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E-mail: hyxbe@263.net

Causes of seasonal sea level anomalies in the coastal region of the East China Sea

WANG Hui[1], LIU Kexiu[1], QI Dongmei[1], GAO Zhigang[1*], FAN Wenjing[1], ZHANG Zengjian[1], WANG Guosong[1]

[1] National Marine Data and Information Service, State Oceanic Administration, Tianjin 300171, China

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Abstract

Based on the analysis of sea level, air temperature, sea surface temperature (SST), air pressure and wind data during 1980–2013, the causes of seasonal sea level anomalies in the coastal region of the East China Sea (ECS) are investigated. The research results show: (1) sea level along the coastal region of the ECS takes on strong seasonal variation. The annual range is 30–45 cm, larger in the north than in the south. From north to south, the phase of sea level changes from 140° to 231°, with a difference of nearly 3 months. (2) Monthly mean sea level (MSL) anomalies often occur from August to next February along the coast region of the ECS. The number of sea level anomalies is at most from January to February and from August to October, showing a growing trend in recent years. (3) Anomalous wind field is an important factor to affect the sea level variation in the coastal region of the ECS. Monthly MSL anomaly is closely related to wind field anomaly and air pressure field anomaly. Wind-driven current is essentially consistent with sea surface height. In August 2012, the sea surface heights at the coastal stations driven by wind field have contributed 50%–80% of MSL anomalies. (4) The annual variations for sea level, SST and air temperature along the coastal region of the ECS are mainly caused by solar radiation with a period of 12 months. But the correlation coefficients of sea level anomalies with SST anomalies and air temperature anomalies are all less than 0.1. (5) Seasonal sea level variations contain the long-term trends and all kinds of periodic changes. Sea level oscillations vary in different seasons in the coastal region of the ECS. In winter and spring, the oscillation of 4–7 a related to El Niño is stronger and its amplitude exceeds 2 cm. In summer and autumn, the oscillations of 2–3 a and quasi 9 a are most significant, and their amplitudes also exceed 2 cm. The height of sea level is lifted up when the different oscillations superposed. On the other hand, the height of sea level is fallen down.

Key words: sea level anomalies, ECS, wind, air pressure, SST, air temperature, oscillations

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1 Introduction

Ocean thermal expansion and glacier mass loss are very likely the dominant contributors to global mean sea level rise during the 20th century (IPCC, 2013). Regional sea level change and global average sea level change are significantly different. Regional sea level changes are affected not only by the global sea level change, but also by the oceanographic and meteorological elements as local sea surface temperature (SST), ocean current, wind, air temperature, atmospheric pressure and precipitation (State Oceanic Administration, 2011). The rise of local air temperature and SST and the drop of air pressure cause the sea level rise (State Oceanic Administration, 2012). In recent years, with the frequent occurrence of extreme weather and climate events, the number of seasonal sea level anomalies increased (Wang et al., 2012a). *2012 Chinese Sea Level Bulletin* reported that the coastal sea level of the East China Sea increased significantly in 2012 with the highest value in June and August since 1980. *2013 Chinese Sea Level Bulletin* reported that the coastal sea level of the ECS reached the highest value in May and October since 1980 (State Oceanic Administration, 2013).

Impacted by solar radiation, seasonal sea level is caused by variations in air pressure, winds, water temperature, salinity, currents or river discharge (Zervas, 2009). Concerning the monthly MSL in the coastal areas of China, the lowest value generally appears in winter and spring, while the highest value appears in summer. The highest seasonal sea level appears in July each year at the Bohai Sea and the Yellow Sea, gradually postponing to October at the South China Sea. Anomalously 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).

Since China offshore waters have a north–south strip with a long coastline of twists and turns, uneven distribution and seasonal variation of solar radiation make the climate of offshore areas different along the north–south direction. Affected by the weather systems of different latitudes, cold tide in winter, cyclone in spring, and tropical cyclone in summer and autumn are active, which increases the diversity of climate. Variation of the East Asian monsoon is an important factor influencing the sea level changes of China offshore and adjacent sea areas. Controlled by the East Asian monsoon, Chinese offshore wind is lar-

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*Corresponding author, E-mail: gzg_ocean@163.com

ger than that at the same latitude, and winter monsoon is stronger than summer monsoon. North by northwest monsoon prevails in the Bohai Sea, the Yellow Sea and the ECS in winter (from December to next February) with higher air pressure and lower sea level; south by southwest monsoon prevails in summer with lower air pressure and higher sea level (Cai, 2010).

Seasonal sea level variations contain the long-term trends and the low-frequency periodic changes, showing obvious inter-annual and inter-decadal variations (Yu, 2004). In Chinese coastal area, significant oscillation periods of annual sea level variation are quasi 2 a, 4–7 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 constituents near the coast of China, and the oscillation of 4–7 a is generally considered to be related with ENSO (Yu and Xu, 2003); the periodic oscillation of 11 a may be connected to the sunspot activity (Du et al., 1984); the oscillation of 19 a is caused by the tidal force of celestial bodies (Zheng, 1999). The sea level shows different oscillation periods in different decades. All kinds of periodic oscillation cross or overlay in different periods of time, producing the effect of uplifting or lowering sea level (Wang et al., 2012b, 2013b).

In this paper, we utilize the data of sea level, air temperature, SST, air pressure and wind during 1980–2013 to analyze the causes of seasonal sea level anomalies in the coastal region of the ECS.

