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Characteristics and possible causes of the seasonal sea level anomaly along the South China Sea coast

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Abstract

Based on sea level, air temperature, sea surface temperature (SST), air pressure and wind data during 1980–2014, this paper uses Morlet wavelet transform, Estuarine Coastal Ocean Model (ECOM) and so on to investigate the characteristics and possible causes of seasonal sea level anomalies along the South China Sea (SCS) coast. The research results show that: (1) Seasonal sea level anomalies often occur from January to February and from June to October. The frequency of sea level anomalies is the most in August, showing a growing trend in recent years. In addition, the occurring frequency of negative sea level anomaly accounts for 50% of the total abnormal number. (2) The seasonal sea level anomalies are closely related to ENSO events. The negative anomalies always occurred during the El Niño events, while the positive anomalies occurred during the La Niña (late El Niño) events. In addition, the seasonal sea level oscillation periods of 4–7 a associated with ENSO are the strongest in winter, with the amplitude over 2 cm. (3) Abnormal wind is an important factor to affect the seasonal sea level anomalies in the coastal region of the SCS. Wind-driven sea level height (SSH) is basically consistent with the seasonal sea level anomalies. Moreover, the influence of the tropical cyclone in the coastal region of the SCS is concentrated in summer and autumn, contributing to the seasonal sea level anomalies. (4) Seasonal variations of sea level, SST and air temperature are basically consistent along the coast of the SCS, but the seasonal sea level anomalies have no much correlation with the SST and air temperature.

Key words: seasonal sea level anomalies, ENSO, wind, air pressure, oscillations

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1 Introduction

Ocean thermal expansion, polar ice sheet and glacier mass loss derived from global warming are very likely the dominant contributors to global mean sea level rise (IPCC, 2007). Regional sea level changes are significantly different from global average sea level change, and they are not only affected by the global sea level change, but also by the oceanographic and meteorological elements such as local sea surface temperature (SST), ocean current, wind, air temperature, atmospheric pressure and precipitation. In recent years, due to frequent occurrences of extreme weather and climate events, the number of the coastal seasonal sea level anomaly (SSLA) increased, and they become more and more severe. Abnormally high sea level uplifts the basic water level, which correspondingly leads to the rising of high tide water level and the increasing of disaster degree resulting from storm surge. Conversely, anomalously low sea level reduces the navigable capability of coastal ports (State Oceanic Administration, 2011). "2012 Chinese Sea Level Bulletin" reported that the coastal sea level of the SCS increased significantly in 2012, reaching its highest in March, August and October respectively in the same periods since 1980. From January to March 2012, the coastal sea level in Guangdong was 16.2 cm higher than the normal level. At the same time, the upland water of the Zhujiang River (Pearl River) became less, which led to four times saltwater intrusion at the Zhujiang (Pearl River) Estuary and affected water supply. In August 2012, sea level along the west coast of Guangdong Province was abnormally high while tropical storm "Qide" landed at the coast of Zhanjiang on August 17, coincided with the astronomical tide, more than 1 650 000 people in Zhanjiang, Maoming and other places were affected.

The average seasonal cycles for coastal water levels are caused by a combination of the effects of the average seasonal cycles of air pressure, wind, water temperature, salinity, ocean currents, and river discharge (Zervas, 2009). Concerning the monthly mean sea level (MSL) along the coastal region of China, the lowest value generally appears in winter or spring, the highest value occurs in summer or autumn. The highest value of the monthly sea level appears in July in the Bohai Sea and the Yellow Sea, and gradually postpones to October in the South China Sea. Affected by the weather system at different latitudes, cold tide in winter, extra-tropical cyclone in spring, and tropical cyclone in summer and autumn are active, increasing the diversity of climate. Variation of the East Asian monsoon is an important factor influencing the sea level changes along China's coast and adjacent areas (Cai, 2010). Abnormally high or low sea level is a kind of short-term sea-level changes caused by non-astronomical factors (i.e., air pressure, wind, rainfall and runoff changes), referring to the increasing water or storm caused by low pressure and strong typhoon (Fang et al., 1986).

Seasonal sea level variations contain the long-term trend and

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the periodic low-frequency changes, with obvious inter-annual and inter-decadal variations (Fang et al., 1986; Yu, 2004). In China's coastal area, significant oscillation periods of annual sea level variation are quasi 2 a, 3–7 a, 9 a, 11 a and 19 a. The period of quasi-2 a is very common in the variation of the hydrological and atmospheric factors near the coast of China, and the oscillation of 3–7 a is generally considered to be correlated with ENSO (Yu and Xu, 2003; Zhen, 1999; Zuo et al., 1994). ENSO shows a close connection with the sea level anomaly. ENSO can affect the SCS sea level through the north wind anomaly and the variation of the North Pacific Gyre (Kuroshio) (Rong et al., 2007). The periodic oscillation of 11 a may be related to the Sunspot activity; the oscillation of 19 a is caused by the tidal force of celestial bodies (Fang et al., 1986). The sea level shows different oscillation periods in different decades. All kinds of periodic oscillations cross or overlay in different time periods, uplifting or lowering sea level (Wang et al., 2013b).

