1940s to 1950s, a weak cool period from 1960s to 1970s, and a recent warm period from 1980s to present. Fig. 5 also shows the climate regime shifts of the SST for different sea areas. The warm (cool) periods and the regime shifts are evident, with the ECS and BYS undergoing the most frequent regime shifts. Besides the BYS, all other sea areas witness significant regime shifts in 1980s, implying an abrupt change to the recent warm period. Meng et al. (2011) also reported the phenomenon of the abnormal warming in the China seas after mid-1980s. The BYS and the ECS see another regime shift in late 1990s. It is clear that the inter-annual to decadal variability is larger in the BYS, and it is smaller in the SCS, indicating an increase in SST variability with latitude.

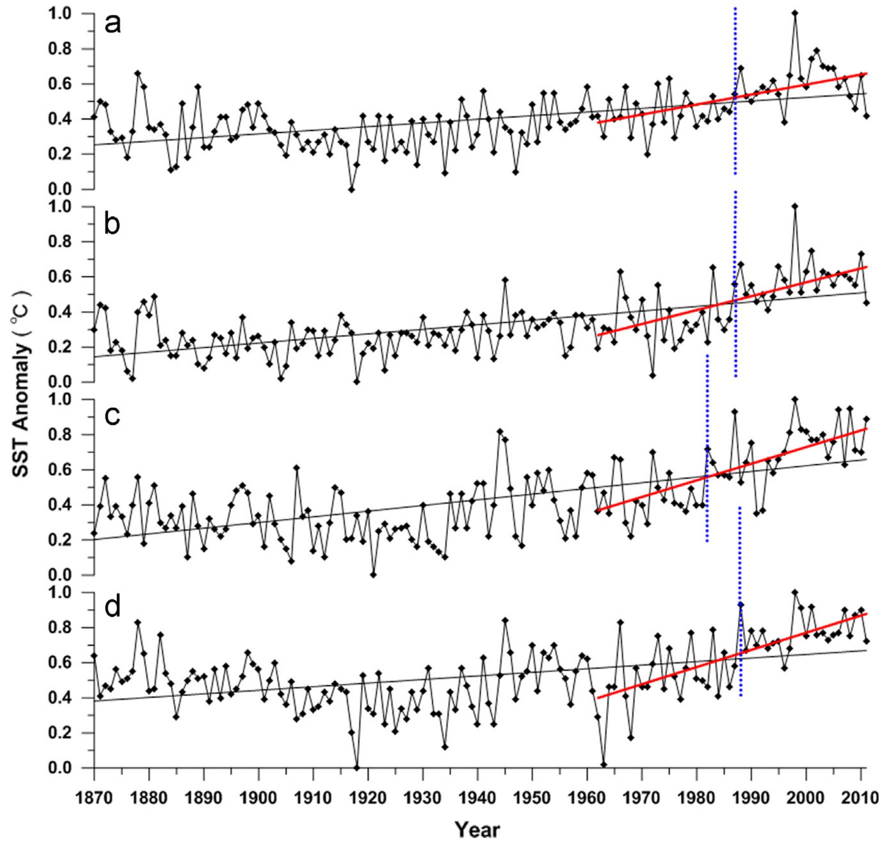


**Fig. 6.** Regional averaged seasonal mean SST anomalies for the marginal seas of China during 1870–2011. Black (red) lines indicate the latest 140 (50) years linear trend; blue dashed lines indicate regime shift years. (a) Spring; (b) Summer; (c) Autumn; (d) Winter. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

**Table 1**
Linear trends of SST anomalies for four seasons and year in different areas of the marginal seas of China during 1870–2011 and 1962–2011 (Unit: °C/10 yr).

| | Spring | | Summer | | Autumn | | Winter | | Annual | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1870–2011 | **1962–2011** | 1870–2011 | **1962–2011** | 1870–2011 | **1962–2011** | 1870–2011 | **1962–2011** | 1870–2011 | **1962–2011** |
| Whole region | 0.047** | **0.129**** | 0.053** | **0.161**** | 0.068** | **0.199**** | 0.057** | **0.273**** | 0.057** | **0.194**** |
| BYS | 0.055** | **0.129**** | 0.036** | **0.122**** | 0.076** | **0.168**** | 0.080** | **0.268**** | 0.061** | **0.181**** |
| ECS | 0.073** | **0.198**** | 0.071** | **0.175**** | 0.108** | **0.302**** | 0.094** | **0.379**** | 0.087** | **0.262**** |
| SCS | 0.033** | **0.093**** | 0.043** | **0.160**** | 0.044** | **0.145**** | 0.035** | **0.225**** | 0.040** | **0.167**** |