2 Data

The data used in this paper includes the monthly sea level, SST, air temperature and air pressure during 1980–2013 from 11 coastal hydrological and meteorological observation stations evenly distributed along the coast of ECS (Fig. 1). All the data have been supplemented and revised (Wang et al., 2013a), based on the same zero reference. In this paper, we utilized the monthly sea level anomaly (MSLA) data, which is caiculated by eliminating multi-year monthly MSL from the MSL in the same month. In order to compare with each other, the MSL at all stations during 1975–1993 was chosen as multi-year monthly MSL. Air temperature, SST and air pressure data of these stations during the same period are also selected, and the data are corrected, and quality controlled. The wind field and air pressure field we used is America NCEP/NCAR monthly mean data of 1 000 hPa. (Note: All the elements in this paper use the average values during the years 1975–1993 as the multi-year average, and the monthly mean values of that period as the monthly multi-year average.)

3 Seasonal sea level variation along the coast of ECS

3.1 *Characteristics of sea level annual variation*

Chinese coastal sea level has significant seasonal variation and obvious regional characteristics. Annual range gradually decreases from north to south. It is the largest at the Bohai Sea and the Yellow Sea, larger at the ECS and smallest at the South China Sea. The time of seasonal high and low sea level gradually delays from north to south (Zuo et al., 1994).

Seasonal high sea level of the ECS coast generally appears in September and October when southward monsoon prevails and the southward surface coastal current is strong. The lowest sea level appears during February to April. Annual sea level variation range is 30–45 cm. Seasonal sea level variation has obvious regional characteristics in the coastal region of the ECS. Annual range is larger in the north than in the south. The time of occurrence of high and low values gradually delays from north to south (Fig. 2). The highest sea level generally appears in September and the lowest value occurs in January or February at the Changjiang River (Yangtze River) Estuary and in the coastal area of the Hangzhou Bay. Influenced by the runoff, the annual range of sea level at the coastal area of Wusong in the Changjiang River Estuary is up to 56 cm. Annual range at the north shore of the Hangzhou Bay is about 35–40 cm (Li et al., 1982). The sea level at the west coastal area of Taiwan Strait is lower in April and July, rapidly rising after July, reaching the highest value in October. The annual variation range is about 30 cm. From north to south, the phase of sea level changes from 140° to 231°, with a difference of nearly 3 months (Table 1, Fig. 1).

3.2 *Seasonal sea level anomalies*

In this section, the characteristics of the monthly MSL anomaly variation in the coastal region of the ECS are analyzed. The monthly MSL anomaly values larger than 10 cm or less than –10

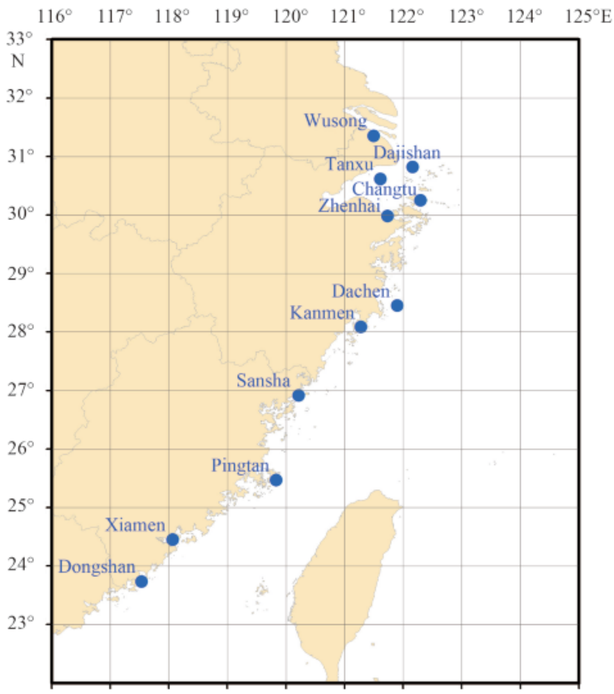

Fig. 1. Stations selected along the coastal region of the ECS.

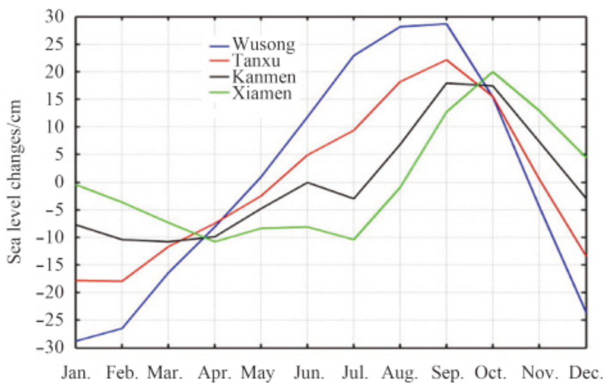

Fig. 2. Annual variations of MSL in the coastal region of the ECS.

Table 1. Annual and semi-annual harmonic constants of stations

Station	Annual		Semi-annual		The occurrence time of the highest and lowest sea level	
	Amplitude/cm	Phase/(°)	Amplitude/cm	Phase/(°)	The highest sea level (month)	The lowest sea level (month)
Wusong(WSO)	28	140	4	54	Sep.	Jan.
Dajishan(DJS)	18	157	4	16	Sep.	Feb.
Tanxu(TXU)	18	156	5	10	Sep.	Feb.
Changtu(CTU)	18	158	3	55	Sep.	Feb.
Zhenhai(ZHI)	17	163	4	22	Sep.	Feb.
Dachen(DCN)	14	179	4	38	Sep.	Feb.
Kanmen(KMN)	13	185	4	36	Sep.	Mar
Sansha(SSA)	13	189	5	75	Oct.	Mar
Pingtan(PTN)	12	210	5	86	Oct.	Apr.
Xiamen(XMN)	13	225	4	70	Oct.	Apr.
Dongshan(DSN)	14	231	4	72	Oct.	Apr.