Under the background of global warming, the sea level rise has become one of the major environmental problems in the world. As a kind of delayed disaster, the long-term cumulative effects of the sea level rise will submerge the coastal lowlands and destroy the ecological environment, therefore seriously affect the economic and social development in the coastal areas.

In this paper, we utilize the data of sea level, air temperature, SST, air pressure and wind during 1980–2014 to analyze the characteristics and possible causes of SSLA along the SCS coast.

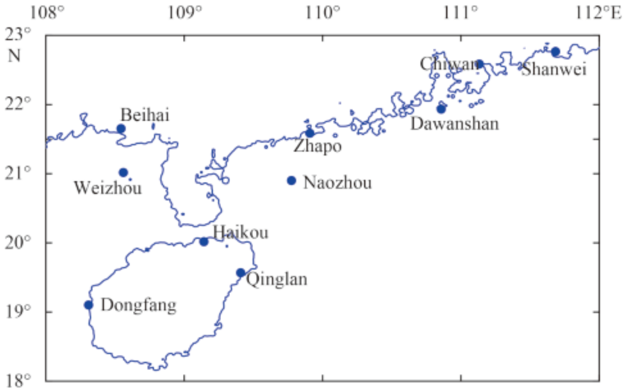

Fig. 1. Typical stations selected along the SCS coast.

2 Data

The data used in this paper include the sea level, SST and air temperature during 1980–2014 obtained from 10 coastal hydrological and meteorological observation stations along the SCS coast (Fig. 1). These stations are distributed evenly, and the sea level data have been supplemented and corrected (Lau and Weng, 1995), unified by the same zero reference (Wang et al., 2013). Air temperature and SST data of these stations during the same period are also quality controlled and corrected. Wind data used in this study are provided by the America National Centers for Environmental Prediction (NCEP)/US National Center for Atmospheric Research (NCAR) (Reanalysis II), the spatial resolution is 0.3°×0.3° (10 m Wind) during 1981–2014.

For all the variables in this paper, the multi-year average indicates the average values during 1975–1993, and the monthly multi-year average represents the monthly mean values during that period. The anomalies are the difference between mean values and the multi-year average.

3 Seasonal sea level variation along the SCS coast

3.1 *Seasonal variation of sea level*

Sea level along the SCS coast takes on strong seasonal variation. The annual range is about 15–30 cm, larger in north and smaller in south. From north to south, the phase of sea level changes from 135° to 166°, with a time difference of nearly 1 month (Table 1).

Table 1. Annual and semi-annual harmonic constants at stations along the SCS coast

Station	Annual		Semi-annual		The occurrence time of the highest and lowest sea level	
	Amplitude/cm	Phase/(°)	Amplitude/cm	Phase/(°)	The highest sea level	The lowest sea level
Shantou	12	135	6	–152	Oct.	Apr.
Shanwei	10	134	5	–152	Oct.	Apr.
Huangpu	12	150	9	36	Oct.	Feb.
Zhapo	11	134	7	–164	Oct.	Apr.
Naozhou	14	128	9	–166	Oct.	Apr.
Haikou	9	147	5	–175	Oct.	Feb.
Qinglan	12	127	6	–172	Oct.	Jul.
Dongfang	9	128	5	–174	Oct.	Jul.
Beihai	9	–176	4	164	Oct.	Feb.
Weizhou	8	166	4	172	Oct.	Feb.

Except for in the Zhujiang Estuary, the seasonal variation of sea level off Guangdong Provine is consistent with that off eastern coast of Hainan Provine. The lower sea level appears from January to August and the variation is not significant. After August, the sea level rises rapidly. By October, it reaches the maximum, 20 cm higher than the average. The lowest sea level occurs most frequently in July, which is 10 cm lower than the average. In the northern gulf, the lowest sea level appears in February and the highest sea level appears in October. Sea level annual range is small, from 15 cm to 25 cm. The seasonal variation of the sea level in the Zhujiang Estuary presents bimodal pattern and the peak values occur in June and October respectively. The lowest sea level appears from January to February in the Zhujiang Estuary, and sea level annual range is 20–30 cm (Table 1, Fig. 2).

3.2 *SSLA*

In this section, the characteristics of the monthly MSL anomaly variation along the SCS coast are analyzed. The average seasonal cycles and linear trend are removed from the monthly MSL data series of the 10 selected stations. The monthly MSL anomaly values larger than 10 cm or less than -10 cm are considered abnormal (Zervas, 2009). The statistical results are shown in Table 2.

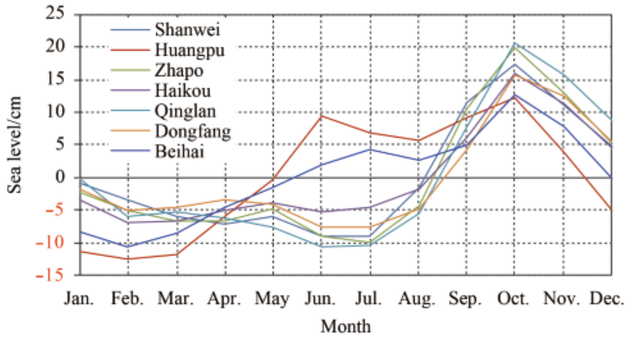

Fig. 2. Annual cycle of sea level off the SCS coast.

