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LONG TERM TRENDS OF THE REGIONAL SEA LEVEL CHANGES IN HONG KONG AND THE ADJACENT WATERS

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Direct consequences of global warming are thermal expansion of sea water and melting of glaciers and ice caps. Both effects would lead to a rise of the mean sea level. According to the fourth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), the global mean sea level rose at a rate of 1.8 mm per year for 1961-2003 and 3.1 mm per year for 1993-2003. The fourth assessment report also projects that the sea level could rise by 0.59 metre in the 21st century while some recent studies suggest that the amount could be even higher - at one to two metres.

Located at the coast of the South China Sea, Hong Kong has experienced a rise in the sea level. Previous studies show that the sea level at the Victoria Harbour has risen significantly by about 2.6 mm per year since the 1950's. However, some other factors such as ocean currents, water discharge, subsidence and sedimentation are also influencing sea level at the regional scale. As the eastern side of Hong Kong is open to the Taiwan Strait and Luzon Strait, while the western side is at the Pearl River Estuary and the southern end is open to the South China Sea, the change in sea levels in Hong Kong and the adjacent waters would have regional variations. This study aims at determining the long term trends of the regional sea level changes in Hong Kong and the adjacent waters by examining the sea level data recorded since the 1950s by tide gauges at various coastal locations in Hong Kong and Macau. The satellite altimetry data are also used to corroborate the sea level change in the South China Sea with those in the Hong Kong Waters.

1. Introduction

Global warming would lead to rise in sea level due to thermal expansion of the upper layer of the ocean and melting of mountain glaciers and polar ice-caps. The rise of sea level has a potential impact on coastal regions, such as increased coastal erosion, more extensive coastal inundation, higher storm surge flooding, landward intrusion of seawater in estuaries and aquifers, and changes in surface water quality and groundwater characteristics. In the forth assessment report (AR4) of the Intergovernmental Panel on Climate Change (IPCC), it was found that the global mean sea level had risen at a rate of 1.8 millimetres per year from 1961 to 2003 and the recent rising rate even increased to 3.1 millimetres per year from 1993 to 2003. The AR4 also predicts that the sea level could rise by 0.59 metre in the 21st century while some recent studies suggest that the amount could be even higher - at one to two metres [6].

The sea level observed at a location can be considered as the superposition of tide and meteorological residuals [4]. Tides along coastal basins are strongly affected by geometry of the coastline, bathymetry and hydrology of estuaries. Meteorological residuals are the irregular components due to the weather elements such as atmospheric pressure and wind stress. Some other factors such as ocean currents, water discharge, subsidence and sedimentation also affect sea levels at the regional scale.

Hong Kong is open to influences of the coastal cold current that carries colder water from the East China Sea along the Taiwan Strait to the south China coast in winter, and the Kuro Shio current that transports warm water from the Pacific across the Luzon Strait into the South China Sea in springtime. During summer months, the Hainan current that carries warm water up to the northeastern coast of the South China Sea prevails. At the western end of Hong Kong is at the Pearl River Estuary. Fresh water discharge via the Pearl River Estuary and sedimentation distribution at the Estuary exert an influence on the Hong Kong waters, with the influence declining from west to east. The western part of Hong Kong waters is estuarine while the eastern part is predominantly oceanic; between the two is a region of mixing [2].

Hence, it is expected that sea level change in Hong Kong should have a regional variation to a certain degree. The objective of this study is to determine the long term trends of the regional sea level changes in Hong Kong and the adjacent waters. The short term sea level trends and inter-annual variability will also be analyzed and compared to those in the South China Sea.

2. Tide Data for the Study

Tide data collected by the Hong Kong Observatory's tide gauge network and collected by the tide gauge operated by the Maritime Administration of Macau are used for this study.

Figure 1 shows the locations of the tide gauge stations for this study. The data period and data availability of these stations are given in Table 1. Due to telecommunication problems, data availability for the remote stations at Tsim Bei Tsui, Waglan Island and Tai Mui Wan was relatively low particularly in the early years of operation.

Figure 1. Locations of the tide gauge stations for this study.

