Journal of Coastal Research	17	3	749–754	West Palm Beach, Florida	Summer 2001

Long-Term Sea-Level Changes in Hong Kong from Tide-Gauge Records

Xiaoli Ding†, Jason Chao†, Dawei Zheng†,‡ and Yongqi Chen†

†Department of Land Surveying and Geo-Informatics
Hong Kong Polytechnic University
Hung Hom Kowloon
Hong Kong, China

‡Center for Astrogeodynamics Research of Shanghai Astronomical Observatory
Chinese Academy of Sciences
80 Nandan Road
Shanghai, China

ABSTRACT

DING, X.; CHAO, J.; ZHENG, D., and CHEN, Y., 2001. Long-term sea-level changes in Hong Kong from tide-gauge records. *Journal of Coastal Research,* 17(3), 749–754. West Palm Beach (Florida), ISSN 0749-0208.

Over four decades of tide-gauge data and leveling measurements collected at two tide-gauge stations in Hong Kong are analyzed to study the long-term tendency and the frequency features in the sea-level changes in the region. The results show that there has been a long-term sea-level rise of 1.9 mm per year and a land subsidence of over 4 mm per year at the tide-gauge stations. The variations in sea-level from seasonal through to decadal time scales are detected by using the time-frequency spectrum of wavelet transform. The annual, semiannual and the 18.6-year variations are most significant and exhibit stable periodicity. The local atmospheric pressure variations mainly influence the annual sea-level change and the effect amounts to 33% of the magnitude calculated before the inverted barometer corrections are applied. It is also projected from the extrapolation of the current trends of sea-level rise and ground subsidence that the absolute and relative mean sea-levels in Hong Kong may further rise by 10 cm and 30 cm respectively by the middle of the next century. The possible maximum relative mean sea-level change, when considering the various temporal variations, can be as high as 50 cm in the next half century.

ADDITIONAL INDEX WORDS: *Sea-level change, land subsidence, wavelet transform, atmospheric pressure.*

INTRODUCTION

Sea-level rise and ground subsidence of populous coastal cities represent one of the slowly occurring yet potentially severe natural hazards (*e.g.,* WARRICK *et al.,* 1996). The Asia-Pacific region, which has the highest concentration of human population in the world, is one of the areas most threatened by the rise of relative sea-level. Analyses using 30–50 years of coastal tide-gauge data in the coastal region of China indicate that the sea-level has been rising at a rate of 1.5–2.5 mm per year (ZHENG *et al.,* 1995; CHEN, 1996; MA *et al.,* 1996).

Recent studies also show that some of the coastal cities in the region are subsiding. For example, the Shanghai metropolis has subsided at a rate of over 5 mm per year in the last decade or so (SIRS, 1994).

Hong Kong is situated near the mouth of the Pearl River and at the edge of the tropical western Pacific Ocean. It is one of the most populated areas in the world, and especially vulnerable to such natural hazards as storm surges, flooding, and coastal erosion. Therefore, study of sea-level change and land subsidence in Hong Kong is especially important.

In this study, we analyze the past 45 years of contiguous tide-gauge records and leveling measurements at the two tide-gauge stations (North Point and Quarry Bay) in Hong Kong, to determine the long-term tendencies in the sea-level change and land subsidence in the area. The variations from seasonal through to decadal time scales in the sea-level are also examined by using the time-frequency spectrum of the wavelet transform. The future sea-level change in Hong Kong will also be assessed based on the analysis.

99129 received 13 December 1999; accepted in revision 12 February 2001.

TIDE-GAUGE RECORDS IN HONG KONG

The Hong Kong Observatory operates several tide-gauge stations in Hong Kong. The North Point station is the longest operational tide-gauge station within the territory with 32 years (1954.0–1986.0) of collected data at hourly intervals. This station was subsequently moved to Quarry Bay (about half a kilometer from the original station) where it has been in operation since the beginning of 1986. The same stilling well type tide-gauges have been used at both locations. An analysis of the data indicates a stationary random RMS instrument error within the range of 1–2 cm over the past 44 years (1954.0 to 1998.0) (IZ and SHUM, 1998).