Table 2 shows the statistics on the monthly MSL anomalies during 1980–2014 along the SCS coast. Monthly MSL anomalies often occur from January to February and from June to October along the SCS coast. The highest frequency of sea level anomalies happens in August, showing an increasing trend in recent years. In addition, the occurring frequency of negative sea level anomaly accounts for 50% of the total abnormal times of the year. From the temporal distribution characteristic of sea level anomalies, the distribution of sea level anomaly is closely related to ENSO events. Most of the negative anomalies appear during El Niño, while the positive anomalies appear during La Niña (late El Niño). From the occurrence time of the storm surges over the years, it can be found that storm surges mostly happened from June to the end of October along the SCS coast. Intensive typhoons and larger fluctuation ranges of water level certainly affect the coastal monthly MSL (State Oceanic Administration, 2012). Winter wind prevails from January to March and it is strong in January. The northeast wind prevails along the SCS coast, while the wind in equatorial buffer zone of the SCS is weak with an average speed of 3–4 m/s (Cai, 2010). The abnormal wind arouses the coastal waters shoreward accumulation or offshore divergence, which causes the coastal sea level abnormal increasing or decreasing (State Oceanic Administration, 2013). The sea level anomalies happened less from April to May and from November to December, also with small short-term fluctuations

Table 2. Monthly MSL anomalies statistics during 1980–2014 along the SCS coast

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1980	0	–5	0	0	0	–5	0	0	+5	0	0	0
1981	+3	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	–3	0	–5	–5	0
1983	0	0	0	0	0	–5	0	0	–5	0	0	0
1984	0	0	0	0	0	0	0	+3	–5	0	0	0
1985	–3	0	0	0	0	+3	0	0	–5	0	0	0
1986	–3	0	0	0	0	0	0	+5	0	–3	0	0
1987	0	0	0	0	0	0	0	–3	0	–5	0	0
1988	0	0	0	0	0	0	0	–3	0	+5	0	0
1989	+3	0	0	0	0	0	0	+3	0	0	0	0
1990	+3	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	–3	0	+3	+3	0	0	0
1992	0	0	0	0	0	0	0	0	0	+3	0	–3
1993	0	0	0	0	0	–5	0	0	+3	0	0	0
1994	0	0	0	0	0	0	+3	0	0	0	–3	0
1995	0	0	0	0	0	–3	0	–5	0	0	–5	0
1996	0	0	–3	0	0	–3	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	–5	–5	0
1998	0	–3	0	–3	0	0	0	–3	0	0	0	+3
1999	+3	+3	+3	0	0	0	0	0	0	+3	+3	+3
2000	+3	+3	+3	0	0	0	+3	0	0	0	+5	+5
2001	+5	+3	0	0	0	0	+3	+3	+5	0	0	0
2002	–5	0	–5	0	0	0	0	0	0	–5	0	+5
2003	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	–5	0	0	0	0	0	0	0	0	–5	0
2005	0	0	–5	–5	0	0	0	–5	0	0	0	0
2006	0	0	0	0	0	–5	0	0	0	–3	0	0
2007	0	–5	0	0	0	–5	–5	0	0	0	0	0
2008	+3	0	–5	0	0	0	0	0	0	–5	0	0
2009	0	–3	0	0	0	0	0	0	+3	0	–3	0
2010	0	–5	0	0	0	–5	0	0	–5	+3	0	0
2011	0	0	0	–5	0	–3	0	0	+3	0	0	+3
2012	0	0	+5	0	0	+3	0	+3	0	+3	0	0
2013	0	0	0	+5	0	0	0	0	+3	0	0	–5
2014	0	0	0	0	0	0	0	–5	0	0	0	0
Total number of sea level anomalies	**10**	**9**	7	4	0	**12**	4	**13**	**11**	**12**	8	7

Note: The number represents the levels of sea level anomalies along the SCS coast; the red color represents positive anomaly; and the blue color represents negative anomaly.

in sea level.

3.3 *Linear MSL trend of typical months*

Since 1980, the rising rate of sea level in the SCS has increased, which uplift the basic water level. Besides, more frequent extreme climate events lead to increasing number of sea level anomalies. In this paper, June, August, September and October are selected as typical months, since sea level anomalies mostly happened in these months during 1980–2014. The long-term changes of sea level are also given in Fig. 3.

