Sea Level Change in Hong Kong from Tide Gauge Records

X.L. DING [1], D.W. ZHENG [1, 2], Y.Q. CHEN [1] and C. HUANG [2]

[1] Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China
Tel: (852)-2766 6701 or (852)-27665965, Fax: (852)-2330 2994
E-mail: lsxlding@polyu.edu.hk or lszheng@polyu.edu.hk

[2] Center for Astrogeodynamics Research, Shanghai Astronomical Observatory
Chinese Academy of Sciences, 80 Nandan Road, Shanghai 20030, China.

Abstract.

The results from the study indicate that there is a rising trend of 1.9±0.4 mm per year in the sea level of Hong Kong. The effect of local atmospheric pressure variations on the amplitude of the annual sea level change is about 30% of the amplitude. It is also found that the interannual variations in the sea level of Hong Kong are related to El Nino and La Nina events that occur frequently in the tropical Pacific. It is projected from an extrapolation of the current trends of seal level rise and ground subsidence that the possible maximum relative mean sea level change will be as high as 50 cm in the next half century when considering the various temporal variations.

1 Introduction

The sea level varies over a wide spectrum of spatial and temporal scales. Recent global warming that is due mainly to human-originated greenhouse effect has contributed to a rise of the mean sea level of about 1.8 mm/yr (Douglas, 1991 and 1996). It has also been estimated that the sea level may further rise 20-70 centimeters by the year 2070 (Warrick et al., 1996). Beside the long-term rising trend, there are variations in the sea level of varying time scales. Tidal activities, atmospheric pressure variations, sea surface winds, oceanic circulation patterns as well as the interactions between the ocean and the atmosphere, such as the ENSO phenomena, all contribute to the movement and redistribution of seawater on local and/or regional scales (Lambeck, 1980; Zheng and Chen, 1994). For various reasons, the sea level can vary very differently from one region to another. Therefore, it is necessary to study sea level changes on a local or regional basis to determine both the long-term trend and the various short wavelengths of signals, and to understand the various geophysical processes associated with such changes.

In this study, we will use data from two of the tide gauges and sea surface atmospheric pressures recorded in Hong Kong over the past forty five years (1954.0 - 1999.0), as well as data sets of the global sea surface atmospheric pressures, southern oscillation index (SOI) and sea surface temperatures (SST) in the eastern equatorial Pacific to analyze the basic features in the sea level changes in the region. Possible links of the results with some local and global geophysical processes will also be established. And the future sea level change in Hong Kong will also be assessed based on the analysis.

2 Tide gauge records and trend of sea level change in Hong Kong

The Hong Kong Observatory operates several tide gauge stations in Hong Kong. The North Point station has 32 years (1954,– 1986) of hourly data and has been the longest operational tide gauge station in Hong Kong. This station was subsequently moved to an adjacent location at Quarry Bay that has been in operation since the beginning of 1986. The tide gauges at both of the stations are the same stilling well type. Periodic calibrations, twice a year, as well as an analysis of the data using a variety of algorithms (Iz and Shum, 1998) indicate a stationary random RMS instrument reading error in the range of 1-2 cm.

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All the tide gauge records are referred to the Principal Datum (PD) of Hong Kong which is approximately 1.23 m below the mean sea level (SMO, 1995). The Civil Engineering Department (CED) of Hong Kong has been responsible for monitoring the settlement of the tide gauge stations since 1954. Leveling measurements are carried out from benchmarks built on bedrock to the tide gauge stations at varying time intervals (from once every a few years to a few times a year). The tide gauge data have been adjusted for the settlement by the Hong Kong Observatory.

Daily mean sea level data are obtained by simple averaging the hourly data of each full day and are shown in part (a) of Fig. 1. Monthly mean sea level data are similarly obtained and given in part (b) of Fig. 1. Two offset corrections, -14.89 cm for the pre-1957.0 data and –1.02 cm for the pre-1986.0 data, are applied to reduce the data to the same reference as that for the tide-gauge records of the Quarry Bay station (Ding et al., 2001). Signals of seasonal variations in the sea level are obvious from both the daily and the monthly tide gauge data. The settlements of the tide gauge stations in North Point and Quarry Bay since 1954 as determined from leveling measurements are plotted in Fig. 1 (c).