** Indicates that the trend is significant at the 99% confidence level.

It is also interesting to note that the latest 30 years see a smaller increasing trend of annual mean SST than that for the last 50 years, indicating a slowdown of warming in the study regions, and the last 14 years actually undergo an evident downward trend especially for the BYS and the ECS. This slowdown of warming in the past decade is found apparent in global scale (Kosaka and Xie, 2013; Smith, 2013). Besides, regional and seasonal characteristics of the phenomenon were also reported (Kosaka and Xie, 2013). Mechanisms for this hiatus were documented in terms of natural climate variability (Kosaka and Xie, 2013; Trenberth and Fasullo, 2013), stratospheric water vapor concentration (Solomon et al., 2010; Held, 2013), solar irradiance (Fröhlich, 2012; Held, 2013), and Pacific Decadal Oscillation (Trenberth and Fasullo, 2013) etc. Kosaka and Xie (2013) studied this global warming hiatus with regard to equatorial Pacific surface cooling and pointed out that natural climate variability caused the hiatus through La-Ninã-like decadal cooling. Solomon et al. (2010) pointed out that stratospheric water vapor concentration decrease lead to the warming slowdown significantly in the last decade. Trenberth and Fasullo (2013) found that negative phase of the Pacific Decadal Oscillation in the last decade is one reason for the hiatus in global warming.

Fig. 6 shows seasonal mean SST anomalies and their trends for the whole region during 1870–2011, and Table 1 gives linear trends of the seasonal and annual mean SST anomalies for various areas and the whole region during 1870–2011 and 1962–2011. For the region on a whole, significant warming occurs in all seasons with those of autumn and winter being the largest, reaching 0.07 °C/10 yr and 0.06 °C/10 yr respectively, and that of spring the smallest. All of the linear trends of seasonal mean SST anomalies for the whole region are significant at the 99% confidence level. The warming in spring and summer begin earlier and exhibit a more monotonous rise, and the increase in SST in autumn and winter begin later and is accompanied by a larger decadal and multi-decadal variability. The same as the annual pattern, seasonal pattern for the latest 50 years shows more significant warming trend than recent 140 years. Caputi et al. (2009) found that austral winter and autumn are more warming than spring and summer for the SST off the lower west coast of Australia.

The seasonal mean SST regime shifts are shown in Fig. 6 with blue dashed line. The most significant shifts for four seasons all happened in 1980s. He and Wang (2012) found that there is a decrease in the East Asian Winter Monsoon (EAWM) intensity beginning from 1986, and Ren et al. (2005a, 2005b) reported the rapid increase in annual and winter mean surface air temperature in mainland China beginning around mid-1980s, which are all consistent with the SST regime shift in the marginal seas revealed in this study. Decrease of inter-annual variability of the EAWM intensity after mid-1980s was also reported in other studies (He, 2013; Wang and Fan, 2013). EAWM related systems like Siberian high, Aleutian low, East Asian trough, East Asian jet stream and meridional wind at 850 hPa also show sign of weakening during 1986–2010 compared to 1956–1980 (He, 2013).

**Table 2**
Linear trends of annual mean SST for the study region and the global and northern hemispheric average surface temperature reported by the IPCC AR4 (Trenberth et al., 2007) (Unit: °C/10 yr).

| | Whole region | BYS | ECS | SCS | Global | Northern hemisphere |
|---|---|---|---|---|---|---|
| **1901–2005** | 0.093** | 0.108** | 0.151** | 0.061** | 0.067** | 0.071** |
| **1979–2005** | 0.267** | 0.387** | 0.444** | 0.190** | 0.133** | 0.190** |