Figure 3 shows that the monthly MSL anomalies along the SCS coast show a rising trend since 1980, with the range of –20 – 20 cm. The rate of sea level change is 2.4, 2.9, 3.9, and 3.7 mm/a in June, August, September and October respectively since 1980. The largest rate is in September, smaller in October, and the smallest in June. In June 2012, sea levels were the highest during the same period in the history, 16.5 cm higher than normal; in June 1993, sea levels were the lowest during the same period in the history, 8 cm lower than normal; in August 2001, sea levels were the highest during the same period in the history, 14.5 cm higher than normal; in August 1982, sea levels were the lowest during the same period in the history, 10 cm lower than normal. In September 2009, sea levels were the highest during the same period in the history, 17.3 cm higher than normal; in September 1983, sea levels were the lowest during the same period in the history, 9.3 cm lower than normal. In October 2012, sea levels were the highest during the same period in the history, 15 cm higher than normal; in October 1987, sea levels were the lowest during the same period in the history, 8.5 cm lower than normal.

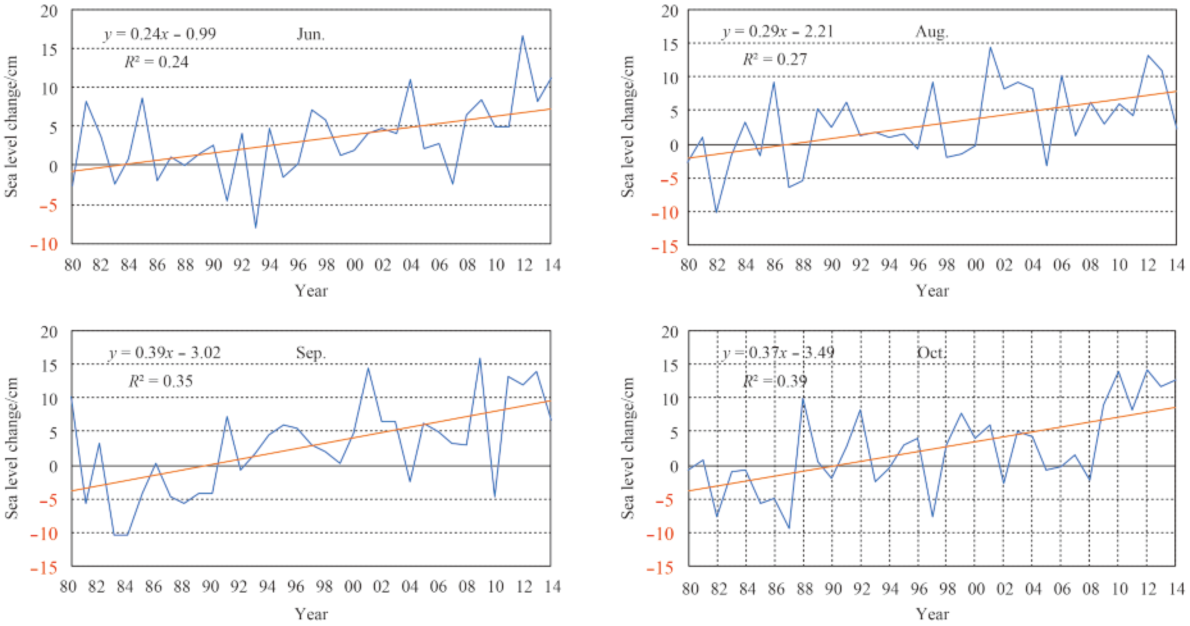

Fig. 3. Sea level changes of typical months along the SCS coast during 1980–2014. The horizontal coordinate is the monthly multi-year average. x represents time, and y sea level anomaly.

4 Possible causes of SSLA

The changes of the regional sea level anomaly, on one hand, are affected by global ocean climate events (such as ENSO). On the other hand, they are closely related to the abnormal changes of local climate. This section discusses the possible causes of sea level anomaly through the analysis of the oceanographic and meteorological factors such as marine events (ENSO), air pressure, wind, air temperature and SST.

4.1 *Relationship between the sea level anomaly changes and ENSO*

Periodic fluctuations in different time scales exist in marine climate change, which has a certain effect on the sea level anomalies. In this paper, the sea level along the SCS coast in spring, summer, autumn and winter was analyzed based on Morlet wavelet transform analysis method (Farge, 1992; Lau and Weng, 1995) (Fig. 4). Figure 4 shows that the long-term change of seasonal sea level has five significant oscillation periods, which are 2 a, 3–7 a, quasi 9 a, 11 a, and quasi 28 a, respectively. As the length of time series of sea level data is only 35 a, quasi 28 a is considered as false period. Oscillation period of sea level is different with seasons. The periods of quasi 2 a and 9 a are more significant in spring, with oscillation amplitude over 1 cm. The periods of quasi 2 a and 3.5 a are most significant in summer, with oscillation amplitude over 2 cm. The period of quasi 9 a is less significant in summer, with oscillation amplitude close to 2 cm. The periods of quasi 2 a, 7 a and 11 a are most significant in autumn, with oscillation amplitude close to 2 cm. In the four seasons, the oscillation period of 3–7 a associated with ENSO is of the strongest in winter, weaker in summer and autumn, and the weakest in spring. When periodic oscillation in the different time scales are superposed on their high phase, the height of sea level is lifted up, otherwise the sea level is fallen down. For example, in the winter 2011, the sea level was in the high phase of the periodic oscillations of 3 a, 5 a and 11 a, and the sea level was significantly high.