Table 2. Monthly MSL anomaly statistics during 1980–2013 along the coast of ECS

Year	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1980	0	–5	0	0	0	–5	0	0	0	0	0	0
1981	0	0	0	0	0	0	0	0	0	0	0	0
1982	0	0	0	0	0	0	0	0	0	–2	–2	0
1983	0	0	0	0	0	0	0	0	0	0	0	0
1984	0	0	0	0	0	0	0	0	–5	0	0	0
1985	0	0	0	0	0	+3	0	0	–5	0	0	0
1986	–3	0	0	0	0	0	0	0	0	–3	0	0
1987	0	0	0	0	0	0	0	–5	0	0	0	0
1988	0	0	0	0	0	0	0	–2	0	0	0	0
1989	0	0	0	0	0	0	0	+5	0	0	0	0
1990	+3	0	0	0	0	0	0	0	0	0	0	0
1991	0	0	0	0	0	0	0	+3	+3	+3	0	0
1992	0	0	0	0	0	0	0	0	0	0	0	0
1993	0	–2	0	0	0	–2	0	0	0	0	0	0
1994	3	0	0	0	0	0	0	0	0	0	0	0
1995	0	0	0	0	0	0	0	–5	0	0	–5	0
1996	0	0	0	0	0	0	0	0	0	0	0	0
1997	0	0	0	0	0	0	0	0	0	–5	0	0
1998	+5	+5	0	0	0	0	0	–5	0	0	0	0
1999	0	0	+5	0	0	0	+5	0	0	+5	+5	0
2000	+5	0	0	0	0	0	0	0	0	0	+5	+5
2001	+5	+5	0	0	0	0	0	0	+5	0	0	0
2002	0	0	0	0	0	0	+5	0	+3	0	0	+5
2003	0	0	0	0	0	0	0	0	0	0	0	0
2004	0	–2	0	0	0	0	0	+3	+3	0	0	+3
2005	0	+3	–2	0	0	0	0	0	0	0	0	0
2006	+5	0	0	0	0	0	0	0	0	0	0	+3
2007	0	0	0	0	0	0	0	0	0	0	+3	0
2008	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	+3	0	0	0
2010	0	+5	0	0	0	0	0	–2	–2	+3	0	0
2011	+3	0	0	0	0	0	0	0	+3	0	0	+3
2012	+5	+5	0	0	+3	+5	0	+5	+3	0	0	+5
2013	0	0	0	0	+3	0	0	0	0	+3	0	0
Total number of sea level anomalies	**8**	**8**	2	0	2	4	2	**9**	**9**	**7**	5	6

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

cm are considered abnormal (Zervas, 2009). The statistical results are shown in Table 2.

Table 2 shows the statistics on the monthly MSL anomalies during 1980–2013 along the coastal region of the ECS. It is found that the monthly MSL anomalies occurred from August to the next February. The number of monthly MSL anomalies is at most from January to February and from August to October with a growing trend in recent years. Time from August to October is the outbreaking period of storm surge in the coastal region of the ECS. Typhoon landing time is more concentrated and water level fluctuation range is bigger, which has certain influence on coastal monthly MSL. Time from November to the next February is the period when winter wind prevails. The winter wind is strong in January. The northeast wind prevails in the coastal region of the ECS, with the average speed of 5–7 m/s. The wind speed is 9–10 m/s at the Taiwan Strait (Cai, 2010). Wind field anomaly results in the abnormal monthly MSL in the coastal region of the ECS. Their correlations will be discussed in later section.

Investigating on the monthly MSL anomaly variations along the coastal region of the ECS, we found that most of the monthly MSL anomalies are negative during 1980–1997 and positive during 1998–2013. Especially, the ECS coast experienced a period of high anomalies during 1999–2002 and 2011–2013, when the sea level is high in the history. Monthly MSL anomaly has also indicated that the sea level is in a rising trend along the coastal region of the ECS in recent 30 years.

3.3 *Linear MSL trends of typical months*

Table 2 indicates that in recent years, the number of monthly MSL anomalies highly increases along the coastal region of the ECS, and the levels become more severe. The monthly MSL of 10 long-term national observation stations are analyzed along the coastal region of the ECS during 1980–2013. In this paper, we select the January, February, August and September as the typical months (Fig. 3), and use the average values in 1975–1993 as the multi-year average, and the monthly mean values during that period as the monthly multi-year average.

In January, the rate of sea level change is 3.2 mm/a along the coastal region of the ECS during 1980–2013. Sea levels are the lowest in 1986, higher in 1998, 2000, 2001, 2006 and 2011, and the highest in 2000.

In February, the rate of sea level change is 3.0 mm/a along the coastal region of the ECS during 1980–2013. Sea levels are lower in 1980, 1993 and 2004 than those in the same term in the history. The lowest sea level is in 1980. Sea levels are higher in 1998, 2001, 2005, 2010 and 2012 than those in the same term in the history and the highest in 2012.

