Recent Sea Level Variations in Southern China from Tide Gauge Observations

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Proceedings of the Asia-Pacific Space Geodynamics Symposium,
Singapore, 6 - 8 July 2004, p.126-136

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Abstract

Recent tide gauge records covering time periods of 45 years or longer from twelve stations along the coasts of southern China (SC), eastern China (EC) and Macau-Hong Kong (Macau-HK) are used to study the recent sea level changes in the regions. Data sets of the Southern Oscillation Index (SOI) and the Sea Surface Temperature (SST) of the same time span are also used to study the possible links between the sea level changes and ENSO events. The results show that the rising trends for the Macau-HK, SC and EC regions are 2.2±0.2, 2.5±0.2 and 1.7±0.2 mm/yr, respectively over about the past half a century. Beside stable seasonal signals, unstable spectral signals of intra-seasonal to inter-decadal time scales are found from the wavelet spectra of the sea level data. The estimated phases of the annual and semi-annual sea level signals in SC and Macau-HK match each other well. They may be mainly influenced by the dominant westbound wind and oceanic currents in the tropical Pacific. It is also found that the inter-annual sea level variations in South China Sea are related to the ENSO events.

Key Words: Tide gauge – Sea level change – ENSO event

1. Introduction

The sea level varies over a wide spectrum of temporal and spatial scales. Recent global warming that is due mainly to greenhouse effect has contributed to a rise of the mean sea level of about 1.8 mm/yr [1, 2]. It has also been estimated that the sea level may in the future rise for 20-70 centimeters by year 2070[3]. Beside the long-term rising trend, there are variations in the sea level on various time scales. Tidal activities, atmospheric variations, temperature changes, sea surface winds, ocean circulation patterns as well as the interactions between the oceans and the atmosphere, such as the ENSO phenomena, all contribute to the movement and redistribution of sea water on the global and regional scales[4, 5].

As the sea level can vary very differently from one region to another, it is necessary to study sea level changes on regional basis to determine both the long-term trend and the various signals of shorter wavelengths and to understand the various geophysical processes associated with such changes.

In this study, we will use tide gauge data from twelve stations in China covering the past forty-five years or longer and some corresponding atmospheric and oceanic data sets to analyse the features in the recent sea level changes in southern China. The research will be mainly focused on the long-term tendency, and seasonal and inter-annual changes in the sea level. Possible links of the results with some local and global geophysical processes such as the ENSO events will also be established.

2. Tide Gauge Data

Distributions of Tide Gauge Stations

Data from twelve tide gauge stations along the coast of southeastern China are used for the study. Four of the stations are in Macau and Hong Kong (Macau-HK), five are in southern China (SC) and three are in eastern China (EC). The names, locations and time spans of the data series are summarized in Table 1. The data of North Point and Quarry Bay (NPQB) will be combined to form one data series as the locations of the two are very close to each other.

Table 1. Tide gauge records used

No	Station Name	Latitude	Longitude	Data Period (years)
1	North Point	22° 18' N	114° 12' E	1954-1985 (32)
2	Quarry Bay	22° 18' N	114° 13' E	1986-2003 (18)
3	Tai Po Kau	22° 27' N	114° 11' E	1963-2003 (41)
4	Macau	22° 12' N	113° 33' E	1925-2003 (79)
5	Bei Hai	21° 29' N	109° 05' E	1966-2003 (38)
6	Zha po	21° 35' N	111° 50' E	1959-2003 (45)
7	Shan Wei	22° 45' N	115° 21' E	1971-2003 (33)
8	Hai Kou	20° 01' N	110° 17' E	1976-2003 (28)
9	Dong Fang	19° 06' N	108° 37' E	1965-2003 (39)
10	Wu Song	31° 24' N	121° 30' E	1945-2003 (59)
11	Kan Men	30° 49' N	121° 38' E	1959-2003 (45)
12	Lu Si	32° 08' N	121° 37' E	1969-2003 (35)

The tide gauge records have been corrected for gauge zero offsets determined from leveling measurements. There are some offsets in Macau's data from January 1925 to December 1965 and in Dong Fang's data from August 1972 to December 1981. The offset values derived from least squares adjustments are -62.6 and 18.6 cm, respectively, and are used to correct the concerned data.

Station Settlements from Leveling Measurements

Land settlement at any tide gauge station can directly affect the readings from the station. It is a common practice to determine the amount of land settlement with periodic leveling measurements from a tide gauge station to some bench marks set on stable ground. The settlement measurements of some of the stations and the linear rates determined from the measurements are given in Figure 1.

It can be seen from Figure 1 that North Point and Quarry Bay stations in Hong Kong were settling at a rate of 4-5 mm/yr, while Tai Po Kou station were rising slightly. The settlement of Wu Song station in Shanghai shows a pattern of a quadratic function. The linear rate estimated for the last ten years (the heavy line in panel (4)) reaches –0.76±0.01 cm/yr.