** Indicates that the trend is significant at the 99% confidence level.

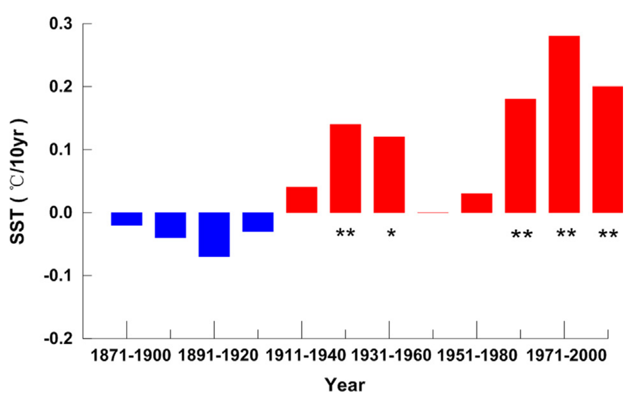


**Fig. 7.** Linear trends of annual mean SST anomaly for every 30 years for the marginal seas of China during 1870–2011. ** and * indicate the trends are significant at 99% and 95% confidence level respectively.

Table 1 shows that, except for the SCS, the autumn and winter warming trend is more significant than annual trend in the past 140 years, with the summer and autumn SCS SST experiencing more significant warming than those for the annual SST trend. For recent 50 years, all the sea areas see 3–5 times larger warming trends than those for the past 140 years. These are consistent with the previous analyses of the marginal sea SST (Meng et al., 2011) and of the mainland surface air temperature of eastern China (Ren et al., 2005a; Tang and Ren, 2005).

Among the various areas of the study region, the ECS shows the largest warming trends for all seasons, with the trends for spring, summer, autumn and winter reaching 0.07 °C/10 yr, 0.07 °C/10 yr, 0.11 °C/10 yr and 0.09 °C/10 yr respectively. The trends of autumn and winter SST anomalies in the BYS are also relatively larger, reaching 0.08 °C/10 yr and 0.08 °C/10 yr respectively.

Comparing the results of this analysis with those reported for global and northern hemispheric averages (Table 2), it can be found that the trends of annual mean SST in the marginal seas of China are generally higher than those of global and hemispheric averages for the same time periods (Jones et al., 2012; Trenberth et al., 2007). Except for the SCS for period 1901–2005, all the seas have larger warming rates than global and hemispheric averages during 1901–2005 and 1979–2005. Figs. 5 and 6 show that the slowdown of warming in the marginal seas of China over the last 14 years is also more evident than the global, northern hemispheric and China mainland averages as reported by some recent analyses (Easterling and Wehner, 2009; Jones et al., 2012; Ren et al., 2012; Hartmann et al., 2013). China marginal sea SST is generally influenced by East Asian monsoon system. Studies found that East Asian Winter Monsoon is weakening in recent 60 years and 100 years (Shi et al., 1996; R.H. Zhang et al., 2005; He and Wang, 2012), and this may well explain the rapid warming of the surface water as a result of decline of heat transfer from the air to deep water due to the slugging northerly wind. The unusual warming in East Asia including eastern mainland China may have

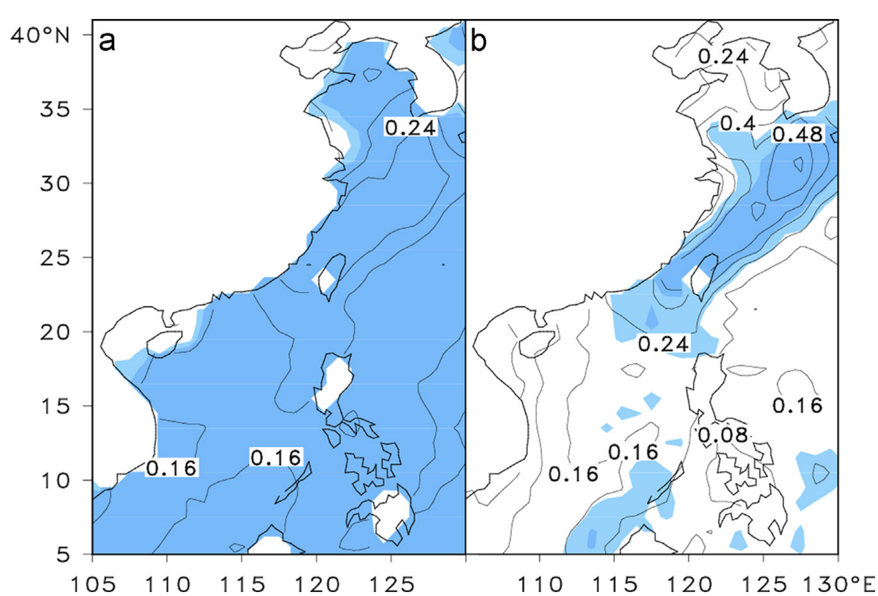


**Fig. 8.** Linear trends of annual mean SST during 1951–2011 (a) and 1979–2011 (b) (Unit: °C/10 yr). Blue color indicates the trends are significant at the 99% confidence level, and light blue indicates the trends are significant at the 95% confidence level.

been another reason for the large increase in the marginal sea SST in cold seasons (Ren et al., 2005b, 2012; Ding and Ren, 2008).