In August, the rate of sea level change is 1.7 mm/a along the coastal region of the ECS during 1980–2013. Sea levels are lower in 1987, 1995 and 1998 than those in the same term in the history and that is the lowest in 1995, 190 mm lower than the monthly multi-year average. Sea levels are higher in 1989, 1991, 2004 and 2012 than those in the same term in the history and that is the highest in 2012, 191 mm higher than t the monthly multi-year average.

In September, rate of sea level change is 3.5 mm/a along the coastal region of the ECS during 1980–2013. Sea levels are lower in 1984 and 1985 than those in the same term in the history. Sea levels are higher in 1991, 2001, 2004, 2009, 2011 and 2012 than those in the same term in the history and that is the highest in 2001, 206 mm higher than the monthly multi-year average.

4 Causes of seasonal sea level anomalies

Local abnormal climatic variations are the main causes of regional sea level anomalies. Abnormal changes of meteorological conditions (water temperature, salinity, winds, air pressure, currents, or river discharge) result in large positive or negative residuals in the coastal areas. Long-term positive or negative residuals are able to cause the monthly MSL high or low abnormally. This section discusses the causes of sea level anomaly through analysis of oceanographic and meteorological factors, such as air temperature, SST, air pressure and wind.

4.1 *Changes of wind field and air pressure field*

Based on the analysis on the anomalies of monthly MSL, mean wind field, air pressure field, wind-driven sea surface

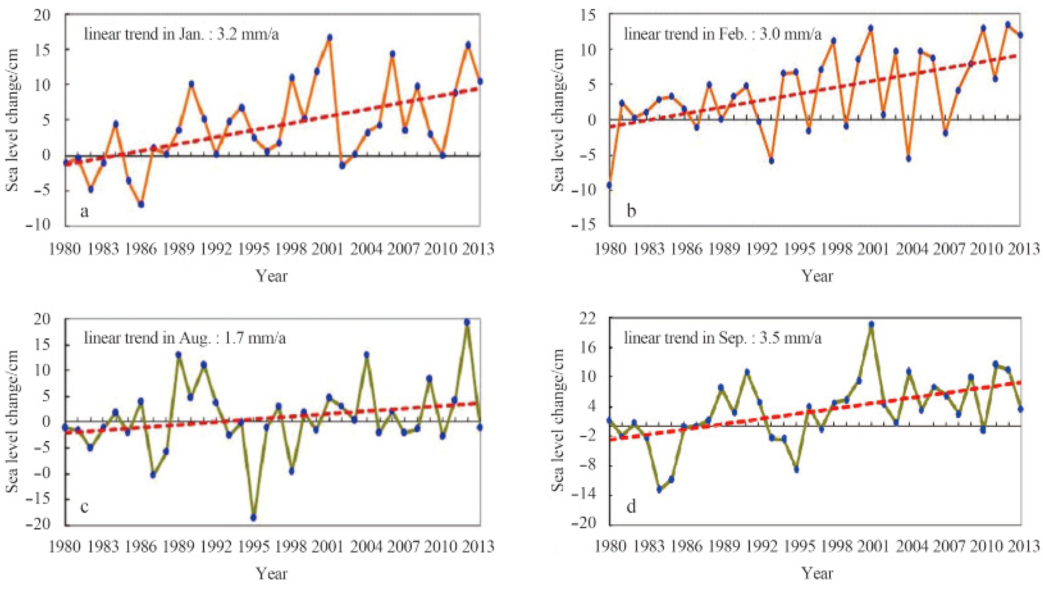

Fig. 3. Sea level changes of typical months along the coastal region of the ECS during 1980–2013 (The horizontal coordinate is the monthly multi-year average).

height (SSH) and wind-driven current, it is discovered that monthly MSL anomaly is closely related to wind field anomaly and air pressure field anomaly. Wind-driven current is in agreement with the change of height field of sea level.

The Northwest Pacific-China offshore ocean numerical model is established using ECOM (Esturine Coastal Ocean Model). The horizontal resolution of model calculation is 5'×5', and 10 sigma layers are divided vertically. The upper boundary of meteorology applies the mixing wind field of NCEP/QuickScat, obtaining wind-driven SSH and wind-driven current.

This section gives the analysis of the typical months with the most abnormally high sea level in recent years. The Section 3.3 shows that the sea level along the coastal region of the ECS in August 2012 was 191 mm higher than the monthly multi-year average, which was the highest in the same period in the history. Analysis results of the wind and the wind-driven current in Chinese offshore and adjacent waters in August 2012 are shown in Fig. 4. Figures 4a and b are wind anomaly and air pressure field anomaly at China offshore and adjacent waters in August 2012, respectively. The figures show that anomalous wind field sustains strong in this month, forming strong onshore wind in the coastal region of the ECS, which is conducive to the shoreward accumulation of sea water. Low sea surface air pressure anomaly forms in the coastal region of the ECS, and coastal air pressure is 0.7 hPa lower than the monthly multi-year average. Figure 4c is the wind-driven sea surface height (SSH) in August calculated by ECOM, which indicates that, along the coastal region of the ECS, SSH driven by wind increases gradually from south to north. The sea level rises 90–150 mm, contributing 50%–80% of the overall rising of sea level.