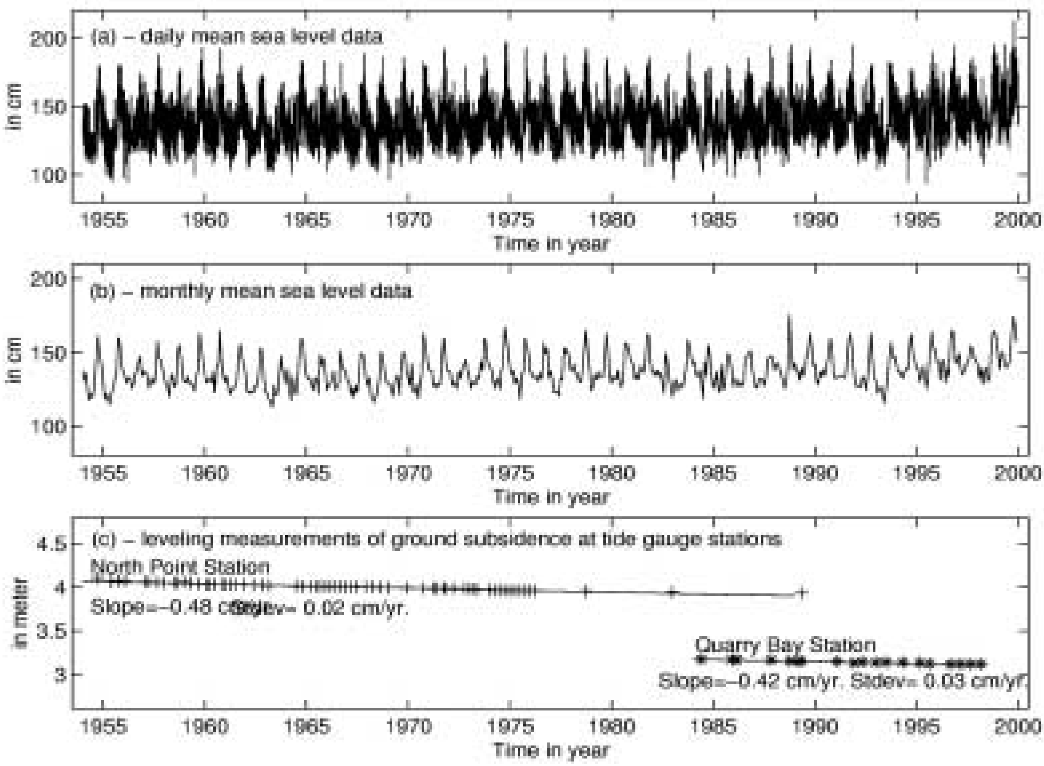

Figure 1. Tide gauge and ground subsidence measurements at North Point and Quarry Bay stations in Hong Kong during 1954.0-1999.0.

The monthly mean data of 1954.0 - 1999.0 shown in Fig.1 (b) will be used here to determine the trend in the variations of the sea level. The equation used for the computation is,

$$SL_t = a + bt + \sum_{k=1}^{3} c_k \sin(2\pi t / P_k + \varphi_k) + \varepsilon_t \qquad (1)$$

where P_k, c_k and φ_k are the periods, amplitudes and phases of the 18.6-year tidal, the annual and the semiannual terms, respectively; a and b are constant and the linear tendency coefficient. The estimated parameters from equation (1) by using the least squares method of Householder Transform (Feng et al., 1978) are given in Table 1. It can be seen from Table 1 that there is a rising trend of 1.9±0.4 mm/yr in the sea level of Hong Kong. This result is quite compatible with results obtained using tide gauge data averaged globally (Douglas, 1991; Warrick et al., 1996) and those along the coastal areas of China (Zheng et al., 1995; Ma et al., 1996; Chen, 1996). Besides, there are quite stable annual and semiannual periodic oscillations that have amplitudes of 10.8 cm and 5.4 cm respectively in the sea level changes.

Table 1. Estimated parameters in equation (1) from monthly mean sea level data of 1954.0-1999.0 in Hong Kong. The estimated phase values are referred to epoch of 1954.0.