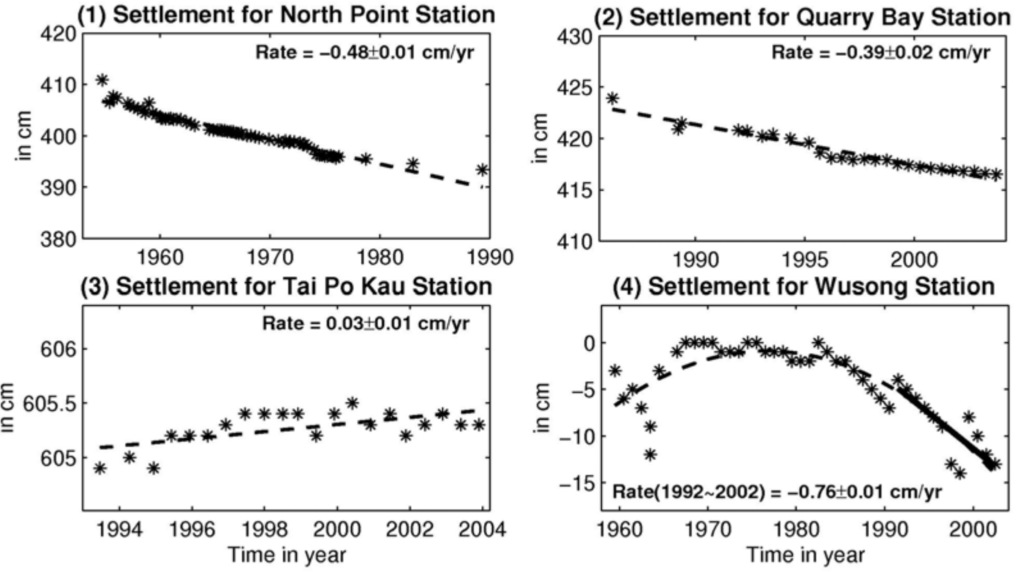

Figure 1. Settlement measurements of North Point, Quarry Bay, Tai Po Kou and Wu Song stations

Monthly Mean Sea Level

The monthly mean sea levels of the twelve tide gauge stations calculated from the hourly data are shown in Figures 2, 3 and 4 respectively for the three regions, Macau-HK, SC and EC. It can be seen from Figure 2 that very similar sea level variation patterns exist for the three stations in Macau-HK, especially during 1964-65, 1974-75, 1984-86, 1987-88, and 1995-2003. Similar situations can be seen in Figure 3.