Combined with Table 3, it can be seen that low sea level anomaly along the SCS coast almost appears during the El Niño. While high sea level anomaly mostly appears during the La Niña. For example, during the 6 times strong El Niño events (1982/1983, 1986/1987, 1997/1998, 2002/2003, 2006/2007 and 2009/2010), the number of low sea level anomaly along the SCS coast

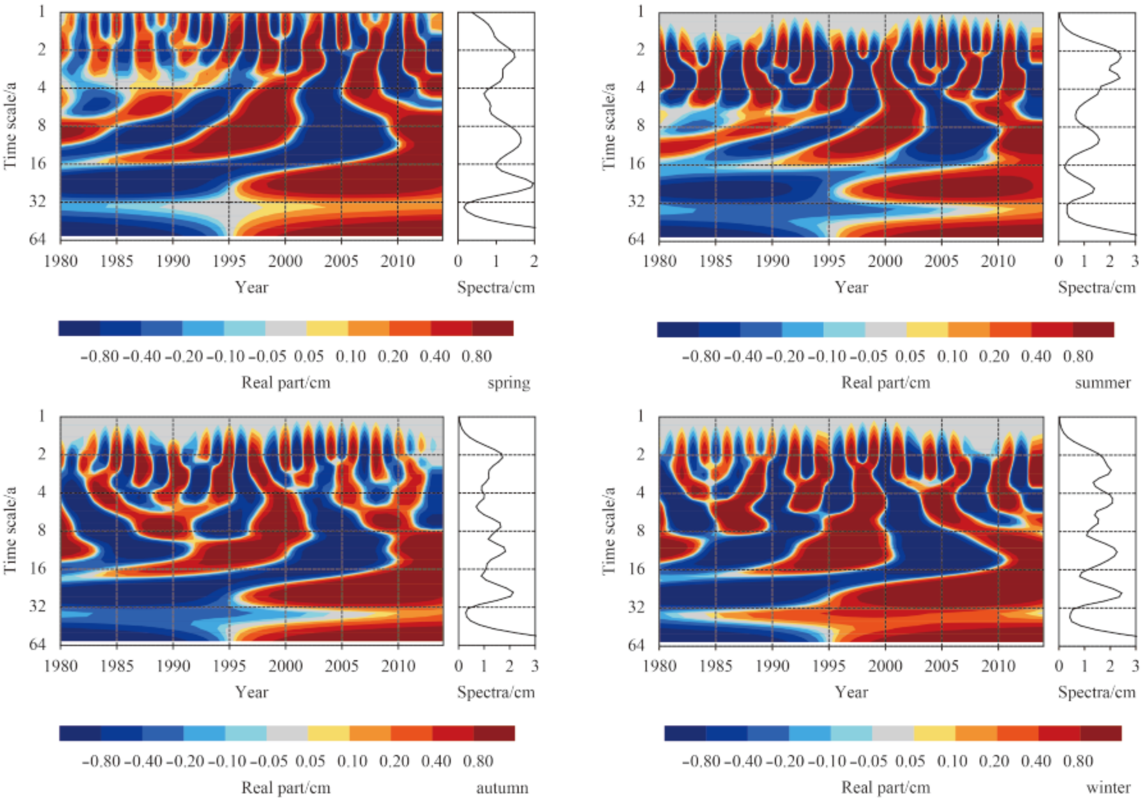

Fig. 4. Wavelet transform analysis on seasonal sea level along the SCS coast. All the left panels are the real part of wavelet spectrum and the right panels are wavelet spectrum.

Table 3. Monthly MSL anomalies (unit: cm) and annual constituent at the Zhapo Station

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Amplitude/cm	Phase/(°)
1997	2.9	7.5	0.3	1.2	−2.2	−1.1	10.9	9.8	0.7	−13.5	−11.4	−3.4	6.7	203.8
1998	−0.9	−10.0	−0.4	−9.0	−0.8	−2.5	−4.7	−9.0	−1.5	−1.9	5.0	11.8	13.8	231.9
1999	10.0	−3.3	7.8	9.2	0.4	−10.1	−0.1	−5.0	−3.2	5.8	9.6	9.2	13.9	247.6
2000	9.1	7.9	7.1	−0.2	4.8	−9.0	10.5	−6.2	2.9	2.5	3.1	3.2	10.0	243.9
2009	−0.4	−8.4	−2.4	6.2	1.2	−4.8	−2.3	−4.3	10.4	0.2	−9.5	−6.0	9.3	206.6
2010	−3.5	−10.0	−8.1	−1.5	−6.0	−7.7	−5.0	−0.9	−17.3	7.8	3.0	−4.4	12.7	222.6
2011	6.1	−7.3	1.9	−11.9	−6.2	−7.4	−3.9	−5.3	7.9	1.6	−0.3	6.4	16.2	226.9
2012	5.3	5.5	9.1	−1.6	6.6	4.3	4.8	6.2	5.3	2.8	−4.5	5.9	8.8	220.8