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 as determined based on 19 years (1965–1983) of tide-gauge records (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 bench

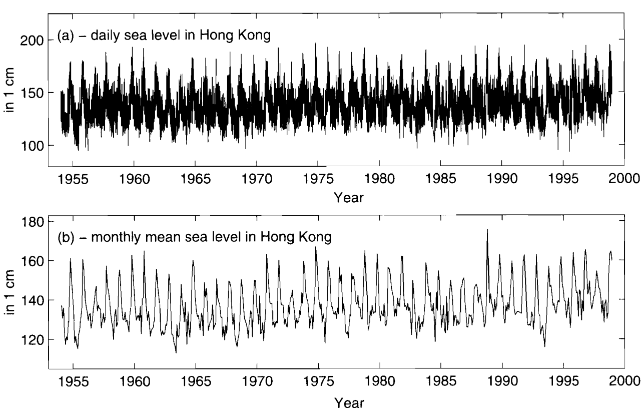

Figure 1. The daily, (a), and monthly, (b), mean sea-levels from tide-gauge records of 1954.0–1999.0 in Hong Kong.

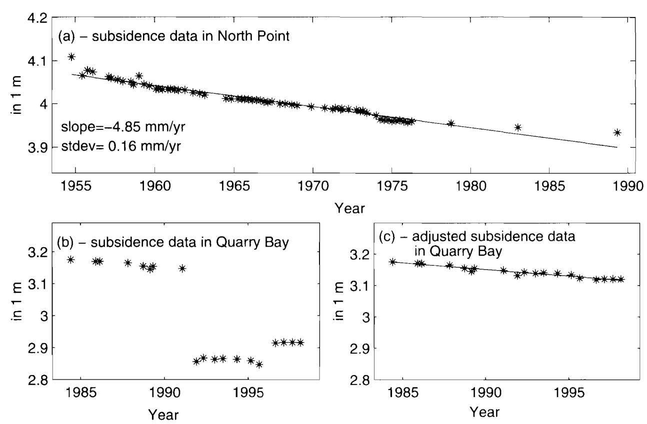

Figure 2. Ground subsidence from leveling measurements, (a) North Point station, (b) and (c) Quarry Bay station.

marks built on the 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 ground settlement by the Hong Kong Observatory.

The hourly tide-gauge records of the North Point station (from January 1, 1954 to December 31, 1985) and of the Quarry Bay station (from January 1, 1986 to December 31, 1998) are combined and used in this study. Daily mean sea-level data are obtained by means of simple average of the hourly data of each full day and are shown in part (a) of Figure 1. During the period of 1954.0 through to 1999.0, out of the 16436 days of data, the gaps and anomalous erroneous points are respectively 274 and 128 days only. Therefore, the availability of daily tide-gauge data in Hong Kong is 97.6 percent within the period. Similarly, monthly mean sea-levels are obtained from the daily data and plotted in part (b) of Figure 1. Signals of seasonal variations in the sea-level are obvious both in the daily and the monthly tide-gauge data. 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).

Since the most important aspect of the analysis of long term sea-level change is the decoupling of the long term land vertical movement from the oceanic signals, repeated leveling measurements will be discussed in the section below.

LAND SUBSIDENCE AT TIDE-GAUGE STATIONS AND THE CALIBRATION OF TIDE-GAUGE RECORDS

The North Point tide-gauge station, which has the longest records, was located on reclaimed land and was subsequently moved to the Quarry Bay station due to the rapid urbanization of Hong Kong during the mid 1970's. Unfortunately, the Quarry Bay is also located on reclaimed land. Luckily, periodic monitoring of the tide-gauge stations using leveling measurements to nearby benchmarks located in the bedrock was carried out over the years.

Part (a) of Figure 2 shows the leveled heights of the reference mark at the North Point station from October 1954 to May 1989. Although the tide-gauge station has been moved to the Quarry Bay at the end of 1985, the leveling measurements were continued until 1989. The leveled heights display typical vertical land movements that are observed in areas of reclamation, *i.e.,* a rapid subsidence followed by a linear rate and a period of deceleration. The subsidence can be characterized by a statistically significant overall rate of -4.85 ± 0.16 mm per year. We must emphasize here that the above estimated linear rate of subsidence is by no means representative of the whole series since the vertical movements in the early 5 to 15 years have very different velocities, as can also be seen from the plot.