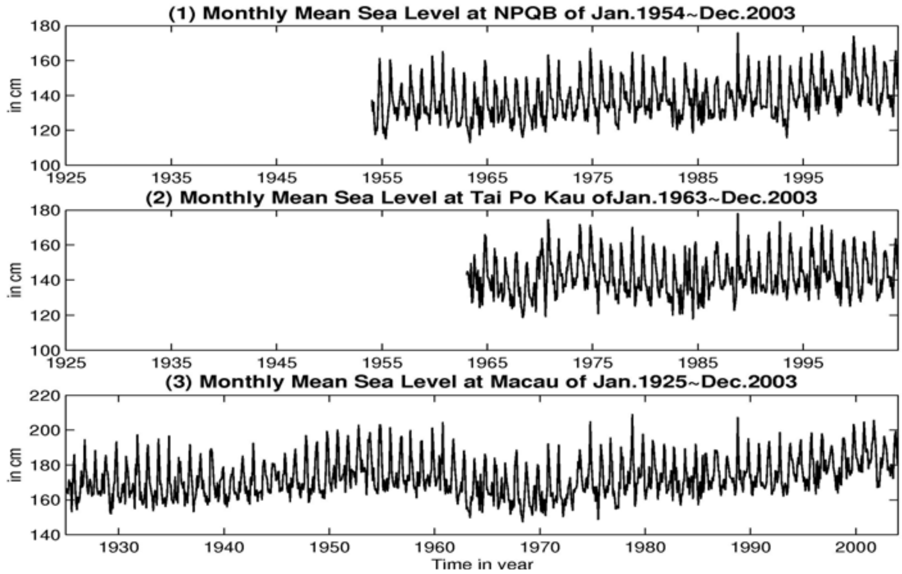

Figure 2. Monthly mean sea level in Macau-HK region

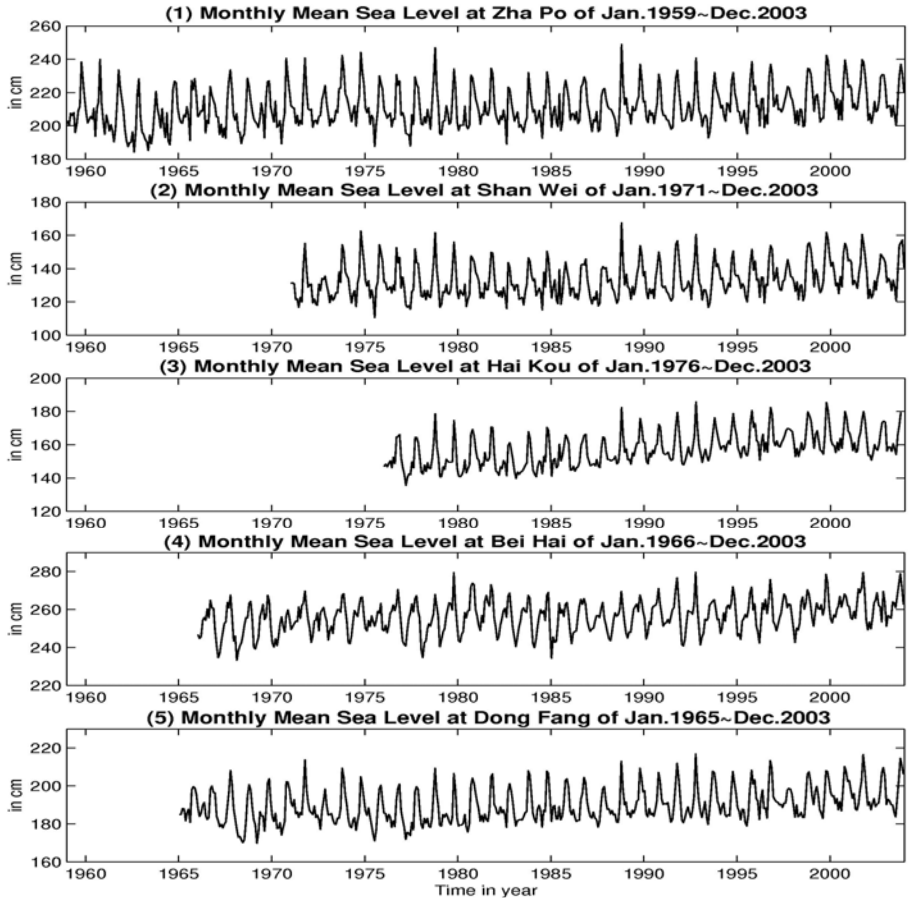

Figure 3. Monthly mean sea level in the SC region

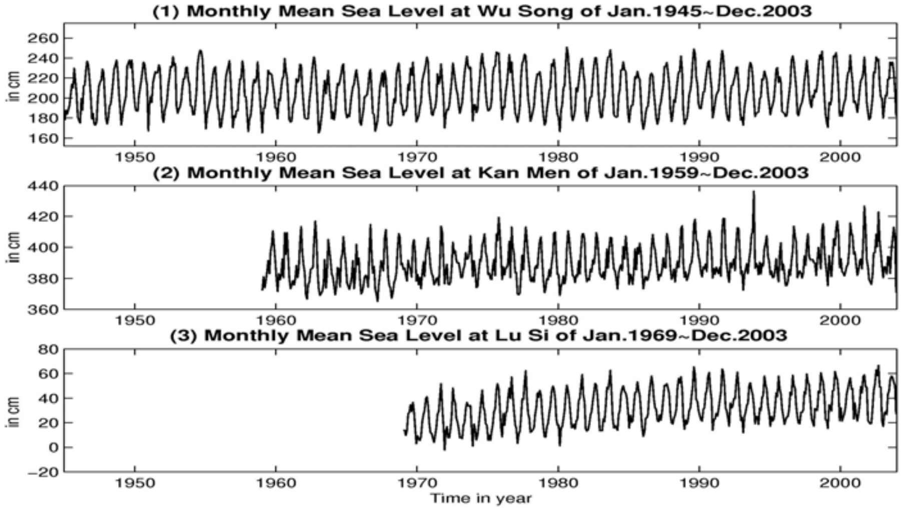

Figure 4. Monthly mean sea level in the EC region

It can be seen in Figure 4 that the similarity between the different stations in the EC region is not as good as those in the Macau-HK and SC regions.

The mean sea levels calculated for the three regions are shown in Figure 5. The mean sea levels are derived by taking the simple mean of the monthly values of the stations in each of the regions after removing the overall station mean sea level from each station.

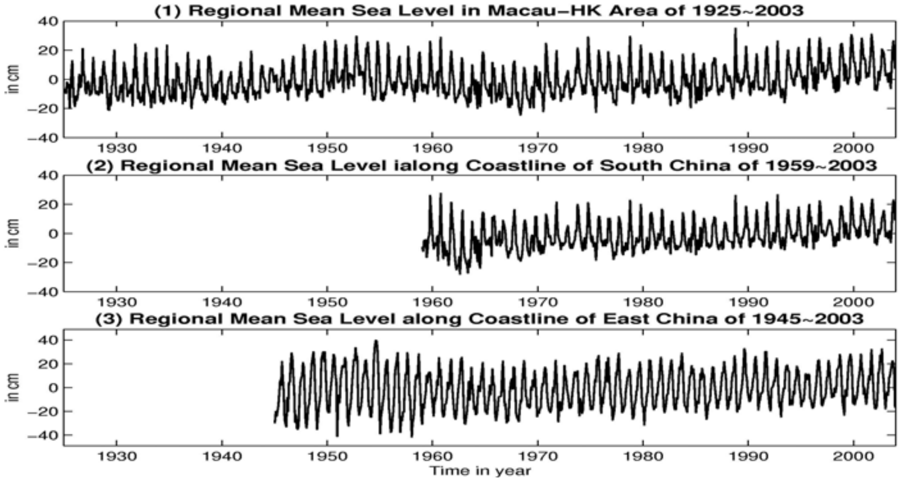

Figure 5. Regional monthly mean sea levels of Macau-Hong Kong (1), SC (2) and EC (3)

3. Frequency Features

Spectral Structure of Sea Level Change

The wavelet time-frequency spectra of the monthly regional mean sea levels are calculated to understand the frequency features of the oscillating signals[6, 7] (Figure 6).