Table 1. Tide gauge stations for this study, their data periods, data availability and water depth nearby the stations

Station Name	***Latitude and Longitude***	***Data Period***	***Data Availability***	***Water Depth (metres)***
North Point/ Quarry Bay	22°18'N 114°12'E/ 22°17'N 114°13'E	1954 – 1985/ 1986 – 2010	98%	10-15
Tai Po Kau	22°27'N 114°11'E	1963 –2010	95%	~10
Tsim Bei Tsui	22°29'N 114°01'E	1974 –2010	79%	~5
Waglan Island	22°11'N 114°18'E	1976 –2010	51%	~30
Tai Miu Wan	22°16'N 114°17'E	1994 – 2010	72%	15-25
Shek Pik	22°13'N 113°54'E	1997 – 2010	94%	5-10
Macau	22°11'N 113°32'E	1984 – 2010	98%	~5

Hourly tidal records are available from the North Point tide gauge station starting from 1954. In 1985, the tide gauge station was relocated to Quarry Bay and has been put into operation since 1986. With both stations sited on reclaimed land, ground settlement was found significant especially for the first ten to twenty years after reclamation. Monitoring of settlement of the stations was carried out by the Port Works Division of the then Civil Engineering Department and the results were used to correct the tidal record [7].

The tidal records measured at North Point and Quarry Bay during the overlapping period were compared and found no noticeable difference [9]. Hence, the tide gauge data from these two stations are regarded as belonging to the same series and regarded as from a single station (denoted as NPBQ thereafter).

Unlike NPQB, other tide gauge stations were not built on reclaimed land. Regular settlement measurements for these stations have been carried out since 1991 and the measurements show that no significant settlement during the observation periods.

As there is no tide data available for the southwestern coast of Hong Kong before 1997, tide data recorded in Macau from 1984 to 2010 are used to illustrate the long term sea level change for the waters to the southwest of Hong Kong.

Tai Po Kau, Tai Mui Wan and Waglan Island are located in the eastern coast of the Hong Kong and more affected by the oceanic currents from the east. Tsim Bei Tsui, Macau and Shek Pik are close to the Pearl River Estuary. Fresh water discharge and sedimentation from the Pearl River affect the sea levels at these sites and shallow water effects on the tide are also more important. NPQB is located centrally in the region of mixing of oceanic and estuarine water [11].

3. Data Analysis

Daily mean sea levels are computed from hourly tidal records using a sea level data processing software package developed by the University of Hawaii Sea Level Centre [8]. Short data gaps less than or equal to 24 hours are filled with linear interpolation via the predicted tide data. A two-step filtering is applied to remove the periodic changes associated with tides. First, the dominant diurnal and semi-diurnal tidal components are removed from the hourly tidal records. Secondly, a 119-point convolution filter centred at noon is used to remove the remaining high frequency energy. Annual means are computed from the daily mean sea levels if not more than 20% of data are missing in the year.

Annual mean sea levels at North Point between 1954 and 1957 are corrected for the error due to resetting of the tide gauge based on the correction table from Watts [3]. Settlement correction based on the results of settlement measurement from the Port Works Division of the then Civil Engineering Department is applied to the annual mean sea levels at NPQB between 1958 and 2010. No correction for settlement is applied to the annual mean sea levels at Tai Po Kau, Tsim Bei Tsui, Waglan Island, Tai Mui Wan and Shek Pik as settlement has been found insignificant.

The trend of annual mean sea level at each station is obtained using a least squares linear fit. All trends shown in this study have been tested for significance at a level of 5%. The error terms are given in one standard deviation.

4. Results and Discussion

4.1. *Long Term Trend*

The annual mean sea levels at NPQB, Tai Po Kau, Tsim Bei Tsui, Waglan Island and Macau which have record lengths of more than 25 years are given in Figures 2(a) to 2(e).