Fig. 7 shows the moving trends of annual mean SST anomalies for every 30 years during 1870–2011. The most significant warming for the study region occur in 1921–1950, 1931–1960, 1961–1990, 1971–2000 and 1981–2010, and the trends during these 30-yr periods pass the significance test at the 95% or even 99% confidence level. The largest warming occurs in 1971–2000, almost reaching 0.30 °C/10 yr. It is also clear that the warming occurs in all of the any 30-yr periods since 1911, in spite of the fact that the positive trends for 1911–1940, 1941–1970 and 1951–1980 are not significant at the 95% confidence level. Four of the early 30-yr periods see decreasing trends of annual mean SST, but the decreases did not passed the significant test.

The detailed spatial pattern of the SST changes during the 140 years is difficult to be identified due to the lack of early-period data. Fig. 8 gives the distributions of the linear trends of annual mean SST for time periods 1951–2011 and 1979–2011 instead, and Fig. 9 shows differences of annual mean SST between climate reference periods 1981–2010 and 1961–1990 over the marginal seas. In the last 60 years and 30 years, the whole region shows increasing trends of annual mean temperature, and almost all of the grids register statistically significant warming. For the last 60 years, there are more grids of the study region where the trends are significant at the 99% confidence level, though the magnitudes of the trends are generally smaller than those for the last 30 years. For both time periods, the most significant warming mainly occurs in the ECS, with the trends usually more than 0.20 °C/10 yr. The weakest warming occurs in central and northern SCS. The most obvious warming is clearly seen in the Taiwan Strait and the ECS, and the weakest warming occurs in northwestern part of the SCS and the Bohai Sea in Fig. 8. The whole study region actually sees significant SST increase in all the seasons in the recent 50 year period, but the most significant trend appears in winter and autumn except for SCS (Table 1).

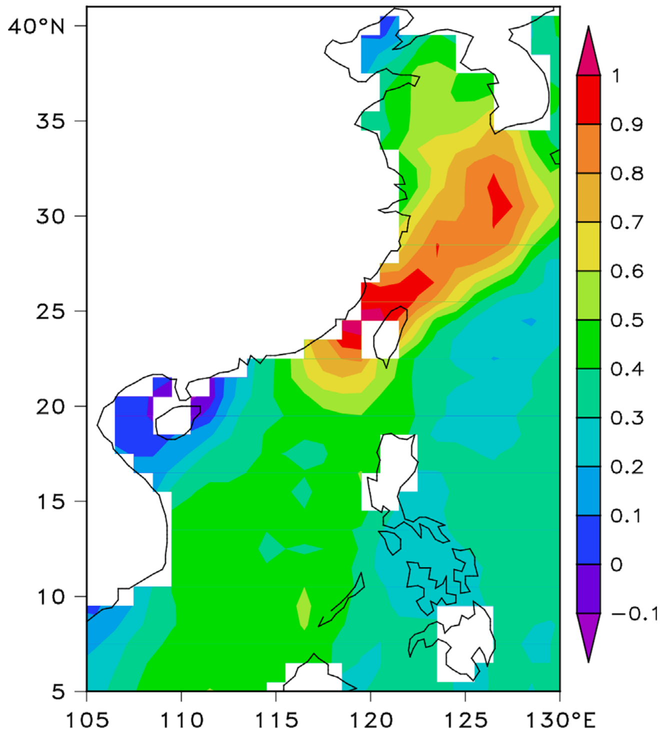


**Fig. 9.** Differences of annual mean SST between climate reference periods 1981–2010 and 1961–1990 over the marginal seas of China.