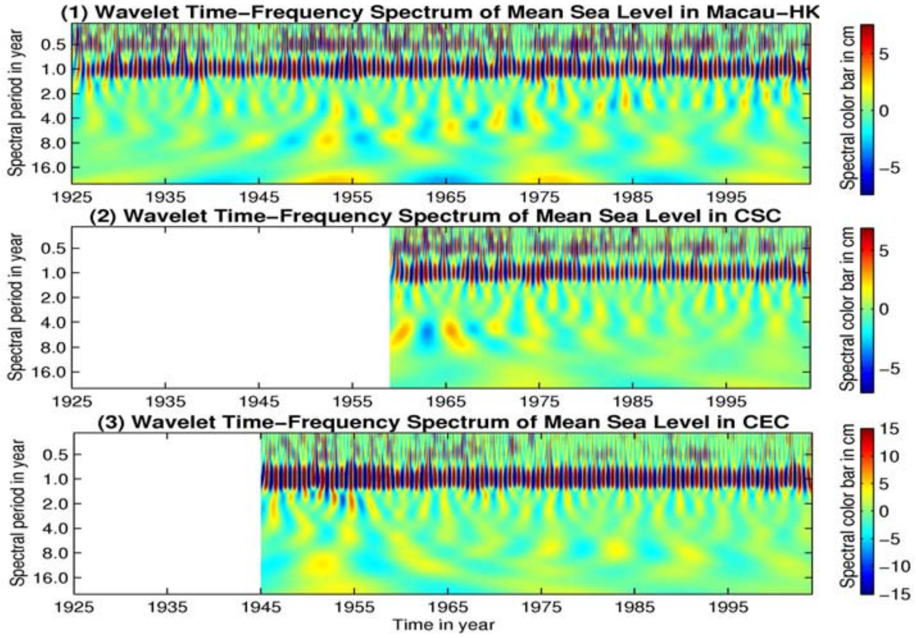

Figure 6. Wavelet time-frequency spectra of regional mean sea level changes

The wavelet spectra show that there are dominant stable annual and semi-annual signals in the sea levels for all the three regions. The annual signals in EC seem stronger than those in Macau-HK and SC. The situations for the semi-annual spectral signals are however opposite to those of the annual signals. There are also weak and unstable oscillating signals of the inter-annual to inter-decadal time scales. The patterns of the inter-annual spectral signals of Macau-HK and of SC are more consistent with each other, indicating common influences on the sea level changes in the two regions.

Signal Parameter Estimation

Weighted least squares adjustment of Householder Transform[8] is used to estimate the parameters of the oscillating signals detected by the wavelet spectral analysis. Since the periods of the inter-annual (including the quasi-biennial oscillations, namely QBO) and the inter-decadal signals are unstable (see Figure 6), the mean period values are determined by trial and errors in the process of least squares computations using the equation

$$SL_t = a + bt + \sum_{k=1}^{6} c_k \sin(2\pi t / P_k + \varphi_k) + \varepsilon_t \qquad (1)$$

The estimated parameters for the periods P_k, amplitudes c_k and phases φ_k of the spectral signals are listed in Table 2. For the mean sea level data in Macau-HK region, two different time spans, 1925-2003 and 1945-2003, are used respectively. The estimated phases given in Table 2 correspond to the start epochs of the sea level data.

Table 2. Estimated parameters of the spectral signals in the regional sea levels

Macau-HK Region					
Jan. 1925-Dec. 2003			**Jan. 1954-Dec. 2003**		
Per(yr)	**Amp(cm)**	**Pha(^{o})**	**Per(yr)**	**Amp(cm)**	**Pha(^{o})**
23.2	3.2±0.3	9.4± 5.4	21.0	3.3±0.4	45.8± 6.1
7.2	1.3±0.3	163.7±12.6	7.2	1.2±0.4	-160.7±17.0
4.3	0.8±0.3	-69.1±19.9	3.7	0.6±0.4	-134.8±32.6
2.0	0.6±0.3	30.6±27.7	1.9	0.7±0.4	-52.1±29.4
1.0	10.2±0.3	171.5± 1.6	1.0	10.3±0.4	170.3± 1.9
0.5	5.6±0.3	-97.8± 2.9	0.5	5.6±0.4	-96.9± 3.6
Rising rate: 1.25±0.10 mm/yr.			**Rising rate:** 2.18±0.18 mm/yr.		
South China			**East China**		
Jan. 1959-Dec. 2003			**Jan. 1945-Dec.2003**		
Per(yr)	**Amp**(cm)	**Pha**(^{o})	**Per**(yr)	**Amp**(cm)	**Pha**(^{o})
22.5	2.1±0.4	-155.6± 9.8	26.2	1.5±0.3	-21.9±13.0
7.2	1.0±0.3	74.2±20.8	7.8	1.7±0.3	120.4±11.6
3.7	0.6±0.3	-159.7±30.9	3.7	0.7±0.3	-39.9±26.5
2.1	0.7±0.3	-12.4±30.1	2.1	1.0±0.3	-115.4±19.5
1.0	10.2±0.3	166.5± 2.9	1.0	18.90±0.3	-125.3± 1.0
0.5	5.8±0.3	-103.4± 3.4	0.5	3.9±0.3	-53.6± 4.9
Rising rate: 2.46±0.22 mm/yr.			**Rising rate:** 1.67±0.16 mm/yr.		

It can be seen from the table that there are fluctuations of about twenty years with mean amplitudes of 1.5-3.0 cm. The mean periods for the seasonal and the three inter-annual (including QBO) signals are similar for the three regions. In particular, the amplitudes and phases of the annual and semi-annual signals in Macau-HK and SC regions are close to each other. It can be seen from the wavelet spectral analysis that the inter-annual signals are unstable so that the amplitudes of the real time variations of the signals should be larger than the estimated values presented in Table 2. The seasonal and inter-annual variations will be discussed further below.