The subsidence of the Quarry Bay tide-gauge station is much more complicated, as shown in part (b) of Figure 2. Large slips appeared in 1991 and 1996, which may be caused by nearby underground construction work. The two offsets have been determined by the method of least squares and adjusted (see DING *et al.,* 2001). After the adjustment of the two offsets, the estimated rate of subsidence at the Quarry Bay station is -4.19 ± 0.26 mm per year, as shown in part (c) of Figure 2.

FREQUENCY CHARACTERIZATION OF SEA-LEVEL CHANGES IN HONG KONG

The time-frequency spectrum of wavelet transform (*e.g.,* MORLET *et al.,* 1982; CHAO and NAITO, 1995; ZHENG *et al.,* 1999) is used in this study to understand the spectral feature and the stability of the various frequency processes in the sea-level of Hong Kong. For a time series $f(t)$, the definition of its wavelet transform is:

$$W_{\psi}(f)(a, b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} f(t)\psi\left(\frac{t - b}{a}\right) dt \qquad (1)$$

where $\psi(t)$ is the basic wavelet; a is the dilation/compression scale factor defining the characteristic frequency; and b is the translational factor in the time domain. It can be seen from (1) that the wavelet transform describes the spectrum char-

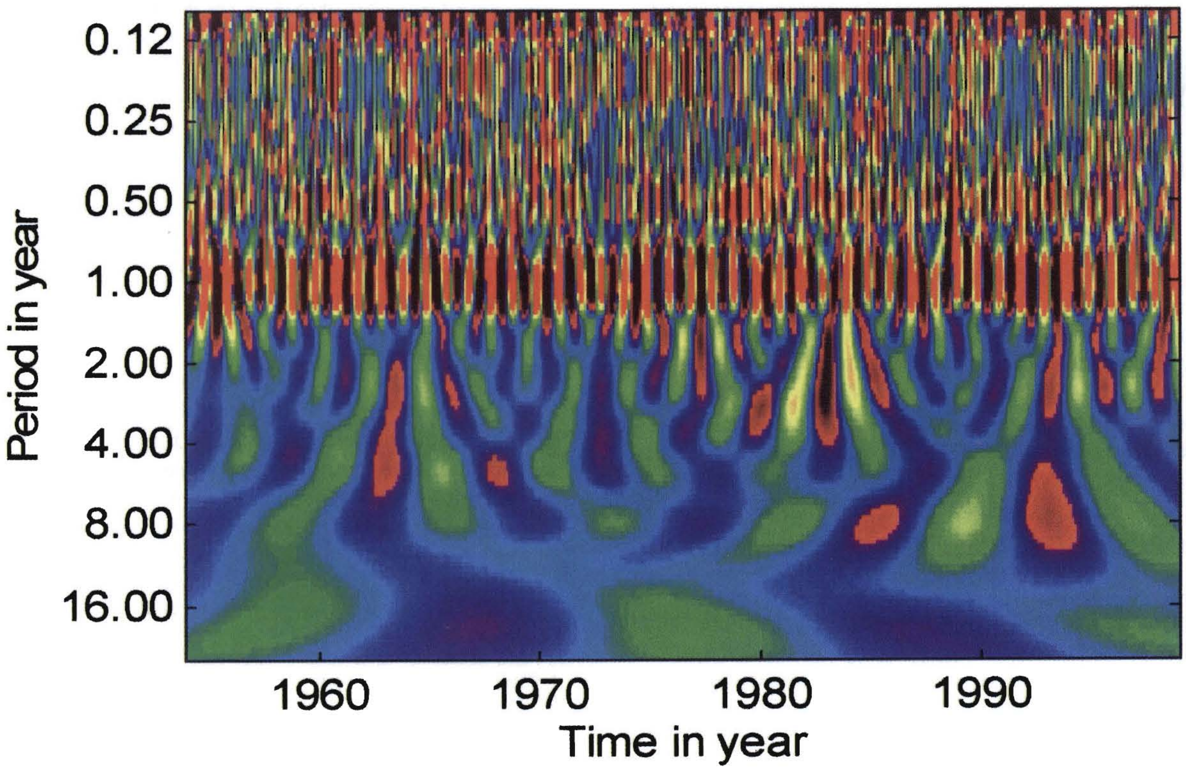

Figure 3. The time-frequency spectrum of wavelet transform of sea-level changes in Hong Kong during 1954.0–1999.0.

acter of time series $f(t)$ in the time-frequency domain (or a–b space).