Fig. 10 exhibits the spatial distributions of linear trends of seasonal mean SST for time periods 1951–2011 and 1979–2011. In the last 60 years, significant warming trends are seen in the whole area, and the largest warming with significance at the 99%

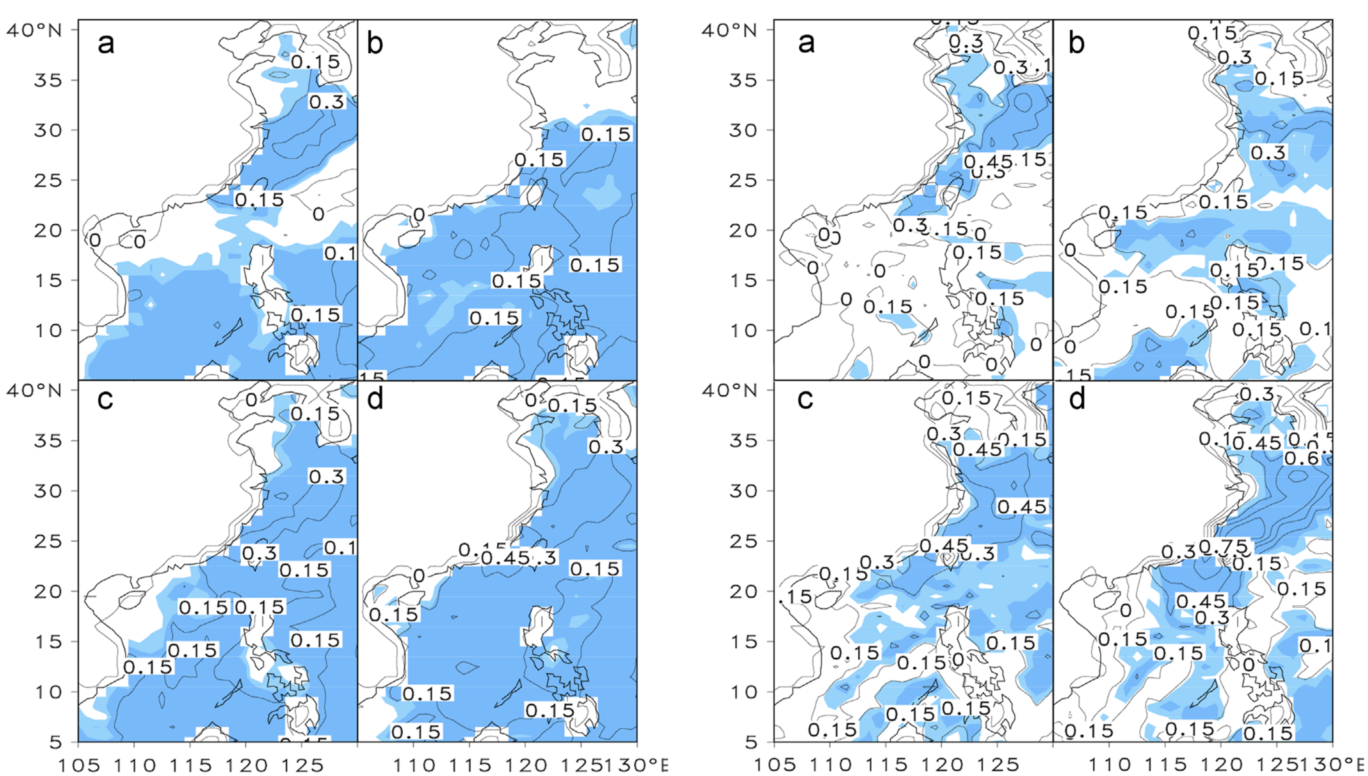


**Fig. 10.** Linear trends of seasonal mean SST during 1951–2011 (left) and 1979–2011 (right) (Unit: °C/10 yr). (a): Spring; (b): Summer; (c): Autumn; (d): Winter. Blue color indicates the trends are significant at the 99% confidence level and light blue indicates the trends are significant at the 95% confidence level.