Period	Amplitude	Phase
18.6-year	2.04 ± 0.39 cm	0.41 ± 0.64 yr
Annual	10.85 ± 0.38 cm	0.46 ± 0.01 yr
Semiannual	5.40 ± 0.38 cm	–0.14 ± 0.01 yr
Constant: 132.34 ± 1.60	Linear rate: 0.19 ± 0.04 cm/yr	

3 Effect of atmospheric pressure variations on seasonal sea level changes

Seasonal sea level changes are mainly caused by variations in regional and global meteorological conditions. Atmospheric pressure variations and the thermal effect are the two most important causes (Lambeck 1980; Chen 1999). The inverted barometer solution is an approximate technique to determine the oceanic response to fluctuations in atmospheric pressure (Dickman, 1985 and 1988). Sea surface height change influenced by atmospheric pressure variations is given by the traditional inverted barometer solution (Dickman, 1988),

$$DSL = -\Delta P / \rho g \tag{2}$$

where, ρ is the density of the seawater; g is the gravitational acceleration; ΔP is the imposed atmospheric pressure variation, $\Delta P = P - P_{mean}$; and P and P_{mean} are the local and global mean atmospheric pressures, respectively. When ρ and g are known, the sea surface change due to atmospheric pressure variations can be determined with equation (2). Sea level change induced by atmospheric pressure variations can also be determined using

$$SL_t = a + bt + \sum_{k=1}^{3} c_k \sin(2\pi t / P_k + \varphi_k) + C_p \Delta P + \varepsilon_t \tag{3}$$

where C_p is a coefficient that can be estimated in a least squares solution. C_p is usually close to $1/\rho g$.

In this study, the global monthly mean atmospheric pressure P_{mean} is calculated based on the global sea surface atmospheric pressure data of 1958.0 - 1999.0 as reanalyzed by NCEP/NCAR of NOAA (Kalnay et al., 1996). The data are plotted as a thick line in Fig. 2(a). The monthly mean local atmospheric pressures P in Hong Kong over the same time span are also given in Fig. 2(a) as a thin line. The monthly mean pressure variations ΔP in Hong Kong are shown in Fig. 2(b). The monthly mean sea level, after the constant and linear trend given in Table 1 is removed, is plotted in Fig. 2(c).

From pressure variations ΔP and sea level changes in Fig. 2(b) and 2(c), it can be seen that their phases are in general opposite. The cross-correlation between the pressure variations and the sea level changes is estimated and the results are shown in Fig. 2(d). The results show that there is a stable annual oscillation in the correlation curve, and that the phase of the pressure variations is about three months earlier than that of the sea level changes.

Using atmospheric pressure variations ΔP shown in Fig. 2(b) and the sea level changes shown in Fig. 1(b), the parameters in equation (3) are estimated by using the least squares method of Householder Transform and the results are given in Table 2. The results that are calculated without the pressure corrections are also listed in the table for comparison.

The estimated value of C_p (= 0.95) is very close to the theoretical value (= 0.99) when the density of the seawater ρ and the gravitational acceleration g are taken as 1027 kg/m^3 and 9.806 m/s^2, respectively. Table 2 also shows that the local atmospheric pressure variations mainly influence the annual sea level variations and the amplitude of the annual variations decreases by 30% of that of the corrected sea level. The effects of atmospheric pressure variations on the 18.6-year and the semiannual terms are less than 0.5 cm. It should be noted however that when the inverted barometer correction is applied, the estimated constant term is about 3 cm larger and the linear rate of change is also slightly higher.

Table 2. Parameters estimated using monthly mean sea level of 1958.0-1999.0, with and without inverted barometer (IB) correction. The phases are referred to January 1958.