4. Sea Level Rise and Seasonal Variations

Sea Level Rise

It can be seen from Table 2 that the estimated mean sea level rising rates are 1.2±0.1 and 2.2±0.2 mm/yr for Macau-HK region using the data of 1925-2003 and of 1954-2003, respectively. The latter estimation may be more reliable than the former as data from only one station (Macau) are available for the period 1925-1953. The estimated sea level rising rates for SC and EC are 2.5±0.2 and 1.7±0.2 mm/yr, respectively.

The annual mean sea levels for the three regions are then calculated to examine the rising rate changes. The results are shown in Figures 7, 8 and 9, respectively, for Macau-HK, SC and EC. The heavy horizontal lines shown are the decadal mean values from the data of 1984-1993 and of 1994-2003, respectively.

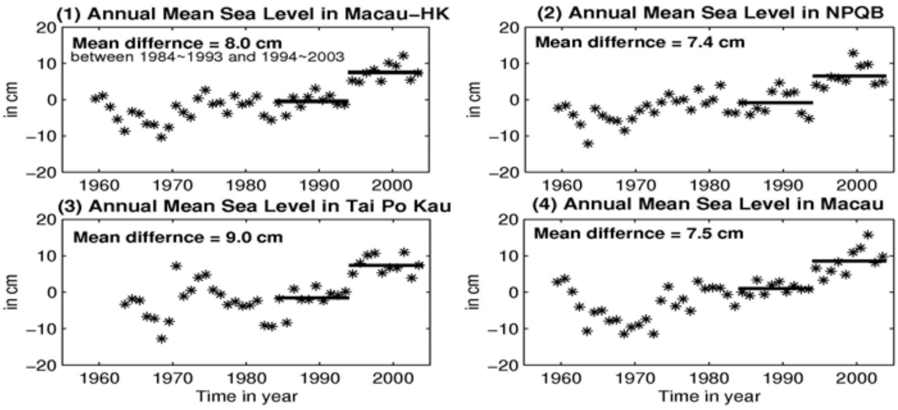

Figure 7. The annual mean sea levels of Macau-HK region, and of NPQB, TPK and Macau stations. The horizontal lines are the decadal mean values of 1984-1993 and 1994-2003

It is found from Figures 7 and 8 that there are significant differences, i.e., 8.0 cm and 5.1 cm respectively between the ten-year mean sea levels of 1984-1993 and 1994-2003 in Macau-HK and SC. This makes the rising trends very sharp in the last two decades. The estimated rising rates from data of the last twenty years are 6.6±0.6 mm/yr for Macau-HK and 4.8±0.5 mm/yr for SC. One possible explanation of the phenomenon is that the tide gauge records have been affected by some regional vertical ground movement. This is however yet to be proven. The phenomenon is however not obvious for EC (see Figures 9).

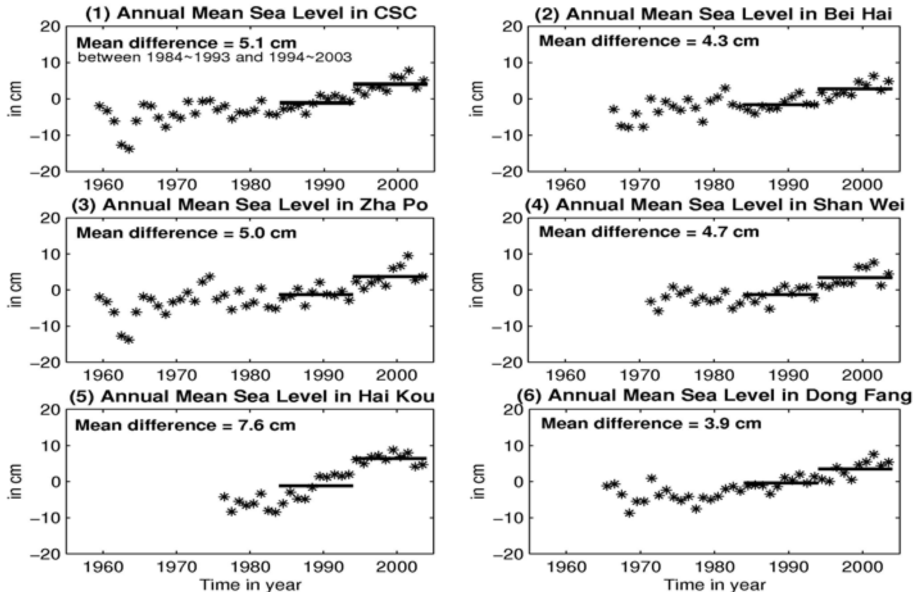

Figure 8. The annual mean sea levels of the SC region, and of Bei Hai, Zha Po, Shan Wei, Hai Kou and Dong Fang stations. The horizontal lines the decadal mean values of 1984-1993 and 1994-2003