confidence level appears in the ECS, especially for spring, autumn and winter. Most parts of the SCS also see a very significant warming for each of the four seasons. The warming in winter is the largest, with the 0.30 °C/10 yr isotherm surrounding a larger extent than those in other seasons. Less significant warming is seen in the BYS and northern SCS for spring and summer. Change of climatology in four seasons during 1981–2010 comparing to 1961–1990 shows that winter saw the greatest warming in various areas. ECS saw the greatest increase in four seasons compared to other regions. Winter is the most warming season for the whole area (figure is not shown). The seasonal trends of China offshore seas were reported in a few of analyses (Yeh and Kim, 2010; Cai et al., 2011; Meng et al., 2011). Cai et al. (2011) showed that both winter and summer experience warming trend and the climate regime shift in mid-1980. The ECS and the Yellow Sea are among the most significant warming areas. The previous findings are basically consistent with the result of this analysis. It is also realized in the previous studies that winter warming is more significant than that of summer in the East/Japan Sea (Yeh et al., 2010). Zhang et al. (2007) analyzed spring SST in Kuroshio region and found significant warming trend, and they also indicated the abrupt change in SST around 1987.

Similar patterns can be found for the last 30 years (Fig. 10b). The strongest warming trends are in the ECS, with winter mean SST increases reaching more than 0.60 °C/10 yr in the Taiwan Strait and central and eastern ECS. Spring and autumn see less warming trends in most areas. Once again the warming in the BYS and northern SCS is smaller in the last 30 years, and this is especially the case for springtime. The abnormal warming in the Taiwan Strait and the ECS in the last 30 years may be related to the strengthened Kuroshio warm current which may in turn be affected by the multi-decadal variability of the coupled air–sea system in the Pacific Ocean (Feng and Lin, 2009).

## 4. Discussion

Changes and variability of SST have been extensively studied in regional scale (Minobe et al., 2004; Caputi et al., 2009; Goikoetxea et al., 2009; Yeh et al., 2010; Skliris et al., 2012; Takeshige et al., 2013) and global scale (Shea and Trenberth, 1992; Smith and Reynolds, 1998). This paper examines the SST change in the marginal seas of China for the past 140 years.

SST changes of the region show diverse spatial and temporal characteristics. The coastal land area has significant effect on the off-shore sea SST, especially for the Bohai Sea (Yan and Li, 1997; Feng et al., 1999; Bao et al., 2002), and the marginal sea SST also affects the adjacent continent climate (Zhao et al., 2007; Ding et al., 2008). SST of the marginal seas of China is affected by many factors, such as Asian monsoon (Liang et al., 2006), ocean currents including the winter coastal currents, latitudinal locations and solar radiation, discharges of large rivers, and the configuration of the coastal lines (Feng et al., 1999), Kuroshio (Oka and Kawabe, 1998; Ichikawa and Beardsley, 2002; Nonaka and Xie, 2003) and other current systems (Ichikawa and Beardsley, 2002). Annual and seasonal mean SST exhibit different patterns due to the combined influences of the various factors.

Different from other regions, China marginal seas are highly affected by monsoon system. Table 3 shows the correlation coefficients between SST of different seas and the summer and winter monsoon index as formulated by methods which were developed by Q.Y. Zhang et al. (2003) and He and Wang (2012). There is a highly negative correlation between winter monsoon intensity and the SST of all the four sea areas, though the correlation between SST and the summer monsoon index is not so significant. Summer monsoon has less effect on SST in the

**Table 3**
Correlation coefficient between Marginal seas SST and East Asian Monsoon.

| | Whole region | BYS | ECS | SCS |
|---|---|---|---|---|
| Summer | −0.129 | 0.302* | 0.001 | −0.324** |
| Winter | −0.631** | −0.577** | −0.646** | −0.560** |

** and * indicate the trends are significant at 99% and 95% confidence level respectively.

whole region and the ECS, but the SCS bears a significant negative correlation with the summer monsoon intensity, which can be attributed to the weak upwelling in western SCS during summer monsoon season as discussed in 3.1. Takeshige et al. (2013) analyzed long-term trend of SST in Omura Bay and found that solar radiation is a dominant factor in heating period and air temperature and wind speed are the dominant factors in cooling period. The mechanism mentioned above may give an explanation to highly correlation between the winter monsoon intensity and SST in the marginal seas and the less significant correlation between the summer monsoon intensity and SST. Frequent and intense cold air bursts related to the strong winter monsoon lead to large air–sea heat exchange and apparent impact on off-shore sea SST (Bao et al., 2002). Yeh and Kim (2010) analyzed Yellow/East China Sea SST during 1950–2008 winter and found increase of SST for this area. They also suggested that anomalous anti-cyclonic circulation caused weakening of winter northerly wind is the main cause for the increase of SST. As winter monsoon becomes weaker during the past decades, the marginal seas of China undergo highly significant warming in winter and spring.