	Solution with IB correction				Solution without IB correction	
	from observations		from theoretical value			
Period	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
18.6-year	2.07±0.40cm	4.20±0.58yr	2.07±0.39cm	4.20±0.85yr	1.94±0.40cm	4.26±0.63 yr
Annual	15.22±1.23cm	0.38±0.01yr	15.50±0.39cm	0.38±0.01yr	10.72±0.40cm	0.46±0.01yr
Semiannual	5.95±0.40cm	–0.15±0.01yr	5.97±0.39cm	-0.15±0.01yr	5.51±0.40cm	–0.14±0.01yr
Constant: 135.51±0.80 cm Rate: 0.22±0.02cm/yr C_p: –0.95±0.20			Constant: 135.64±0.57 cm Rate: 0.22±0.02cm/yr C_p: –0.99		Constant: 132.84±0.58 cm Rate: 0.20±0.02 cm/yr	

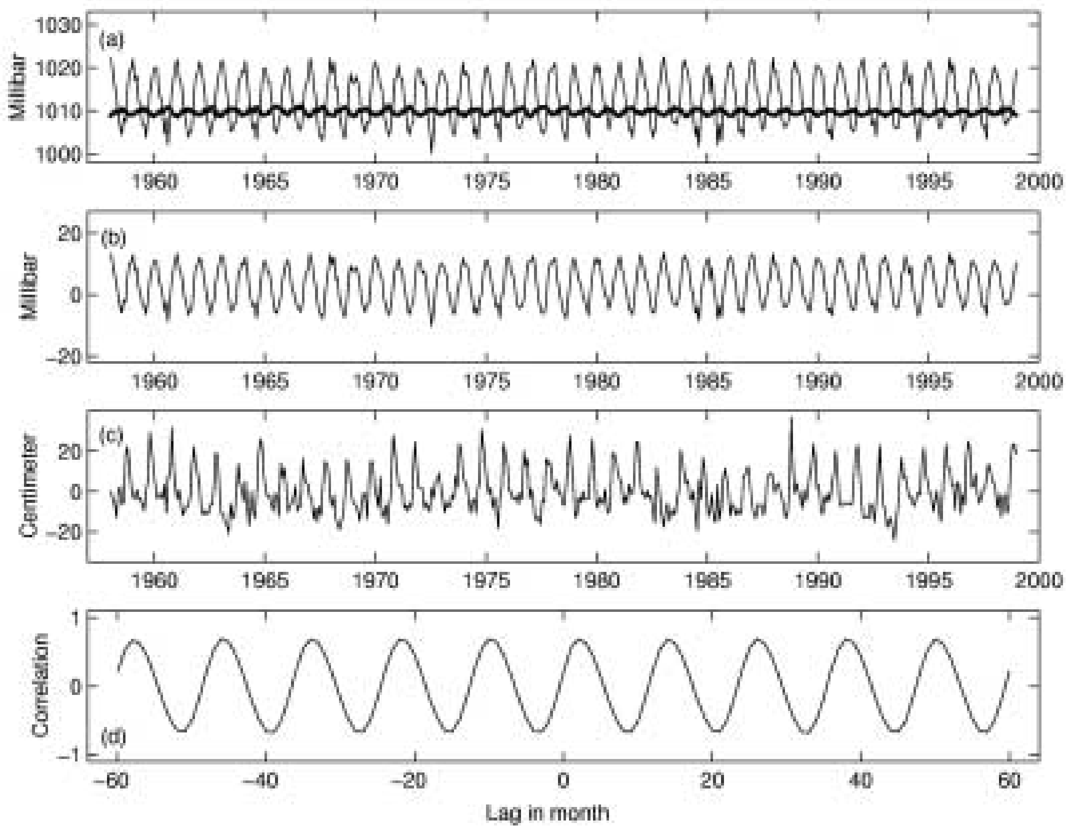

Figure 2. Relationship between HK sea level and atmospheric pressure. (a) Mean atmospheric pressures: Global (thick) and local monthly (thin) during 1958.0-1999.0; (b) Difference between Hong Kong and global mean atmospheric pressures; (c) Monthly mean sea level after the linear trend and the offsets are removed; and (d) Cross-correlation between atmospheric pressure variations and the monthly mean sea level

4 Relationship of Hong Kong sea level with ENSO

The residuals of the monthly mean sea level calculated from equation (1) are shown in Fig. 3(a). Beside the high frequency variations, the residuals also show some longer-term fluctuations that are down to the annual time scales. The filtered residuals by taking a seven-point moving average of the monthly residuals are shown in Fig. 3(b). The results show some obvious interannual fluctuations of several centimeters. Since Hong Kong is located at the edge of the tropical Pacific Ocean, the relationship between the interannual sea level changes and the El Nino Southern Oscillations (ENSO) are studied.