Figure 3 in the Section 3.3 shows that compared with the sea level in August 2012, the sea level falls 203 mm in August 2013, a maximum drop in the history. Results of analysis on the wind and the wind-driven current in China offshore and adjacent waters in August 2013 are shown in Fig. 5. Figures 5a and b show the wind anomaly and air pressure field anomaly of China offshore and adjacent waters in August 2013, respectively. The West Pacific subtropical high pressure is strong and northwestward, covering the ECS. The air pressure of the ECS coast is 0.1 hpa higher than the monthly multi-year average. The wind field anomaly is in the offshore direction in the ECS coast, causing the divergence of coastal seawater. The wind-driven sea surface height calculated by ECOM is shown in Fig. 5c. It indicates that, due to the consistent falling of coastal sea surface driven by wind from the southern Yellow Sea to the ECS coast, the sea level drops in 60–80 mm in the ECS coast.

In order to further verify the influence of wind anomaly on the coastal sea level variation, the observed sea levels of coastal stations in the ECS coast are compared with the sea surface height driven by wind. The comparison results are shown in Fig. 6. It is

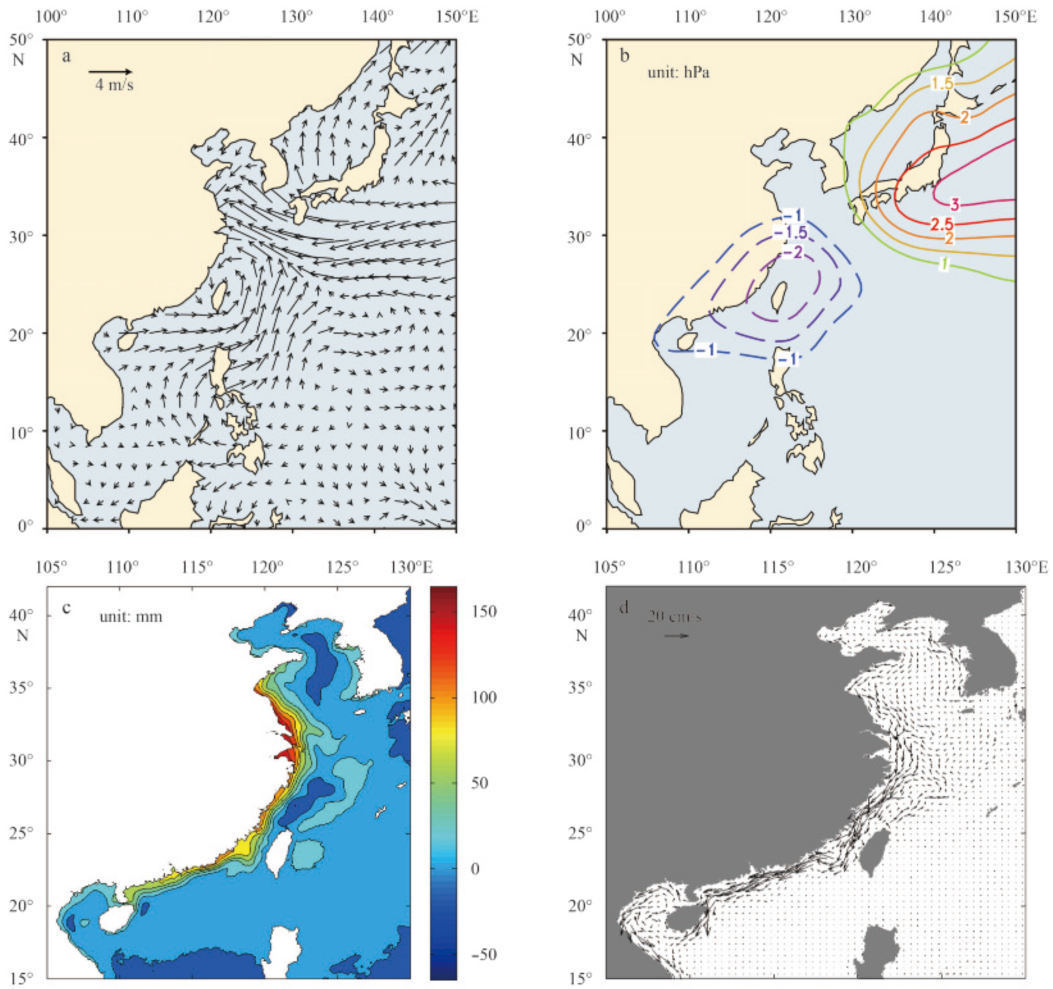

Fig. 4. Anomalies of wind, air pressure, wind-driven SSH and wind-driven current in China offshore in August 2012. a. Wind field anomaly, b. air pressure field anomaly, c. wind-driven SSH anomaly, and d. wind-driven current anomaly.