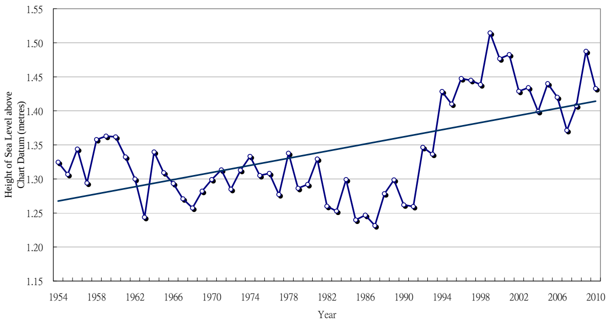

Figure 2(a). Annual Mean Sea Level at North Point/Quarry Bay (1954-2010).

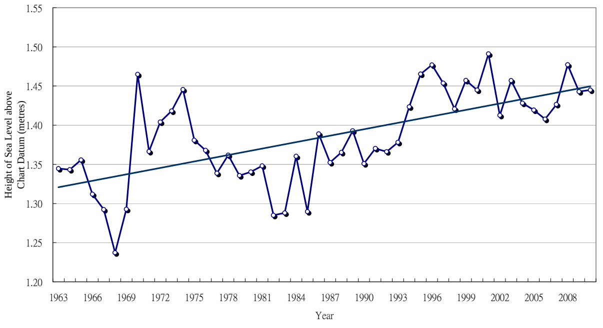

Figure 2(b). Annual Mean Sea Level at Tai Po Kau (1963-2010).

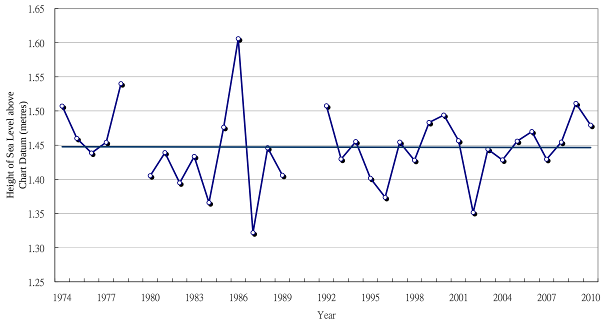

Figure 2(c). Annual Mean Sea Level at Tsim Bei Tsui (1974-2010).

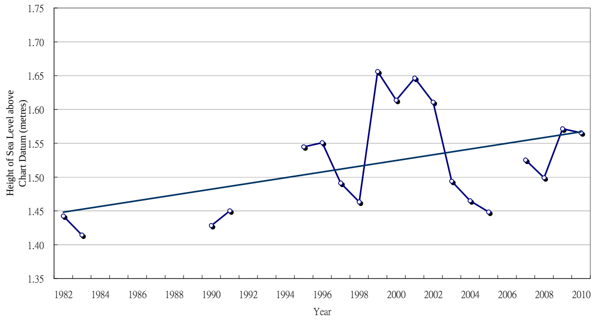

Figure 2(d). Annual Mean Sea Level at Waglan Island (1982-2010).

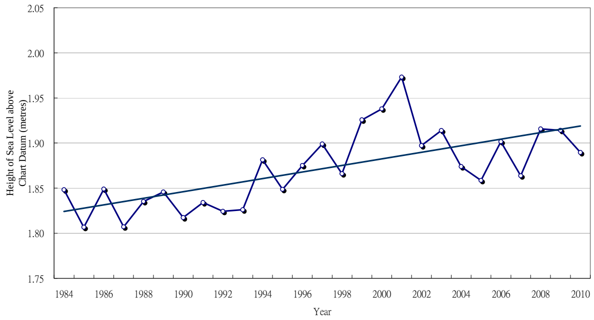

Figure 2(e). Annual Mean Sea Level at Macau (1984-2010).

With the longest record period of 57 years from 1954 to 2010 in the harbour, NPQB's annual mean sea level had risen significantly at a rate of 2.6 ± 0.5 millimetres per year. However, the rising trend is not monotonic. From 1954 to 1987, the annual mean sea levels at NPQB show a general falling trend at a rate of 2.0 ± 0.5 millimetres per year. From 1987 to 1999, the annual mean sea levels rose rapidly at a rate of 22.1 ± 2.3 milllimetres per year. From 1999 to 2010, the annual mean sea levels show a general falling trend at a rate of 5.6 ± 3.2 milllimetres per year.