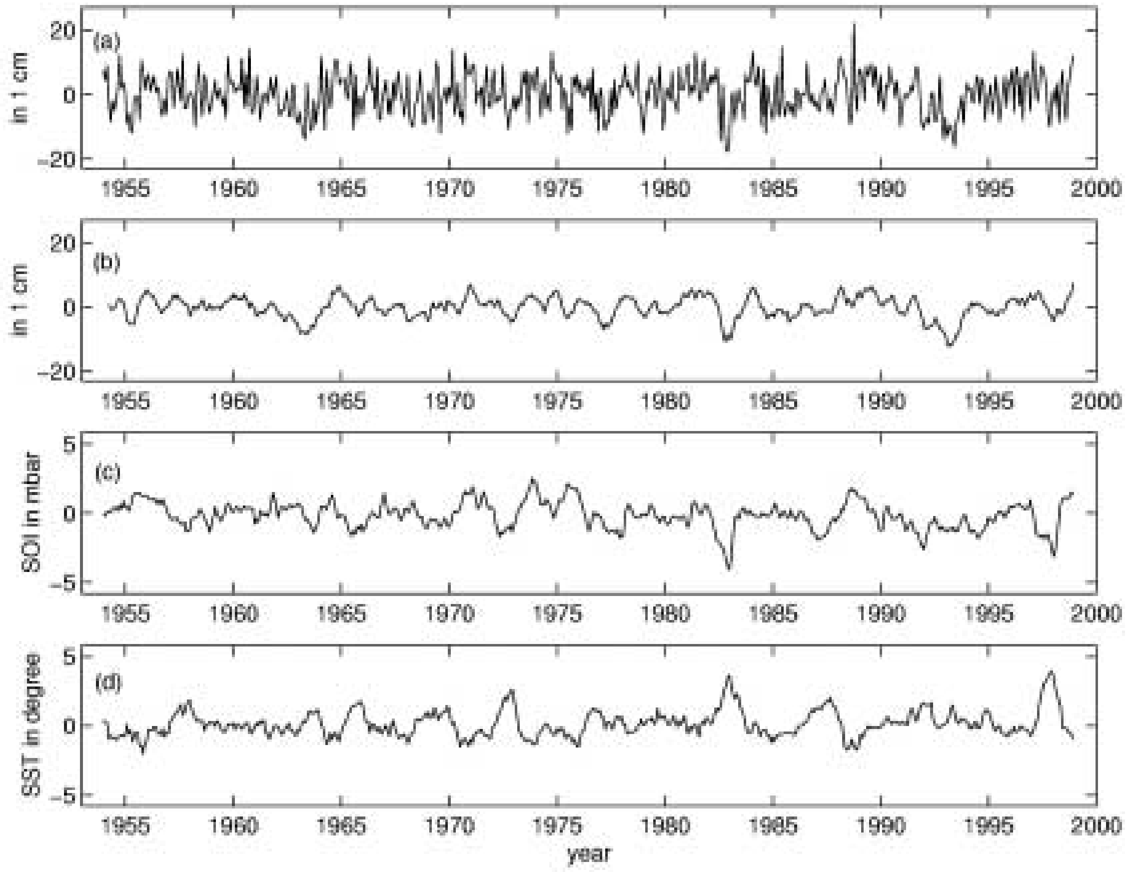

Figure 3. Interannual variations in the sea level of Hong Kong. (a) Residuals of monthly mean sea level from equation (2); (b) Residuals filtered by seven-point moving average; (c) Southern Oscillation Index (SOI); and (d) Departures of sea surface temperature (SST) in the eastern Tropical Pacific.

ENSO are processes of interaction between the ocean and the atmosphere in the eastern and western tropical Pacific. They occur typically over interannual time scales. Studies have shown that the seawater moves east-westerly in the Pacific in association with ENSO (Dickman, 1988; Rasmusson ey al., 1983; Wyrtki, 1985). The Southern Oscillation Index(SOI), which is the sea surface pressure difference between Tahiti and Darwin, is a useful data set to characterize ENSO. The standardized monthly values of SOI of 1954.0 - 1999.0 provided by NOAA are plotted in Fig. 3(c). The departures of sea surface temperature (SST) in the eastern equatorial Pacific is another index to gauge ENSO and the SST data of the same period are given in Fig. 3(d).