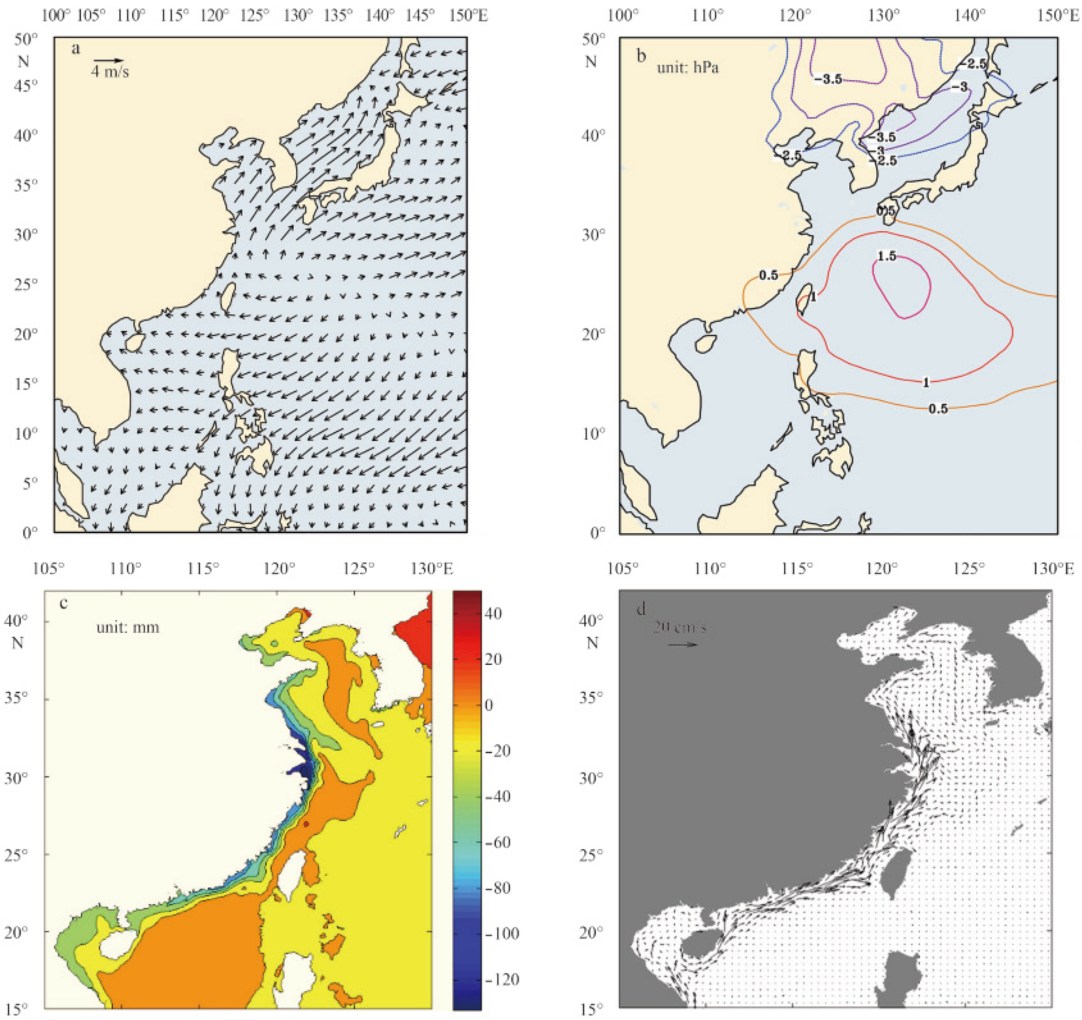

Fig. 5. Anomalies of wind, air pressure, wind-driven SSH and wind-driven current at China offshore in August 2013. a. Wind field anomaly, b. air pressure field anomaly, c. wind-driven SSH anomaly, and d. wind-driven current anomaly.

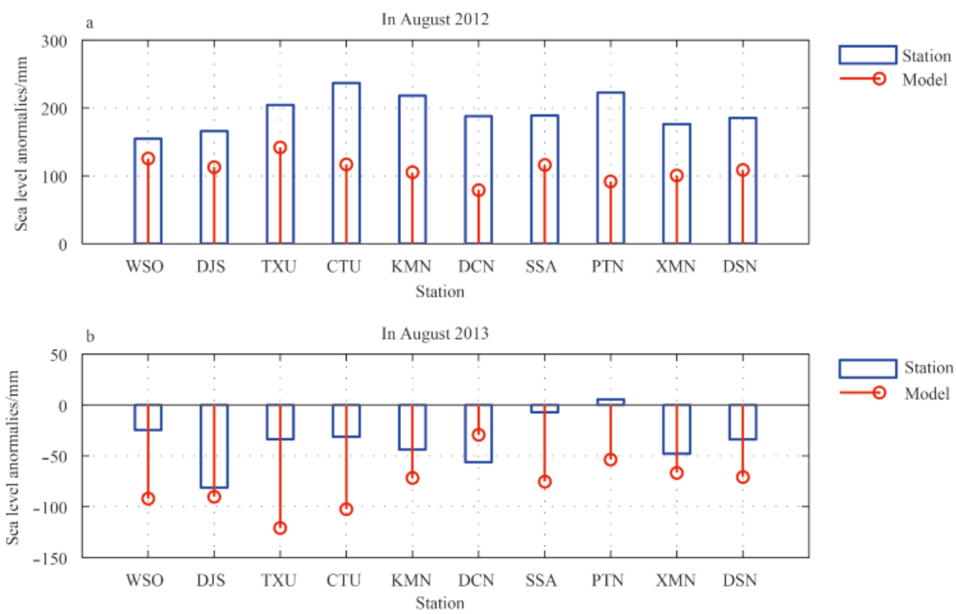

Fig. 6. Sea level anomaly test in the ECS coast in August 2012 (a) and in August 2013 (b).

found that in August 2012, the sea surface heights of the coastal stations driven by wind field have contributed 50%–80% of sea level, in agreement with the above conclusion. In August 2013, sea levels of the coastal stations are generally low, which is closely related to the divergence of sea water caused by offshore wind field.