The results of the wavelet transform for the monthly sea-level time series are depicted in Figure 3. The ordinate of Figure 3 represents the periodic time scale of the time-frequency spectrum. Both the magnitudes and periods of the various frequency signals in the sea-level can be seen from the time-frequency spectrum.

The results show that the seasonal signals, and the annual and long-periodic tidal term of 18.6-year signals in the sea-level change are relatively stronger and their periods are more stable. Besides, the interannual signals of the time scales of approximately 2, 4 and 7 years can also be seen although they are less stable.

The method of least squares is also used to determine the magnitudes and the phases of the various temporal variations. The amplitudes and phases of all the various frequency components as well as a constant and linear rate in the sea-level change are simultaneously estimated by the least squares method of Householder Transform (*e.g.,* FENG *et al.,* 1978) of following equation,

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

where, P_k, c_k and φ_k are the periods, amplitudes and phases of the annual, semiannual, 18.6-year as well as the three interannual terms, respectively, while a and b are the constant and the linear terms. Since the periods of the three interannual fluctuations in the sea-level change are not stable, their mean values are determined by the method of trial and errors in the process of the above least squares computations.

The estimated results are listed in Table 1 where the estimated phases are referred to the epoch of January 1954. It shows from the results that the annual and semiannual variations have the largest amplitudes (over 10 and 5 cm), and the contribution of the interannual fluctuations to the sea-level variations is about 5 cm. In addition, there is an upward trend of 1.9 ± 0.2 mm per year in the sea-level. This rate of sea-level rise is quite compatible to the results obtained using tide-gauge data averaged globally (DOUGLAS, 1991, 1996; WARLICK *et al.,* 1996) and those along the coastal areas of China (ZHENG *et al.,* 1995; MA *et al.,* 1996; CHEN, 1996; SHUM *et al.,* 1998).

Table 1. *The estimated amplitudes and phases of the periodic components in the monthly mean sea-level of Hong Kong from 1954.0 to 1999.0. The phase estimations are referred to the epoch of January 1954.*

Period	Amplitude	Phase (in year)
18.60 year	1.98 ± 0.36 cm	0.52 ± 0.56 year
7.75	2.00 ± 0.37 cm	−2.27 ± 0.23 year
4.94	1.61 ± 0.37 cm	−0.39 ± 0.18 year
2.00	1.06 ± 0.36 cm	0.34 ± 0.11 year
1.00	10.84 ± 0.36 cm	0.46 ± 0.01 year
0.50	5.43 ± 0.36 cm	−0.14 ± 0.01 year

Constant: 132.35 ± 0.52 cm Linear rate: 0.19 ± 0.02 cm/yr. RMS: ±5.97 cm

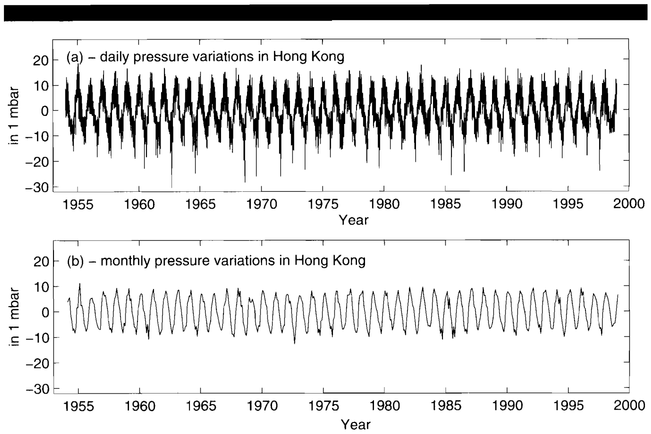

Figure 4. The daily, (a), and monthly, (b), atmospheric pressure variations in Hong Kong during 1954.0–1999.0.