At the northeastern coast of Hong Kong, the annual mean sea level of Tai Po Kau had also risen significantly at a rate of 2.7 ± 0.5 millimetres per year from 1963 to 2010. Similar to NPQB, there was a steep rising trend since the late 1980s and then a slight falling trend from 2001 to 2010

With a record length of slightly less than 30 years, Waglan Island's annual mean sea level on the southern part of Hong Kong had risen significantly at a higher rate of 4.2 ± 2.0 milllimetres per year. Although the annual mean sea levels of some years could not be determined due to poor data availability, the long term rising trend could be inferred from the significantly higher annual mean sea levels in recent years than those in the early years of operation of the station.

For the waters to the southwest of Hong Kong, the annual mean sea level at Macau also had a relatively higher rising trend of 3.9 ± 0.8 milllimetres per year.

Based on the above analysis, the sea levels in the central, eastern and southern regions of the Hong Kong waters have significant rising trends ranging from 2.6 to 4.2 millimetres per year in long term. The rate of rise in the southern region of the Hong Kong waters is relatively faster than those in the central and eastern regions.

Unlike the above four stations, the annual mean sea levels at Tsim Bei Tsui show no noticeable trend from 1974 to 2010. This might suggest that local effects, such as fresh water discharge and sedimentation originating from the Pearl River, have been affecting the sea levels there more significantly than the oceanic effect.

The long term rising trends at NPQB, Tai Po Kau, Waglan Island and Macau are higher than the global mean sea level rise of 1.8 milllimetres per year for 1961-2003 (IPCC, 2007). This suggests that the regional sea level rise at the northern coast of the South China Sea is generally higher than the global mean in long term.

The annual mean sea levels at Tai Mui Wan and Shek Pik are given in Figures 3(a) and 3(b). The lengths of the record of mean sea level at these two stations are too short for any meaningful long term trend to be evaluated.

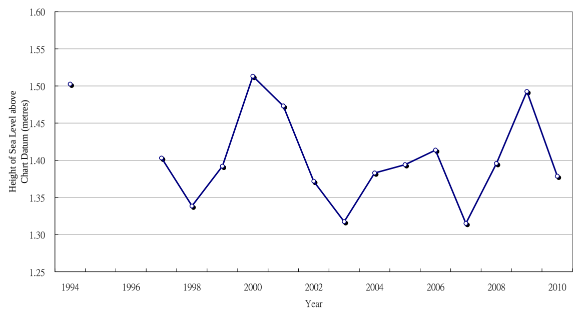

Figure 3(a). Annual Mean Sea Level at Tai Mui Wan (1994-2010).

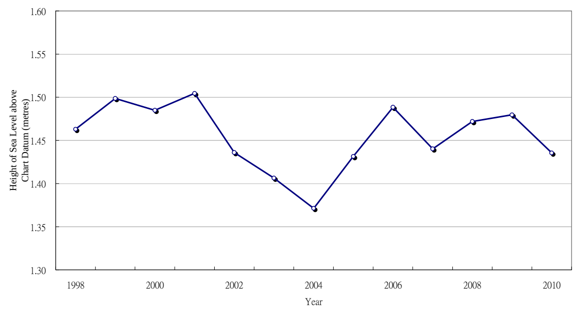

Figure 3(b). Annual Mean Sea Level at Shek Pik (1998-2010).

4.2. *Comparison with South China Sea*

The TOPEX/Poseidon (T/P) satellite is a joint venture of France and the United States to measure the global sea level with respect to the centre of the Earth. An altimeter onboard the satellite sends radar pulses to the ocean surface and measures the time taken for bounced off pulses to return to the satellite. The T/P mission provides sea level data from 1993 to 2001. Jason-1 is successor to the T/P mission and provides sea level data since 2002. The Ocean

Surface Topography Mission on Jason-2 satellite (OSTM/Jason-2) is a follow-on to the Jason-1 mission starting from 2008[a].

Figure 4 shows the average annual mean sea level anomaly over the South China Sea for the period 1993 to 2010 from the T/P and Jason-1/2 satellites published by the University of Colorado[b]. The annual mean sea level anomaly rose rapidly from 1993 to 2001, fell sharply from 2001 to 2005 and rose again from 2005 to 2010 with an overall rising rate of 5.4 ± 1.0 millimetres per year for the period from 1993 to 2010.