4.2 *The relationship between sea level, SST, and air temperature*

The annual variations for sea level, SST and air temperature along the coastal reagion of the ECS are mainly caused by solar radiation with a period of 12 months. Figure 7 shows that the highest SST appears in August and the lowest SST appears in February, and the highest air temperature appears in August and the lowest air temperature appears in January. The correlation coefficient of SST and air temperature exceeds 0.9 (Fig. 7). However, the annual variation for sea level, due to the effect of the runoff and other factors, has a large difference (Fig. 1).

This section uses the average monthly anomaly to analyze the changes of sea level, SST and air temperature along the coastal region of the ECS in August during 1980–2013 (Fig. 8). It is shown in the Fig. 8 that, the correlation coefficients of sea level anomalies with SST anomalies and air temperature anomalies are all less than 0.1, and the correlation coefficient of SST anomalies and air temperature anomalies is more than 0.4. In 1989, 1991, 2004 and 2012, sea levels are higher than normal in the history, and sea level is highest in 2012. Except 2004, SST and air temperature is not high over the same period. In 1995, sea level along the coastal region of the ECS is the lowest in the same period in the history, but SST and air temperature are not obviously low. Seasonal abnormal high or low of sea level has little correlation with SST and air temperature.

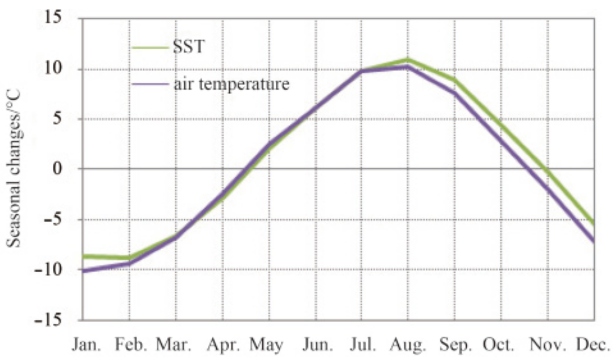

Fig. 7. Annual variations of SST and air temperature in the coastal region of the ECS.

4.3 *Inter-annual and inter-decadal variations*

Sea level variations contain the long-term trends and all kinds of periodic changes, with significant inter-annual and inter-decadal variation characteristics (Fig. 9). Monthly MSL anomalies are correlated not only with wind and air pressure, but also with a variety of periodic variations of marine climate. This paper uses the wavelet transform (Farge, 1992; Lau and Weng, 1995) to analyze seasonal sea level along the coastal region of the ECS in spring, summer, autumn and winter during 1980–2013 (Fig. 10). Figure 10 shows that the seasonal sea level variation has 4 significant oscillation periods: 2–3 a, 4–7 a, 9 a and 11 a. The period of 2–3 a is very common in the variation of the hydrological and atmospheric constituents near the coast of China and the period of 4–7 a is generally thought to be related with ENSO (Yu and Xu, 2003). The 11 a oscillation is possible associated with the action of macula (Fang et al., 1986). The sea level shows different oscillation periods in different decades, and sea level oscillations are different in different seasons along the coastal region of the ECS. The quasi-4 a periodic oscillation of sea level is dominant in spring, and the amplitude of sea level is more than 2 cm. The most significant period in summer is 2–3 a, and the amplitude of sea level is nearly 3 cm, followed by quasi-9 a oscillation with the amplitude of more than 2 cm. The oscillations of 2–3 a and quasi-9 a are most significantly in autumn, and the amplitudes of sea level are both more than 2 cm. The oscillations of 2–3 a and quasi-5 a are most significant in winter with the amplitudes both lager than 2 cm. Among them, the oscillation of 4–7 a related to El Niño is stronger in winter and spring and weaker in summer and autumn. When the different oscillations superposed, the height of sea level is lifted up, whereas it is fallen down. For example, in winter 2011, the vibration of sea level is in the overlap of 2–3 a, 4–5 a and 11 a cycles, and the sea level is significantly high.

5 Conclusions

Based on the sea level, air temperature, sea surface temperature (SST), air pressure and wind data along the coastal region of the ECS during 1980–2013, the causes of seasonal sea level anomaly in ECS are investigated.

(1) Seasonal high sea level in the coastal region of the ECS generally appears in September and October when the southward monsoon prevails and surface southward coastal current is strong. The lowest sea level appears in February to April. Annual sea-level variation range is mostly 30–45 cm. Seasonal sea level variation has obvious regional characteristics. Annual variation

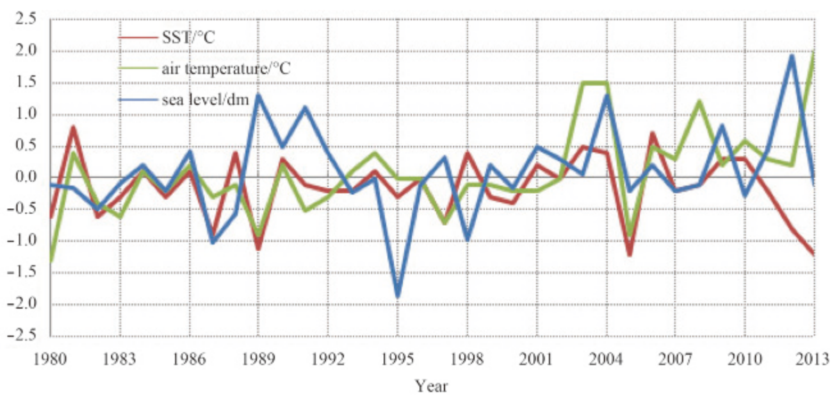

Fig. 8. Changes of MSL, SST and air temperature along the ECS coast in August during 1980–2013.