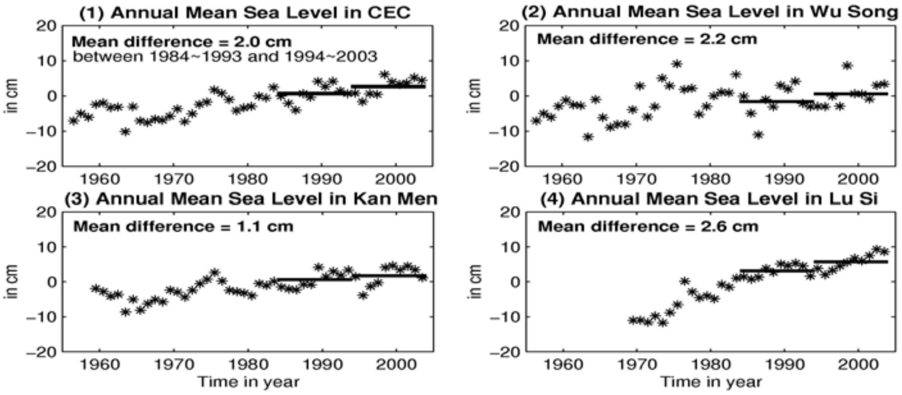

Figure 9. The annual mean sea levels of the EC region, and of Wu Song, Kan Men and Lu Si stations. The horizontal lines are the decadal mean values of 1984-1993 and 1994-2003

Seasonal Variations in Macau-HK and SC

We have seen from the estimated parameters of seasonal sea level variations in Table 2 that the annual and semiannual oscillating signals are stable and have the largest amplitudes in the regional mean sea levels. It is also interesting to note that the estimated amplitudes and phases of the seasonal signals of Macau-HK and SC are consistent to each other. The estimated phase values of both the annual and semi-annual signals of Macau-HK are several degrees earlier than those of SC.

To further examine the relationship between the annual and semi-annual variations of Macau-HK and SC regions, the phase variations over the common time period of 1959-2003 are calculated for the two regions, by carrying out one-year and three-year moving least squares solutions using the equation,

$$SL_t = a + bt + c_a \sin(2\pi t / 1yr + \varphi_a) + c_{sa} \sin(2\pi t / 0.5yr + \varphi_{sa}) + \varepsilon_t \tag{2}$$

where, c_a, c_{sa} and φ_a, φ_{sa} are the amplitudes and phases of the annual and semi-annual signals, and a and b are the constant and linear terms. The resolved phases for the annual and semi-annual signals are plotted in Figure 10. The solid and the dashed-dotted lines are results of Macau-HK and CSC, respectively.

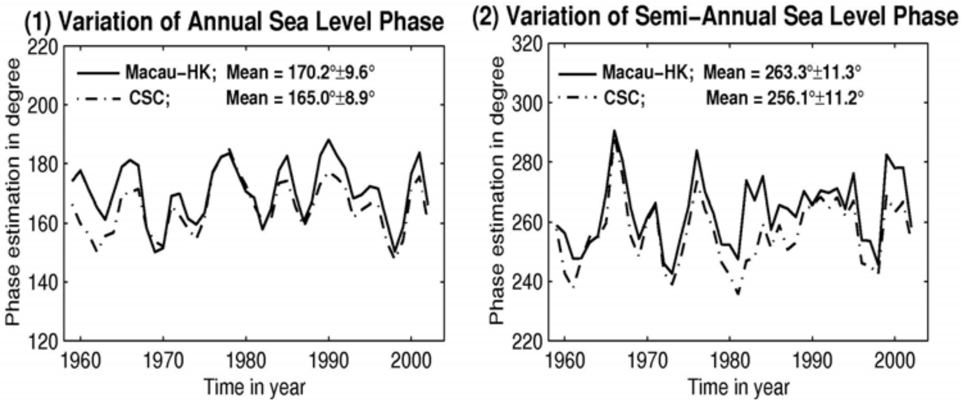

Figure 10. The variations of annual (1) and semi-annual (2) sea level phases for Macau-HK (solid line) and CSC (dashed-dotted line) regions.

It is seen from the results that the phase variations of both the annual and semiannual signals in Macau-HK region leads in general those in SC that is located on the western side of Macau-HK. The mean phase values led are 5.2^o (about 5 days) and 7.2^o (about 4 days) for the annual and semi-annual signals, respectively. The indicates that the strong and stable seasonal sea level changes in this region may be driven by westerly oceanic currents in the South China Sea, induced by the atmospheric circulation in the tropical Pacific and Asia[9, 10].

5. ENSO and Inter-annual Sea Level Variations in Macau-HK and SC

Inter-annual Sea Level Variations

ENSO events characterize the processes of interaction between the ocean and the atmosphere in the eastern and western tropical Pacific. The events occur typically over the inter-annual time scales, following the Southern Oscillation of atmospheric pressures in the southern tropical Pacific. Previous studies based on the tide gauge data at NPQB station have revealed the effect of seawater movements between the eastern and the western equatorial Pacific associated with ENSO events on the sea level at NPQB[11, 12]. Since the geographic positions of Macau-HK and of SC are in the areas of the lowest latitude in China Mainland and are also at the edge of the tropical western Pacific Ocean, the linkages between the inter-annual sea level variations and the ENSO events are examined.

Seasonal signals in the sea levels of the Macau-HK and SC regions are first estimated with Equation (2) after the fluctuations of seven years or longer have been removed with the Multi-Stage Filter[13] from the monthly sea level data shown in Figure 5. "Inter-annual" sea level variations with amplitudes up to about 7 cm are then obtained by calculating the seven-point moving average of the monthly residuals from the seasonal signal estimations. The results are shown in Figure 11 (1) and (2) for Macau-HK of 1950-2003 and for SC of 1959-2003. The monthly standardized values of the South Oscillation Index (SOI) of 1951-2003 and the anomalies of Sea Surface Temperature (SST) in the eastern equatorial Pacific (NINO3.4 area) of 1950-2003 presented by NOAA are also plotted in Figure 11 (3) and (4), respectively.