The general relationship between the interannual sea level variations in Hong Kong and ENSO can be easily seen by comparing the sea level variations shown in (a) and (b) of Fig. 3 with the SOI and SST shown in (c) and (d) of the same figure. For example, the three strong El Nino events in 1972-73, 1982-83 and 1997-98 are clearly associated with the lowering in the sea level during each of the periods, and the drop in SOI as well as rises in the SST. On the other hand, when La Nina occurred following each of the El Nino events, there were apparent rises in the sea level, rises in the SOI and drops in the SST.

To quantify the relationship between the interannual sea level variations and ENSO, cross-correlation and complex coherence spectrum between the different time series are computed. The cross-correlation function $\rho(\tau)$ and the squared coherence spectrum $\gamma^2(f)$ between the two time series are estimated with (Jenkins and Watts, 1968)

$$\rho(\tau) = \frac{\sigma_{12}(\tau)}{\sqrt{\sigma_{11}\sigma_{22}}} \tag{4}$$

$$\gamma^2(f) = |R(f)|^2 \quad R(f) = S_{12}(f) / \sqrt{S_{11}(f) S_{22}(f)} \tag{5}$$

where $\sigma_{12}(\tau)$ is the cross-covariance function of phase lag τ; σ_{11} and σ_{22} are the variances of the two time series, respectively; f is the frequency; $S_{12}(f)$ is the cross-power spectrum between the two time series; $S_{11}(f)$ and $S_{22}(f)$ are the auto-power spectra of the two time series, respectively. In this study, the multi-window spectral technique (Thomason, 1982) are introduced when the power spectrum is calculated with Fourier transform.

We will first analyze in the time domain the correlation between the interannual sea level changes and SOI and SST, respectively. The estimated cross-correlations are plotted in (a) and (c) of Fig. 4. It is shown in (a) that the maximum positive correlation is 0.43 and the phase of the SOI is two months earlier than that of the interannual sea level variations. On the other hand, (c) indicates that the maximum negative correlation is −0.37 and the phase of the SST is about one month earlier than that of the interannual sea level variations. The threshold value for correlation test is ±0.18 at 95% confidence level by using the Monte Carlo test Zhou and Zheng, 1999). It is shown from the results that the southern oscillation may be one of the main excitation sources for the interannual sea level variations in Hong Kong. The corresponding coherence spectra are given in (b) and (d) of Fig. 4. The results show that significant portions of the interannual frequency band exceed the 95% threshold value of 0.39 (Chao, 1988). This confirms the results of analysis in the time domain.