increased significantly, which accounted for 70% of the total number of negative anomalies. During the La Niña events (1988/1989, 1998/1999 and 2011/2012), the number of high sea level anomaly increased, which accounted for 50% of the total number of positive anomalies. Table 3 gives the amplitudes and phases of monthly mean sea level anomalies and tidal harmonic component of S_a (annual change) along the SCS coast at Zhapo Station during 1997–2000 and 2009–2012. It shows that the sea levels at the Zhapo Station have negative anomalies from October 1997 to October 1998 during 1997/1998 El Niño, and they have positive anomalies from November 1998 to March 2000 during 1998/1999 La Niña, negative anomalies from November 2009 to September 2010 during 2009/2010 El Niño and positive anomalies from September 2011 to October 2012 during 2011/2012 La Niña. Based on the harmonic analysis of the tidal data over the same period at this station, it is found that the amplitude and phase of annual period S_a are of large fluctuations. During El Niño, the annual amplitude is small and the phase is advanced. For example, the amplitudes of S_a were 6.7 and 9.3 cm and the phases were 203.8° and 206.6° in 1997 and 2009, respectively. While during La Niña, the annual amplitude increased and the phase lagged significantly. For example, the amplitudes of S_a were 13.9 cm and 16.2 cm and the phases were 247.6° and 226.9° in 1999 and 2011, respectively.

In order to further reveal the relationship between the sea level change and ENSO along the SCS coast, we still take the Zhapo Station as an example and analyze the correlations of the monthly MSL filtered out the inter-annual cycle signal with the index series of Niño4 and Niño3.4 respectively (Fig. 5). It is found that the correlation coefficient between the sea level and Niño4 index is −0.4 with two months ahead and the correlation coefficient between the sea level and Niño3.4 index is −0.4 with four months ahead. In order to examine whether the correlation is significant, the significant levels of α=0.05 and α=0.001 are given. The correlation coefficients of $|r|>r_{0.05}$=0.19, $|r|>r_{0.001}$=0.32 indicate that there is a negative correlation between sea level change and ENSO event along the SCS coast.

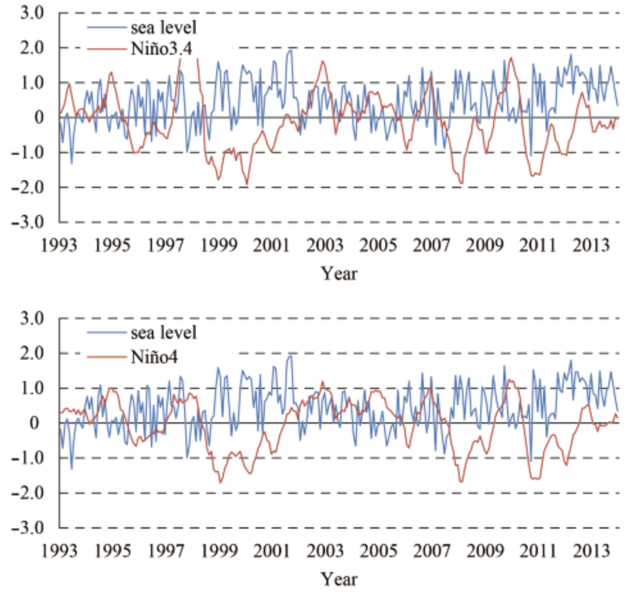

Fig. 5. Relationship between sea level at the Zhapo Station and Niño3.4 and Niño4 indexes.

4.2 *Changes of wind field and air pressure field*

Local abnormal changes of meteorological conditions (air pressure, wind, water temperature, salinity, current, or river discharge) cause large positive or negative residuals in the coastal areas. Long-term positive or negative residuals can result in abnormal high or low monthly MSL. Data analysis on hourly tidal level at ten selected coastal stations indicates that the positive and negative anomalies of sea level are closely related to the magnitude of the residuals. In the months of positive sea level anomalies, the residual water levels are generally positive. While in the months of negative sea level anomalies, the residual water levels are usually negative. Tables 4 and 5 show that in October 1988 and September 2010, the positive and negative anomalies of the sea level are significant, respectively. Naozhou Station is removed from Table 5 due to its poor data quality in 1988.

Through the analysis on the monthly MSL anomaly, mean wind anomaly, air pressure anomaly and wind-driven sea surface height (SSH) anomaly, we find that monthly MSL anomaly is closely related to wind anomaly and air pressure anomaly. Wind-driven flow is in good agreement with the change of sea level height (Ding et al., 2007).

The oceanic numerical model for the Northwest Pacific and Chinese marginal seas is established by use of Estuarine Coastal Ocean Model (ECOM). The horizontal resolution is 5′×5′, and 10 Sigma layers are divided vertically. The upper boundary of meteorology applies the mixing wind of NCEP/QuickScat. The sea level and flow are calculated respectively under the conditions of monthly mean wind and multi-year monthly mean wind, and the difference of the results reflects the status of wind-driven current and sea level height.