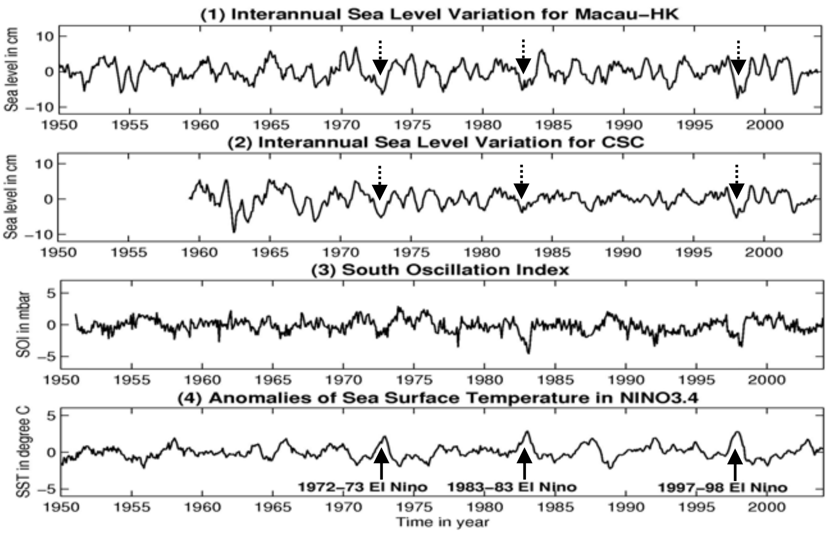

Figure 11. The inter-annual sea level variations in Macau-HK (1) and SC (2), the South Oscillation Index (3) and the anomalies of SST in NINO3.4 (4)

Comparing the sea level variations shown in Figure 11 (1) and (2) with the SOI and SST in (3) and (4) of the figure, the general relationships between the inter-annual sea level variations in Macau-HK and in SC with both the SOI and the SST are obvious. The three strong El Niño events in 1972-73, 1982-83 and 1997-98 over the last century are clearly associated with the lowering in the sea levels in the periods, decreases in the SOI, and rises in the temperatures of the sea water. On the other hand, when La Niña occurred following the El Niño events, there were apparent rises in the sea levels, increases in the SOI and cooling down of the sea water.

Correlation and Coherence of Inter-Annual Sea Levels with SST and SOI

To quantify the relationships between the occurrences of ENSO events and the inter-annual sea level variations in Macau-HK (of 1954-2003) and SC (of 1965-2003), the cross-correlation and complex coherence spectrum between the time series are calculated. The estimated values of the cross-correlations and the coherences are plotted in Figures 12 and 13, respectively, for Macau-HK and for SC. Panels (1) and (2) in the figures show the correlations of the sea level with SST and SOI, and panels (3) and (4) are the squared coherences.

It is seen from the results that the maximum negative correlations between the SST and the inter-annual sea level changes in Macau-HK and SC are all −0.38 and the phases of the SST lead those of the sea level by two months. The maximum positive correlations between the SOI and the sea level changes are all 0.34 and the phase of the SOI is three months earlier than those of the inter-annual sea level variations. The threshold value for significant correlation is ±0.26 at the 99% confidence level (the effects of moving averages on the confidence level have been considered) by using the Monte Carlo test[14]. The estimations of the squared coherence spectra of the inter-annual sea level changes in Hong Kong and SC, respectively, with the SOI and SST indicate that significant portions of the inter-annual frequency band from the squared coherency analysis exceed the 99 % threshold of 0.54, even the 95% threshold of 0.39[15].

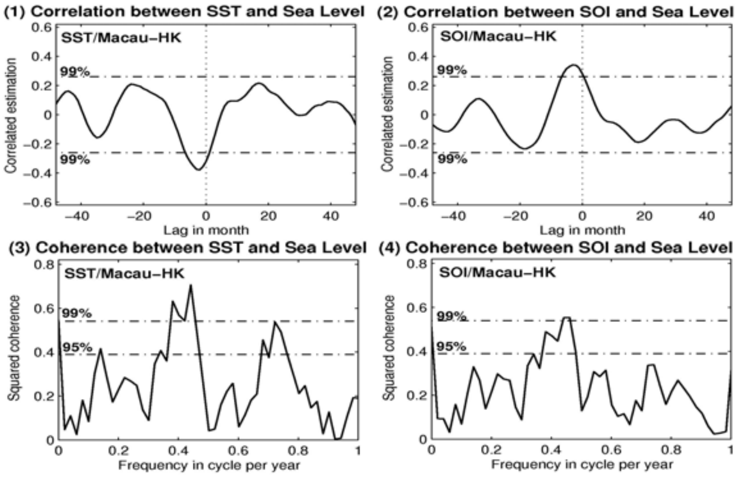

Figure 12. Estimated correlation and coherence between inter-annual sea level variations in Macau-HK and SST and SOI