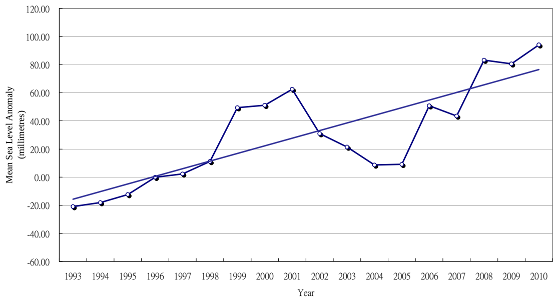

Figure 4. Average Annual Mean Sea Level Anomaly over the South China Sea (1993-2010).

The variations of annual mean sea levels for NPQB, Tai Po Kau, Waglan Island, Macau and the South China Sea for the period from 1993 to 2010 are compared. It can be seen that they all show a very similar pattern with a general rising trend from 1993 to around 2000 followed by a rapid falling one to around 2006 and a rising trend again since then.

4.3. *Inter-annual Variation*

The annual mean sea level variations after trend removal for NPQB, Tai Po Kau, Tsim Bei Tsui, Waglan Island, Macau, Tai Mui Wan, Shek Pik, and the South China Sea for the period from 1993 to 2010 are shown in Figure 5.

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[a] information is available from WWW webpage at: http://topex-www.jpl.nasa.gov/

[b] data are obtained from WWW webpage at: http://sealevel.colorado.edu/

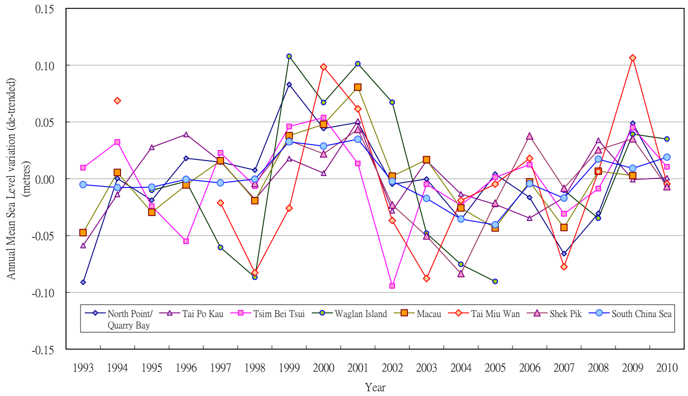

Figure 5. Annual Mean Sea Level Variations after trend removal for various stations.

It can be seen that the de-trended mean sea levels for Waglan Island and Tai Mui Wan have larger fluctuation compared to the others. This could possibly be associated with the relatively deeper water near the tide gauge stations.

Also, it is found that the de-trended annual mean sea levels at the three tide gauge stations in the southern region of the Hong Kong waters, namely Waglan Island, Macau and Shek Pik, , are highly correlated to those for the South China Sea for the period from 1993 to 2010 with correlation coefficients of 0.79, 0.78 and 0.76 respectively. The correlation coefficients for other stations are generally below 0.5.

5. Conclusion

Based on the tide data recorded by the tide gauges of the Hong Kong Observatory and the Maritime Administration of Macau, spatial variations in the trends of sea level rise at the Hong Kong waters were observed. Besides the waters near the Pearl River Estuary where no significant trend was observed possibly due to the fresh water and sedimentation originating from the Pearl River, the sea levels of the Hong Kong waters in general show a long tern rising trend with relatively higher rising rate in the southern region of the Hong Kong waters.

Comparing with the satellite altimetry measurements of the oceans for the period 1993 to 2010, it is found that except the northwestern region, the variations of the annual mean sea levels of the Hong Kong waters are commensurate in general with that of the South China Sea.

It is also found that the variations of the de-trended annual mean sea levels at Waglan Island, Macau and Shek Pik are strongly correlated to that for the South China Sea for the period from 1993 to 2010, reflecting that the inter-annual variation in sea levels in the southern region of the Hong Kong waters is strongly driven by the South China Sea.

Acknowledgments

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