METEOROLOGICAL EFFECTS ON THE SEA-LEVEL IN HONG KONG

The inverted barometer response of the sea-level to the atmospheric pressure variations is important in modeling tidal gauge data. The atmospheric pressure variations are one of the main excitation sources of seasonal sea-level changes (LAMBECK, 1980) beside the thermal effect (CHEN, 1999). The inverted barometer approximation is a technique to determine the oceanic response to atmospheric pressure fluctuations. The sea-surface height change influenced by atmospheric pressure variations is given by the following formula (DICKMAN, 1988),

$$DSL = -\Delta P/\rho g \tag{3}$$

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 variation can be obtained by using Equation (3).

Sea-level change induced by the atmospheric pressure variation can also be determined directly using the following equation,

$$SL_t = a + bt + \sum_{k=1}^{3} c_k \sin(2\pi t/P_k + \varphi_k) + C_p\Delta P + \epsilon_t \tag{4}$$

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

The hourly atmospheric pressure data recorded by the Hong Kong Observatory within a few km of the tide-gauge stations are used for the analysis. The daily and monthly mean atmospheric pressure variations ΔP, from the overall mean atmospheric pressure value of 1954.0–1999.0, are shown in respectively part (a) and part (b) of Figure 4. The parameters in Equation (3) are estimated by least squares Householder transform using the monthly atmospheric pressure variations ΔP given in part (b) of Figure 4 and the monthly sea-level changes in part (b) of Figure 1. The results are given in Table 2.

Table 2. *The estimated amplitudes and phases of the periodic components with inverted barometer corrections. The phase estimations are referred to the epoch of January 1954.*

Period	Amplitude	Phase (in year)
18.60 year	2.04 ± 0.36 cm	0.40 ± 0.53 year
7.75	2.00 ± 0.36 cm	−2.22 ± 022 year
4.94	1.47 ± 0.36 cm	−0.42 ± 0.19 year
2.00	1.06 ± 0.36 cm	0.38 ± 0.11 year
1.00	14.41 ± 0.98 cm	0.39 ± 001 year
0.50	5.80 ± 0.36 cm	−0.14 ± 0.01 year

Constant: 132.15 ± 0.51 cm Linear rate: 0.20 ± 0.02 cm/yr. RMS: ±5.84 cm C_p: 0.87 ± 0.18

Comparing the estimated results in Table 2 with those in Table 1, it is clear that the local atmospheric pressure variations mainly influence the annual term of the sea-level variations; the annual amplitude is increased by 33% of the magnitude without the inverted barometer corrections. The effects of pressure variations on the semiannual and the interannual terms of 4.94-year are about 0.4 cm and 0.1 cm, respectively, while the effects on other terms are insignificant. The estimated value of C_p (0.87) differs from its theoretical value of 0.99 (when the seawater density ρ and gravitational acceleration g are taken as 1027 kg/m^3 and 9.806 m/s^2, respectively) by 12%. The reason for this difference may be that the P_{mean} used in the solution is the local mean atmospheric pressure instead of the corresponding global mean pressures. However, this does not affect significantly the results of estimation of the other parameters (DING *et al.*, 2001).

ASSESSMENT OF FUTURE SEA-LEVEL CHANGE IN HONG KONG

Long term sea-level rise is set to impact on the future living environments and on the occurrences of natural hazards in many parts of the world. Such a problem is especially severe for the populous coastal cities like Hong Kong. The estimated absolute and relative sea-level change in Hong Kong in the next 50 years based on the results of the above analyses is plotted in Figure 5 and summarized in Table 3.