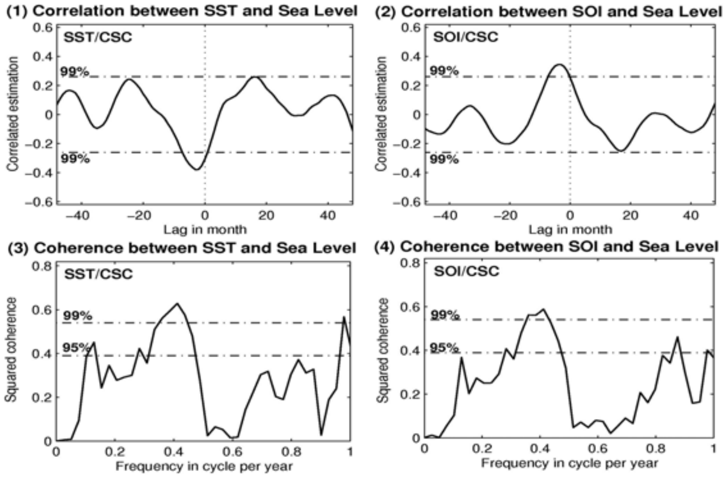

Figure 13. Estimated correlation and coherence between inter-annual sea level variations in SC and SST and SOI

The above results of cross-correlation in the time domain and squared coherence in the frequency domain indicate that the sea level changes in Macau-HK and in SC are significantly affected by the interaction between the ocean and the atmosphere in the tropical Pacific associated with El Niño and La Niña events. A general interpretation of the relationships is given here. When a high pressure state exists in the eastern tropical Pacific, the stronger westerly trade wind in the equatorial Pacific causes a westward flow of oceanic currents and a rise in the sea level, and the warming-up of the surface sea water in the western equatorial Pacific. On the other hand, when a low pressure state exists in the eastern tropical Pacific, the westerly trade wind decreases and the ocean water flows eastwards and resulting in a rise in the sea level and warming-up of the sea water in the eastern equatorial Pacific[5, 9, and 16]. It is shown from the results of this study that the interaction between the ocean and the atmosphere in the tropical Pacific also affects significantly sea level in the South China Sea, which is located in the edge areas of the western Pacific Ocean.

Similarly, the possible relationships between the inter-annual sea level signals in EC (of 1959-2003) and the SST and SOI are also examined. The estimated cross-correlations and squared coherences are shown in Figure 14. The maximum positive correlation between the SST and the inter-annual sea level in EC is 0.22 and exceeds the threshold value of 0.18 at the 95% confidence level. The phase of the SST leads that of the inter-annual sea level variations by six months. Significant portions of the estimated coherence exceed the threshold value of 0.39 at the 95% confidence level. However, the correlations between the inter-annual sea level in EC and the SOI are not statistically significant.

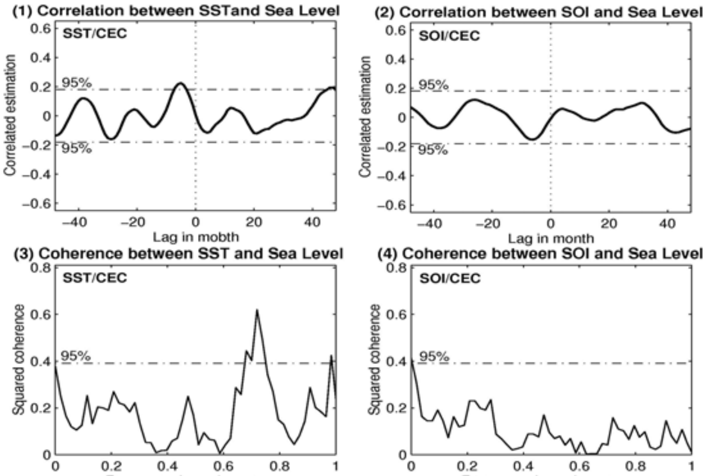

Figure 14. Estimated correlation and coherence between inter-annual sea level variations in EC and SST and SOI

6. Conclusion and Discussion

The following conclusions can be drawn based on the study:

(a) All the three regions studied show long-term rising tendencies in the sea level. The estimated rising rates are 2.2±0.2, 2.5±0.2 and 1.7±0.2 mm/yr respectively for Macau-HK, SC and EC regions in the past half a century. The estimated rising rate became 1.2±0.1 mm/yr for the Macau-HK region when using data of 1925-2003 from the Macau station.

(b) The tide gauge data show that the rising rates of sea level in both Macau-HK and SC have accelerated over the past ten years. The reason for this needs further study although the vertical ground motion is considered one of the possible causes.

(c) The wavelet spectra of the sea level data show strong and stable seasonal signals, and unstable oscillating signals on the intra-seasonal to inter-decadal time scales in all the three regions.

(d) Dominant seasonal sea level variations in the Macau-HK and SC regions may be mainly due to the westerly oceanic currents and surface winds in the South China Sea.

(e) The inter-annual sea level fluctuations of several centimeters in magnitudes in SC and Macau-HK are related to the interaction between the ocean and the atmosphere in the tropical Pacific, i.e., the El Niño and La Niña events.

Further research is necessary to better understand the sea level changes in Southern China, especially the effect of vertical ground movement on the sea level change determined based on tide gauge data.

Acknowledgments. The authors thank the National Marine Data and Information Service, China, the Hong Kong Observatory, the Port Authority of Macau, and the Navigation Route Bureau of Shanghai for supplying tide gauge data for the study. This research was supported by the Hong Kong Research Grants Council (Project No. PolyU5067/00E), the Hong Kong Polytechnic University (Project No. G.34.37.YY42), and the Natural Science Foundation of China and the Chinese Academy of Sciences (Projects 10133010, 10273018, and KJCX2-SW-T1).

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