This section gives the analysis of the typical months with the most abnormal high sea level in recent years. The Tables 2–4 and Fig. 3 show that there was an abnormal low sea level along the SCS coast in September 2010 which was during 2009/2010 El Niño period, and the sea level was 10.7 cm lower than normal. There was an abnormally high sea level along the SCS coast in October 1988 which was during 1988/1989 La Niña period, and the sea level was 11.2 cm higher than normal. Figures 6 and 7 are the results of wind-driven SSH anomaly along the SCS coast in September 2010 and October 1988, respectively. Figure 6a shows the wind anomaly and air pressure anomaly in the SCS in September 2010. The wind anomaly in this month was strong southerly wind from Guangdong to the east coast of Hainan. Figure 6b shows the wind-driven sea surface height anomaly in September calculated by ECOM, which indicates that the coastal water diverges from Guangdong to the east coast of Hainan driv-

Table 4. Abnormal values and residual water levels at selected stations along the SCS coast in September 2010

	Shanwei	Chiwan	Dawanshan	Zhapo	Naozhou	Haikou	Qinglan	Dongfang	Beihai	Weizhou
Abnormal value/cm	–9.7	–13.1	–11.8	–17.3	–16.1	–9.7	–15.3	–12.7	–4.5	–7.3
Residual water level/cm	–8.2	–9.2	–10	–13.5	–16	–9.3	–14	–9.5	–4.1	–6.9

Table 5. Abnormal value and residual water level at the selected stations along the SCS coast in October 1988

	Shanwei	Chiwan	Dawanshan	Zhapo	Haikou	Qinglan	Dongfang	Beihai	Weizhou
Abnormal value/cm	17.2	14.5	14.8	15.5	9.6	10.4	4.7	0	2.7
Residual water level/cm	14.0	14.5	13.8	16.4	11	12.3	9.7	4.4	6.1

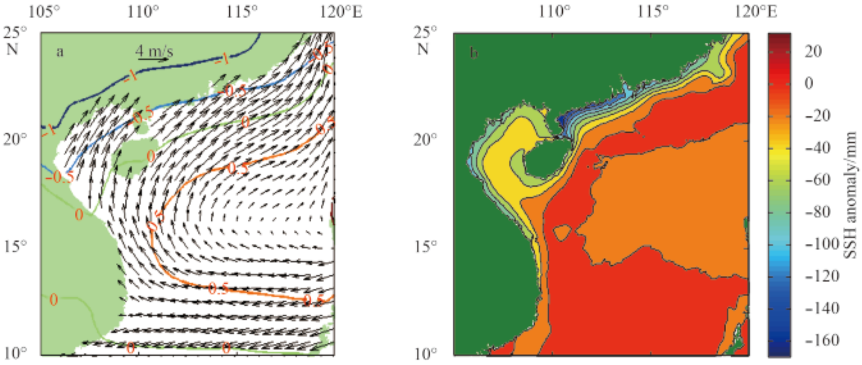

Fig. 6. Anomalies of wind, air pressure and wind-driven SSH in the SCS in September 2010. a. Wind anomaly and air pressure anomaly (unit: m/s, hPa) and b. wind-driven SSH anomaly.

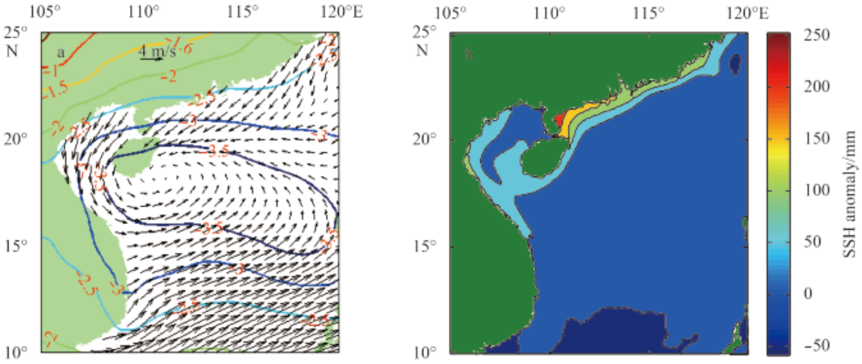

Fig. 7. Anomalies of wind, air pressure and wind-driven SSH along China coast in October 1988. a. Wind anomaly and air pressure anomaly (unit: m/s, hPa); b. wind-driven SSH anomaly.

en by offshore wind. Especially from Zhujiang Estuary to the north of Hainan, the SSH anomaly was from –16 cm to –18 cm.

Results of wind in the SCS in October 1988 are shown in Fig. 7. Figure 7a is wind anomaly and air pressure anomaly in the SCS in October 1988. It shows that the air pressure of this month was obviously low along the SCS coast, which was 2.5–3.0 hpa lower than normal. The coastal area is of a strong northerly wind anomaly, leading to the onshore accumulation of seawater and high sea level. Figure 7b shows wind-driven SSH anomaly calculated by ECOM in October 1988. It indicates that the SSH anomaly is 20–25 cm in the western Guangdong Province.