In Figure 5, the solid curve shows the monthly mean sea-levels in Hong Kong during 1954.0–1999.0, which is the same as part (b) of Figure 1 but with a different scale of plot. The extrapolated value of the absolute mean sea-level (ASL) in Hong Kong with a linear rate of 1.9 mm per year is projected forward to 2050.0 (the solid straight line in the figure). The combined effect of sea-level rise and ground subsidence of the Quarry Bay station (4.2 mm/yr, part (c) of Fig. 2), *i.e.*, the relative mean sea-level (RSL) change is also extrapolated and shown in the Figure as a dotted straight line. The dotted curves in the Figure are the extrapolations of sea-level changes that include the linear rate and the three stable periodic terms (semiannual, annual and 18.6-year, Table 1). The higher curve gives the possible highest mean sea-level, while the lower curve the possible lowest values. Note that, for easier interpretation of the results, the monthly mean sea-level data and the extrapolated values in Figure 5 have all been shifted to zero at the 1999.0 epoch.

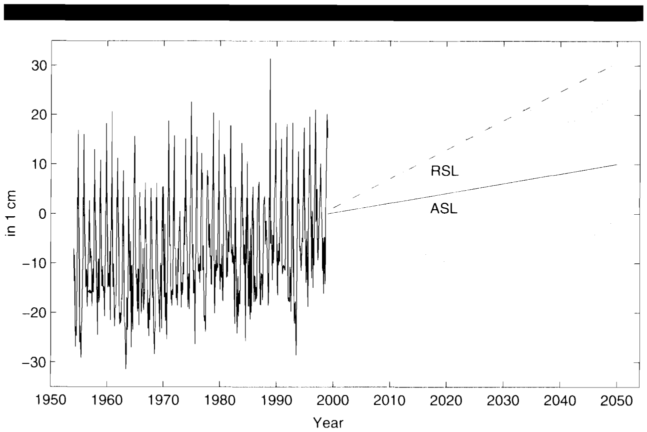

Figure 5. The assessment of future sea-level change in Hong Kong up to the middle of the next century. The values at epoch 1999.0 are shifted to zero.

Table 3 gives the projections of the absolute and the relative mean monthly sea-levels to 2010, 2030 and 2050 respectively. Besides, the various temporal variations are also considered. The first 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), while the second results in the brackets are those that include the linear rate, the three periodic terms and the three interannual fluctuations given in Table 1.

In summary, we can say that when only considering the linear trends of sea-level rise, the absolute monthly mean sea-level in Hong Kong will be 2 cm, 6 cm and 10 cm higher than it is now by the year 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 22 cm, 27 cm, 31 cm and 27 cm, 40 cm, 53 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 be a severe threat to the future living environment in Hong Kong.

CONCLUSIONS

The tide-gauge records, leveling measurements and local atmospheric pressures collected in the last forty five years in Hong Kong have been analyzed and the following conclusions have been reached:

a. There is a rising trend of 1.9 ± 0.2 mm/yr in the local sea-level of Hong Kong in an absolute sense in the past half-century. This rate of sea-level rise is consistent with the results obtained from the global as well as the regional tide-gauge data along the coastal areas of China.
b. The grounds at both of the two tide-gauge stations in Hong Kong, North Point and Quarry Bay, have experienced obvious vertical movements. The rates of the movements are over -4 mm/yr.
c. There are temporal variations of seasonal through to decadal time scales in the sea-level changes in Hong Kong, which are clearly seen from the time-frequency spectrum of wavelet transform. The annual, semiannual and 18.6-year signals exhibit stable periodicity; the annual and semiannual variations have the largest amplitudes, which are over 10 and 5 cm, respectively. The interannual fluctuations are varying with time and their contributions to the sea-level changes in Hong Kong is about 5 cm.
d. The atmospheric pressure variations mainly influence the annual term of the sea-level change and the influence to the annual amplitude is 33% of that before the inverted barometer corrections.
e. The absolute and relative 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 22 cm, 27 cm, 31 cm and 27 cm, 40 cm, 53 cm, respectively for the same time periods. The expected future sea-level rise in Hong Kong can therefore be a potential threat to the living environments for the populous coastal city.