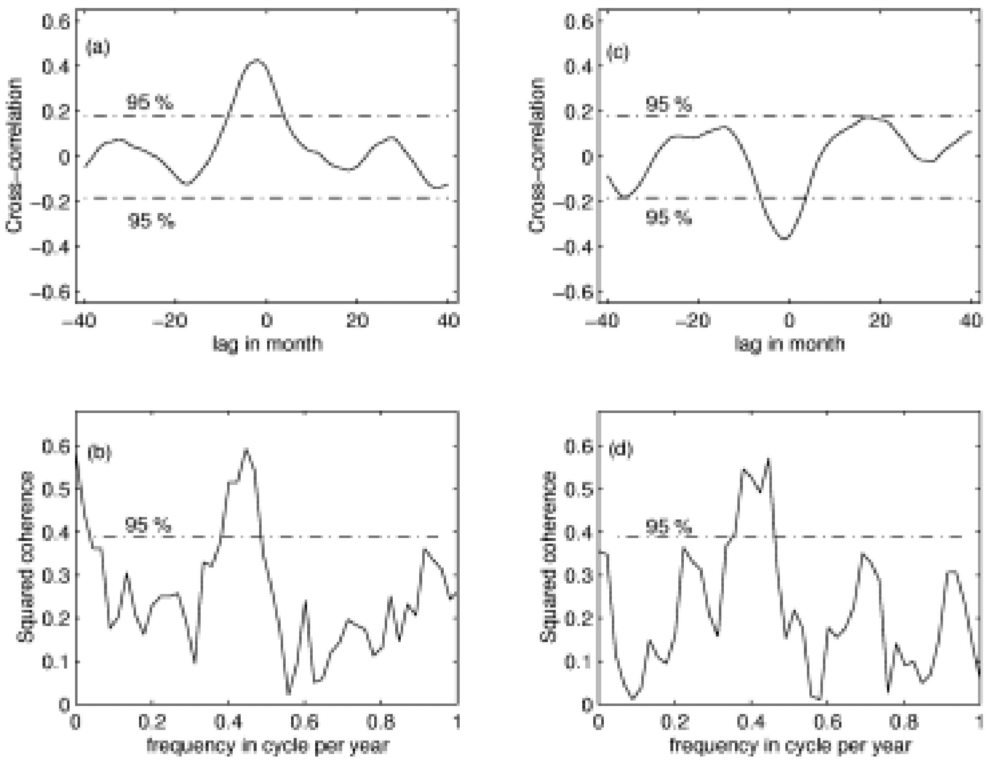

Figure 4. Estimated cross-correlation, (a) and (c), and squared coherence, (b) and (d), between the interannual sea level variations in Hong Kong and the Southern Oscillation Index (SOI) as well as the sea surface temperature (SST).

A general interpretation of the relationship between the interannual sea level variations in Hong Kong and ENSO is given here only. When a high-pressure state exists in the eastern tropical

Pacific, it produces stronger westerly sea surface trade wind in the equatorial Pacific and causes a westward oceanic flow. This leads to higher sea level and warmer surface seawater in the western equatorial Pacific. This process corresponds to a La Nina event. On the other hand, when a low-pressure state exists in the eastern tropical Pacific, the trade wind becomes weaker and causes the ocean to flow eastwards. This results in higher sea level and warmer seawater in the eastern equatorial Pacific. This process corresponds to an El Nino event (Zheng and Chen, 1994; Rasmusson et al., 1983; Wyktki, 1985). The results from this study shows that the interaction between the ocean and the atmosphere in the tropical Pacific also affects significantly the sea level in the South China Sea that is in the edge of the western tropical Pacific Ocean.

5 Assessment of future sea level change in Hong Kong

Long term sea level rise is set to impact on the future living environments in many parts of the world. The problem is especially severe for populous coastal cities like Hong Kong. The estimated sea level change in Hong Kong in the next 50 years based on the above analysis is plotted in Fig. 5 and summarized in Table 3.

Table 3. Projected future sea level change in Hong Kong

Epoch	Projected future sea level rise in Hong Kong	
	absolute sea level	relative sea level
2010	2.3 cm (17.7 cm)	7.3 cm (22.7 cm)
2030	6.2 cm (22.3 cm)	19.6 cm (35.7 cm)
2050	10.0 cm (26.6 cm)	31.8 cm (48.4 cm)