4.3 *Relationship between sea level and SST, air temperature*

Seasonal variations of sea level, SST and air temperature along the coastal region of the SCS, are mainly caused by solar radiation with a period of 12 months (Fig. 8). The highest values of SST and air temperature appear in July, and the lowest values appear in January. The correlation coefficient between SST and air temperature is greater than 0.9. However, the seasonal variation of sea level, due to the effect of the runoff and other factors, has large discrepancy (Fig. 8). For example, in the northern gulf, the lowest sea level appears in February and the highest sea level appears in October. Sea level annual range is 15–25 cm. The seasonal variation of the sea level in the Zhujiang Estuary presents bimodal pattern and the peak values occur in June and October respectively. The lowest sea level appears from January to February, and sea level annual range is 20–30 cm.

Figure 9 shows that the historical changes of monthly mean anomaly of sea level, sea surface temperature and air temperature. It indicates that the correlation coefficients between sea level anomaly and SST anomaly and between sea level anomaly and air temperature anomaly are both smaller than 0.2. However, the correlation coefficient between SST anomaly and air temperature anomaly is greater than 0.8. In September 2010, the sea level along the SCS coast was 5 cm lower than normal, being the lowest value since 1990. However, SST and air temperature are

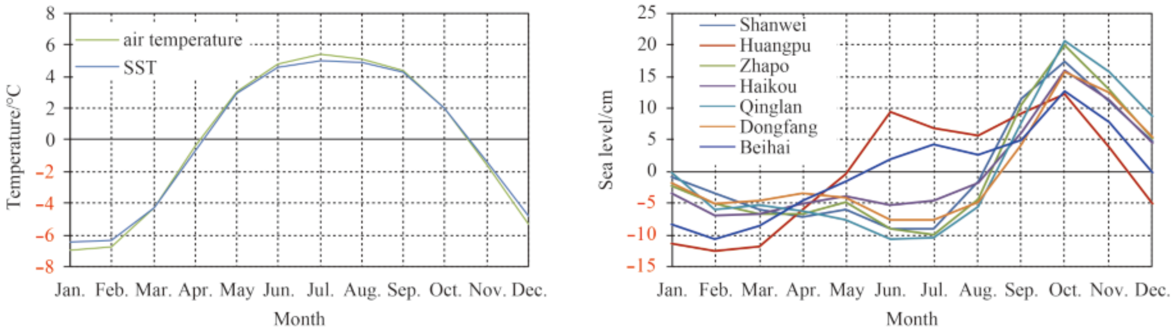

Fig. 8. Annual cycle of SST, air temperature and sea level along the SCS coast.

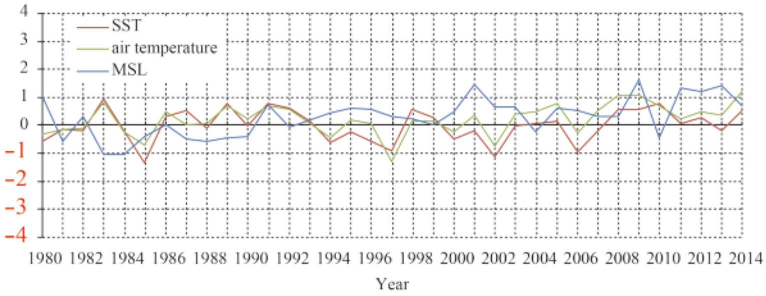

Fig. 9. Changes of MSL (dm), SST (°C) and air temperature (°C) along the SCS coast in September during 1980–2014.

0.77°C and 0.68°C higher than normal respectively. The sea level along the SCS coast in September 2014 fell 7 cm compared with that in 2013, while SST and air temperature increased by 0.7°C and 0.8°C, respectively. The results show that SSLA has no significant correlation with SST and air temperature.

5 Conclusions

Based on the analysis of sea level, air temperature, sea surface temperature (SST), air pressure and wind data during 1980–2014, the characteristics and possible causes of SSLA along the SCS coast are investigated. The main results are as follows:

(1) Sea level along the SCS coast takes on strong seasonal variation. The annual variation range is 15–30 cm, larger in the north and smaller in the south. From north to south, the phase of sea level changes from 135° to 166°, with a time difference of nearly 1 month.

(2) SSLA often occurs from January to February and from June to October. The highest frequency of sea level anomalies happens in August, showing an increasing trend in recent years. In addition, the occurring frequency of negative sea level anomaly accounts for 50% of the total abnormal number.

(3) The SSLA is closely related to ENSO events. The negative anomalies always occur during the El Niño events, while the positive anomalies occur during the La Niña (late El Niño) events. In addition, the seasonal sea level oscillation period of 4–7 a associated with ENSO reaches its strongest in winter, with the amplitude greater than 2 cm.

(4) Abnormal wind is an important factor to affect the SSLA along the SCS coast. Wind-driven SSH is basically consistent with the SSLA. Moreover, the influence of the tropical cyclone along the SCS coast concentrates in summer and autumn, contributing to the SSLA.

(5) The SSLA has no significant correlation with SST, air temperature and air pressure.

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