Nevertheless, East Asian Monsoon system is not the only factor influencing the long term trend of marginal seas SST of China. Large-scale factors, like global warming, Pacific Decadal Oscillation and Atlantic Multi-decadal Oscillation may have also affected the long term trends of SST in the marginal seas of China (L.P. Zhang et al., 2010). The mechanism for the linkage, however, is not clear yet at present, and more research is needed to understand the issue.

The low-frequency ENSO variability may have been important in changes of the marginal sea SST (Wu et al., 2005; Song et al., 2007). The maximum values of annual mean SST for all areas of the marginal seas appeared in 1998, when the strongest El Nino event in 20th century occurred (Wang and Gong, 1999; Wolter and Timlin, 2011). ENSO is closely related to East Asian Monsoon (R.H. Zhang et al., 2003; Zhang and Li, 2004), it can lead to weaker than normal East Asian Monsoon (Tomita and Yasunari, 1996; Ji et al., 1997; Wang et al., 2000), and also in favor of an abnormally high SST in the marginal seas. Takeshige et al. (2013) found that 1963 is a strong EAWM year with strong near-surface wind, low air temperature and low SST. In this paper, abnormally low winter SST is also evident in 1963 (Fig. 6). Nevertheless, the winter monsoon intensity in the year seems not so strong (figure is not shown). This difference may be attributed to different definitions and analysis methods used for EAWMI.

The seasonal rhythm of SST obviously results from the effect of solar radiation variation within a year. The absence of the summer peak in the SCS, however, might be related to the prevailing summer southwest monsoon. With the breakout of summer monsoon in late June, upwelling current forms in the western SCS, or offshore area of the Indochina Peninsula, driven by the southwesterly wind. The weak and stable upwelling in the off-shore area of the Indochina Peninsula keeps the summer SST of the whole SCS relatively low. Meanwhile, significant increase of cloudiness and precipitation during summer monsoon season also contribute to the absence of the summer SST peak in the SCS.

We calculate the summer mean SST anomalies of the core upwelling area (10–14°N, 110–115°E, as indicated in Fig. 3b) for

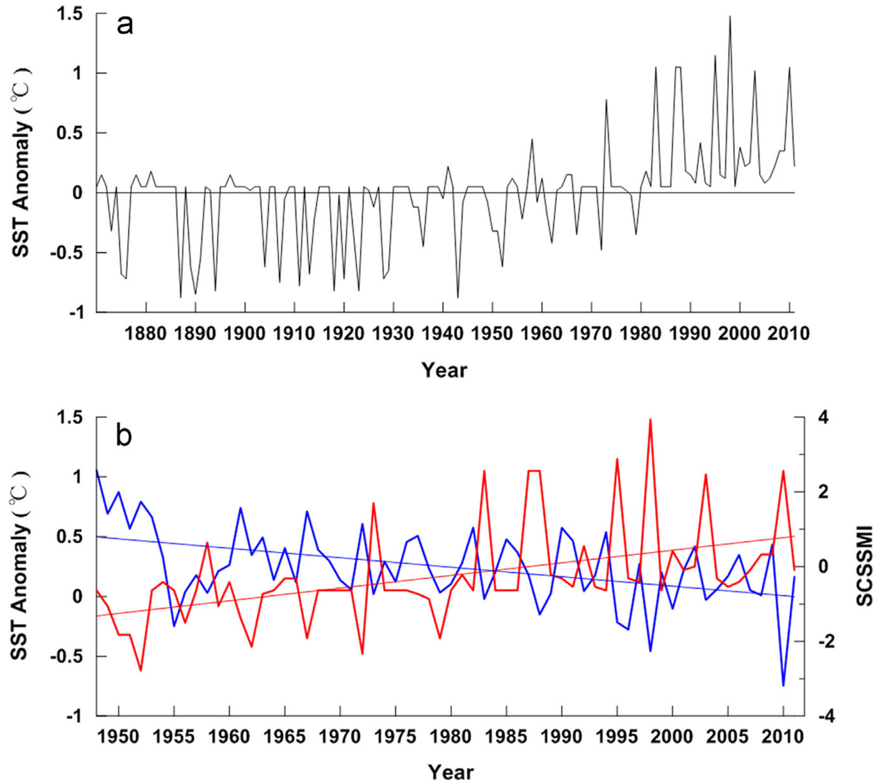


**Fig. 11.** (a) Summer mean SST anomalies of the core upwelling area (10–14°N,110–115°E) for 1870–2011; (b) SCSSMI (blue) and summer mean SST anomalies (red) of the core upwelling area for 1948–2011.