Table 3. *The assessment of future sea-level change in Hong Kong.*

	Projected future sea-level rise in Hong Kong	
Epoch	Absolute sea-level	Relative sea-level
2010	2.3 cm (17.7 cm, 22.4 cm)	7.3 cm (22.7 cm, 27.4 cm)
2030	6.2 cm (22.3 cm, 27.0 cm)	19.6 cm (35.7 cm, 40.4 cm)
2050	10.0 cm (26.6 cm, 31.3 cm)	31.8 cm (48.4 cm, 53.1 cm)

ACKNOWLEDGMENTS

Thanks are extended to Dr. W.L. Cheng and Mr. Y.W. Chan of the Hong Kong Observatory for supplying the tide-gauge records and the local atmospheric pressure data, as well as for useful discussions. Mr. T.W. Ng of the Civil Engineering Department of the Hong Kong Government helped with the clarification of the subsidence at the tide-gauge stations. The research is partly supported by a grant from the Faculty of Construction and Land Use, Hong Kong Polytechnic University under the scheme of Areas of Excellence and by the National Natural Science Foundation of China (project number: 19833030).

LITERATURE CITED

CHAO B.F. and NAITO I., 1995. Wavelet analysis provide a new tool for studying Earth Rotation. *EOS,* 76, 161.

CHEN J.Y., 1996. On the relative vertical movement between crust and sea-level along the Chinese coastal zone: a national basic research project in China. *Marine Geodesy,* 19, 99–104.

CHEN J.L.; SHUM C.; WILSON C.; CHAMBERS D., and TAPLEY B., 1999. Seasonal sea-level change from TOPEX/Posidon observation and thermal contribution. *Journal of Geodesy,* 73(12), 638–647.

DICKMAN S., 1988. Theoretical investigation of the oceanic inverted barometer response. *Journal of Geophysical Research,* 93, 14941–14946.

DING X.L.; ZHENG D.W.; CHAO J.; CHEN, Y.Q., and LI Z.L., 2001. Sea-level change in Hong Kong from tide-gauge measurements of 1954–1999. *Journal of Geodesy,* 74, 683–689.

DOUGLAS B., 1991. Global sea-level rise. *Journal of Geophysical Research,* 96(C4), 6981–6992.

DOUGLAS B., 1996. Global sea-level rise: a redetermination. *Survey in Geophysics.* Also abstract in *GLOSS Bulletin,* Issue 3 (April 1996).

FENG K.; ZHANG J.; ZHANG Y.; YANG Z., and CHAO W., 1978. *Numerical Calculation Method,* Beijing: National Defense Industry Press, 311p.

IZ H. and SHUM C., 1998. Sea-level and GPS project in Hong Kong and East China Sea, *GLOSS Regional Sea-level Meeting* (Taipei, Taiwan).

LAMBECK K., 1980. *The Earth's Variable Rotation.* New York: Cambridge University Press, 449p.

MA J.; ZHANG Q., and CHAI X., 1996. Rising trend of relative sea-level along the coast of East Asia. *Marine Geodesy,* 19, 257–268.

MORLET J.; AREHS G.; FOURGEAU I., and GIARD D., 1982. Wave propagation and sampling theory. *Geophysics,* 47, 203.

SIRS (Shanghai Institute of Rocks and Soils), 1994. *Research on the prediction and counter-actions of land subsidence in Shanghai,* Shanghai Institute of Rocks and Soils.

SHUM C.; PARKE M.; GUMAN M.; HUANG C.; ZHENG D.; TAPLEY B.; WANG J., and WOODWORTH P., 1998. Observing long-term mean sea-level variations in the China Seas. *4th Pacific Ocean Remote Sensing Conference* (Qingdao, Shangdong, China).

SMO (Survey and Mapping Office), 1995. *Explanatory Notes on Geodetic Datum in Hong Kong,* Lands Department, Hong Kong Government.

WARRICK R.; PROVOST C.; MEIER M.; OERLEMANS J., and WOODWORTH P. (Lead Authors) 1996. Chapter 7 (Changes in Sea-level), *2nd Assessment report of the intergovernmental Panel on Climate Change,* HOUGHTON J., et al. (Eds.), Cambridge University Press, Cambridge, U.K., 572p.

ZHENG D.; HUANG C., and YU N., 1995. Sea-level change in the Pacific and along the coast of China, *Global Sea-level Change Workshop* (Miami, Florida).

ZHENG D.; CHAO BF.; ZHOU Y., and YU N., 1999. Improvement of edge effect of the wavelet time-frequency spectrum: application to the length of day series. *Journal of Geodesy,* 74(2), 249–254.