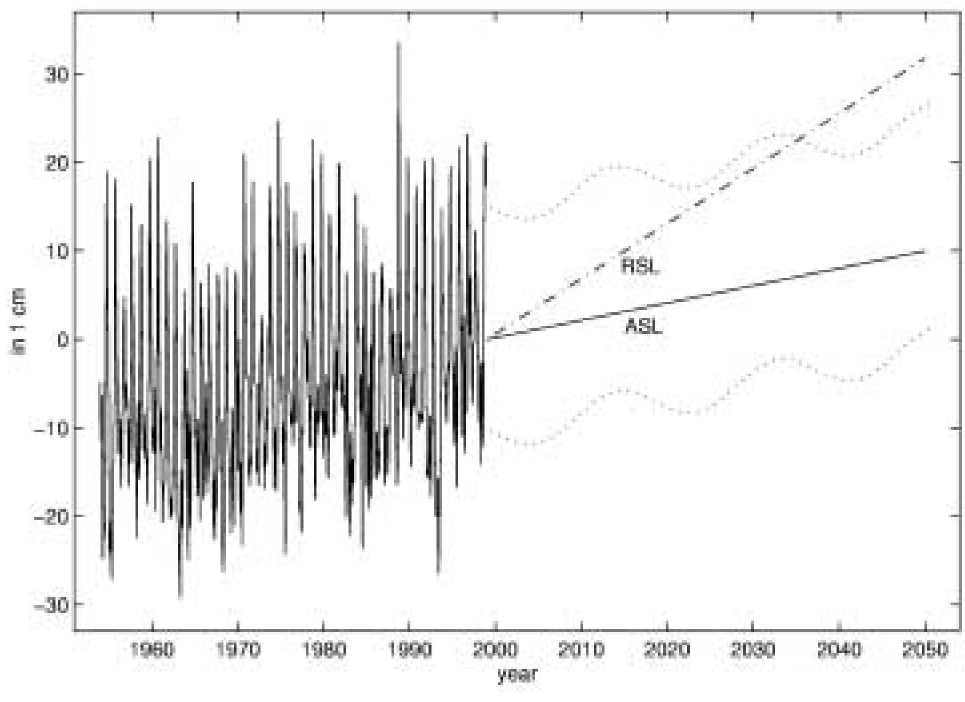

Figure 5. Projected future sea level in Hong Kong. The values at epoch 1999.0 are shifted to zero.

In Fig.5, the solid line is the 1954-1999 monthly mean sea level in Hong Kong. The data are the same as those shown in Fig. 1(b) but are plotted here in a different scale. The absolute mean sea level (ASL) is forward projected to 2050.0 using a linear rate of 1.9 mm per year and is shown as the solid straight line in the diagram. The relative mean sea level (RSL) is also computed when the combined effect of sea level rise and ground subsidence is considered. The RSL is also shown in the figure as a dotted straight line. In the computations, the rate of ground subsidence at the Quarry Bay station, i.e., 4.2 mm per year was used. The dotted curve in the diagram includes both the linear rate and the three stable periodic terms (semiannual, annual and 18.6-year, see Table 1). The higher curve gives the possible highest mean sea level while the lower curve the possible lowest values. For easy interpretation of the results, the monthly mean sea level and the extrapolated values in Fig. 5 have all been shifted to zero at epoch 1999.0. Table 3 lists the projected absolute and relative monthly sea levels to 2010, 2030 and 2050 respectively. The results in the brackets of Table 3 are the projected sea level that includes the linear rate and the contributions of the three stable periodic terms (semiannual, annual and 18.6 years).

In summary, we can say that when only considering the linear trend of sea level rise, the absolute monthly mean sea level in Hong Kong will be 2 cm, 6 cm and 10 cm higher than where it is now by 2010, 2030 and 2050 respectively while the relative sea level will be 7 cm, 20 cm and 32 cm higher within the same periods. If the contributions of the various temporal variations are considered, the absolute and relative sea level changes in Hong Kong can be potentially 18 cm, 22 cm, 27 cm and 23 cm, 36 cm, 48 cm respectively higher in the given time periods. Therefore, should the current trends of sea level rise and ground subsidence be maintained, the problem of sea level change will severely affect the living environment in Hong Kong.

6. Conclusions

The following conclusions can be drawn through the analysis of the 45-year tide gauge records in Hong Kong and the local and global atmospheric pressures, the Southern Oscillation Index (SOI) and the sea surface temperature (SST) in the eastern equatorial Pacific:

There is a rising trend of 1.9±0.4 mm/yr in the local sea level of Hong Kong in the past half-century. This rate of sea level rise is consistent with results obtained from tide gauge records in many other parts of the world, notably those along the coast of China. The local atmospheric pressure variations influence mainly the annual sea level change in Hong Kong. The amplitude of the annual sea level variation depresses by 30% of that after the inverted barometer correction has been applied. There are interannual sea level fluctuations of several centimeters, which are closely associated with ENSO. The sea level rises when a La Nina occurs, while it drops when an El Nino presents. The absolute and relative monthly mean sea levels in Hong Kong can be respectively 2, 6, 10 cm and 7, 20, 32 cm higher by 2010, 2030 and 2050. If the contributions of the various temporal variations are considered, the possible maximum values of sea level changes will be 18 cm, 22 cm, 27 cm and 23 cm, 36 cm, 48 cm, respectively in the same time periods. The expected future sea level rise in Hong Kong can become a potential threat to the living environment for the populous coastal city

Further research is still necessary to better understand the impacts of sea level changes in Hong Kong, especially the land and crustal subsidence in the area.

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