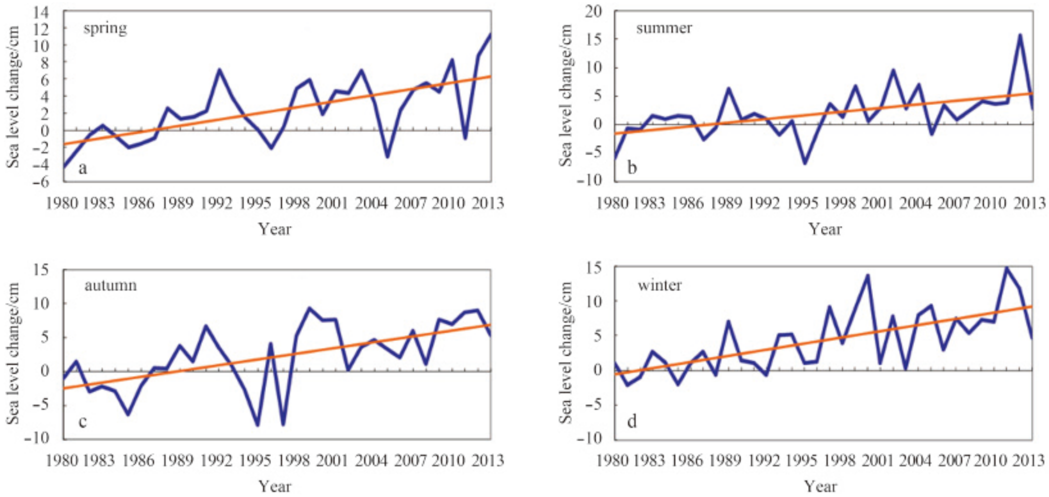

Fig. 9. Changes of seasonal sea level along the coastal region of the ECS during 1980–2013.

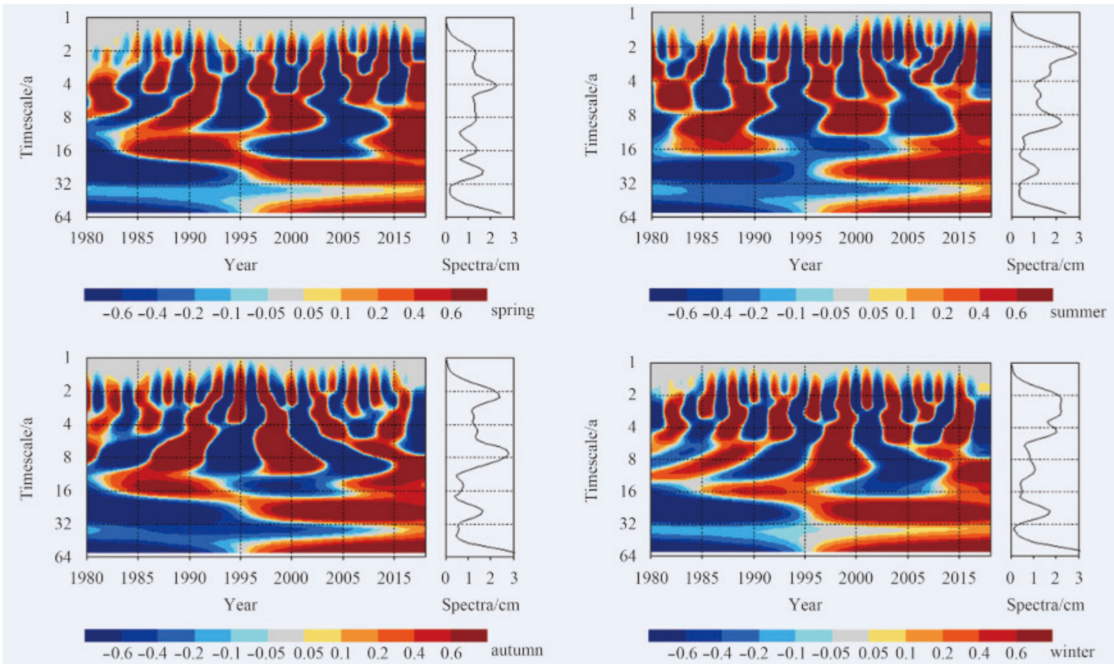

Fig. 10. Wavelet transform analysis on seasonal sea level along the coastal region of the ECS (All the left ones are the real part of wavelet spectrum (cm) and the right ones are wavelet spectrum (cm)).

range is large in north and small in south. The time of high and low values gradually delay from north to south.

(2) Monthly MSL anomaly occurs from August to next February in the coastal region of the ECS. The number of monthly MSL anomaly is mostly observed from January to February and from August to October, with a growing trend in recent years.

(3) Anomalous wind field is an important factor to affect the sea level variation of China offshore areas. Monthly MSL anomaly is closely related to wind field anomaly and air pressure field anomaly. Wind-driven current is essentially consistent to the variation of height field of sea level.

(4) The seasonal abnormal high or low sea level has little correlation with SST and air temperature.

(5) Seasonal sea level variations contain the long-term trends and all kinds of periodic changes. Sea level oscillations are different in different seasons in the coastal region of the ECS. In winter and spring, the oscillation of 4–7 a related to El Niño is stronger and its amplitude exceeds 2 cm. In summer and autumn, the oscillations of 2–3 a and quasi 9 a are most significant, and their amplitudes exceed 2 cm. When the different oscillations superposed, the height of sea level is lifted up, whereas it is fallen down.

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