time period 1870–2011, and compare it to the South China Sea Summer Monsoon Index (SCSSMI) defined by Li and Zeng (2002, 2003) for time period 1948–2011. Fig. 11a shows that the SST anomalies undergo a significant increasing trend in the last 50 years, with the SST anomalies for most years shifting from negative to positive values. Correlation coefficient between the summer SST anomalies and SCSSMI is −0.64 (significant at 99.9%), indicating that the weakening of summer monsoon is one of the main reasons for the increase of the SST anomalies in the upwelling area and the decrease of the upwelling intensity.

The observed variations in annual mean SST in the marginal seas of China bear a good similarity to the reported changes in surface air temperature for mainland China for the last 100 years (Tang and Ren, 2005; Ren et al., 2012) and the last half century (Ren et al., 2005a, 2005b). However, the SST trends in the marginal seas are generally smaller than those in the mainland, and the relatively warm period from 1930s to 1940s and the rapidly warming period from 1980s to 2000s found in the mainland air temperature seem much weaker in the study region (Tang and Ren, 2005; Cao et al., 2013).

Compared to the changes in seasonal mean land surface air temperature, the marginal seas of China show more remarkable warming in autumn and winter, and much less increase in temperature in spring and summer. For example, the increases in seasonal mean surface air temperature in mainland China as a whole during 1908–2007 are 0.19 °C/10 yr and 0.16 °C/10 yr for winter and spring, but they are only 0.06 °C/10 yr and 0.01 °C/10 yr for autumn and summer, with the warming in summer insignificant (Tang and Ren, 2005; Ren et al., 2012). The warming in mainland China in the last 50–60 years is also the largest in winter and spring, and the increase in summer temperature is small (Ren et al., 2005, 2012). Therefore, the differences of the trends and decadal variations of annual mean air temperature and seasonal mean SST in the study region from those of mainland surface air temperature are evident. This difference might have partly been caused by the urban bias existing in the land surface air temperature data applied in the current studies (Ren et al., 2008; Jones et al., 2008; A.Y. Zhang et al., 2010) though a further investigation is needed to understand the underlying causes.

It is also worth noting that there are a few of abnormal values in the HadISST dataset used in this paper. We have replaced the records proved wrong with climatological averages. There might be other errors in the dataset, however, and more effort is needed to identify and deal with them. In addition, the spatial resolution of the dataset is relatively low for analyzing climatology of SST in the Bohai Sea and Yellow Sea, and the inefficiency of records of the early years leaves many blank grids for late 19th century and early 20th century, leading to a large uncertainty for the analysis of long-term trends of SST.

## 5. Conclusions

This paper analyzes the spatial characteristics and long-term change of SST over the marginal seas of China for the last 140 years. The following conclusions can be drawn from the analysis. In conclusion, annual mean SST decreases with increasing latitude, with high temperature ranging from 24–28 °C in the south and low temperature ranging from 12–20 °C in the north. Large seasonal shifts mainly occur in the Bohai Sea and the Yellow Sea. The smallest and largest spatial SST differences among various sea areas and latitudinal zones are seen in August and January respectively, and the coolest month is February for the whole region and various areas. Except for the South China Sea for period 1901–2011, the warming trends of the marginal seas of China during 1901–2011 and 1979–2011 are larger than the global and hemispheric averages, with the East China Sea seeing the largest warming of all areas. In recent 140 years or 50 years, all the sea areas see rising trends of annual mean SST, with the East China Sea experiencing the most significant warming. Larger and more significant warming generally occurs in autumn and winter for both time periods 1901–2011 and 1979–2011. An evident slowdown of warming in the marginal seas of China over the last 14 years is found, and the slowdown is characterized by a decreasing trend of annual and seasonal mean SST, indicating that it is more evident than the global, northern hemispheric and China mainland averages. A weak upwelling current exists in western South China Sea, and the upwelling intensity has a significant positive correlation with the SCS summer monsoon index, with both seeing a decrease in recent 64 years.

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