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Sea-level Change –

Observations, Causes and Impacts

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SEA-LEVEL CHANGE –
OBSERVATIONS, CAUSES AND IMPACTS

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Abstract:

Satellite altimetry and tide gauge measurements show that global sea-level is on the rise. The rate of sea-level rise in the past two decades is faster than any time in the past 6,000 years. There are two main causes: (a) thermal expansion of sea water as a result of global warming; and (b) transfer of water stored in land ice to ocean. With further warming anticipated in the 21st century, sea-level rise is expected to continue. The sea-level rise projection made in IPCC's fourth assessment report published in 2007 was 0.59 metre by the end of the 21st century. In addition to potential inundation to coastal low-lying areas, extreme sea-levels due to storm surges brought by tropical cyclones would become higher and more frequent. In Hong Kong, a once in 50-year extreme sea-level may become a biennial event after the projected sea-level rise.

Keywords:
Climate Change, Global Warming, Sea-level Rise

1. OBSERVATIONS

Sea-levels are always changing, driven by various types of forces and over a wide range of space and time scales. A notable everyday experience of sea-level change for most people is the observation of semi-diurnal and diurnal tidal oscillations, which are primarily caused by rotation of the Earth and gravitational attraction by celestial bodies including the Moon and the Sun. Apart from astronomical tides, sea-levels are also affected by a number of hydrological, meteorological, oceanographic and geophysical factors such as river discharge, atmospheric pressure, monsoon, cyclone, El Nino Southern Oscillation (ENSO), oceanic circulation, and tectonic activities. Figure 1 and figure 2 show the effects of monsoon and ENSO on the sea-levels at Hong Kong and the southern coast of China respectively.

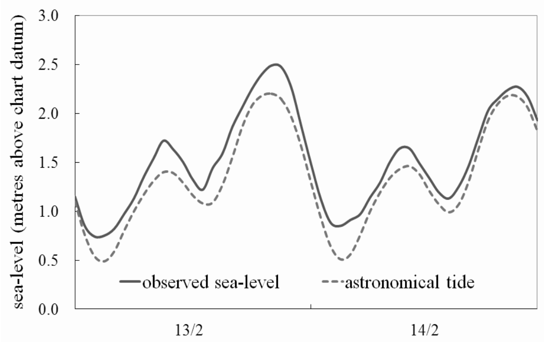

Figure 1 – Raised sea-levels at Victoria Harbour by a strong northeast monsoon on 13-14 February 2010.

Climate is known to change naturally in Earth's history with periods of large scale glaciations. Results of geological and archaeological studies suggest that global mean sea-levels may have varied by hundreds of metres between glacial periods. It is now commonly believed that the current mean sea-level is about 125 metres higher than that during the last glacial maximum about 21,000 years ago, a result of melting of giant glacial ice sheets. The land originally covered by ice sheets rebounded elastically on the melting, a process known as post-glacial rebound (PGR) which still affects some land masses nowadays. Such rapid sea-level rise ended about 6,000 years ago when the climate more or less stabilised.

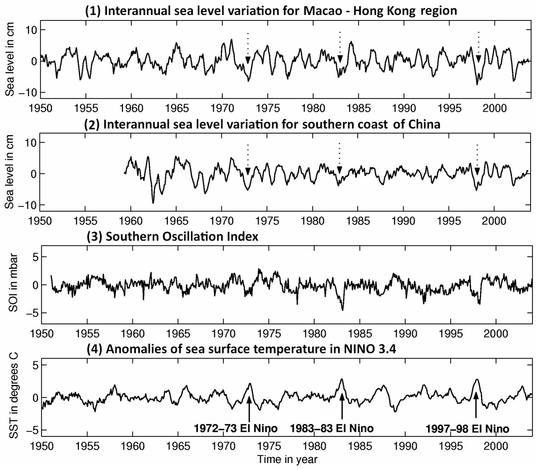

Figure 2 - Effects of ENSO on the mean sea-levels over coast of southern China (Ding et al 2004).

Over the past 6,000 years, the average sea-level rose at a slow rate of about 0.5 mm/yr. This was the time when many ancient civilizations emerged. The rate of sea-level rise was even lower over the past 3,000 years, at 0.1 to 0.2 mm/yr. This quiescence did not last. In the 20th century, the rate of global sea-level rise accelerated to an estimated range of 1.0 to 2.0 mm/yr. Such a rate is alarming as more than one-third of the world's population are now living within 100 km of a coast and the raised sea-level poses a threat to the densely populated low-lying coastal areas during storms.

In studies on contemporary sea-level changes over periods of decades to centuries which are short time scales in the history of the Earth, sea-levels are measured by instruments in order to attain the required accuracy. While tide gauge records provide ground truth of the sea-level at a fixed location, the measurement is actually relative to a land point which may move vertically at rates comparable to the true sea-level signals. Significant vertical land movements are known to occur as a result of PGR (e.g. the Baltic), tectonic activities (e.g. Alaska and Japan) or land subsidence in deltas (e.g. Shanghai). Removal of land movement is required in analysing sea-levels based on tide gauge records.

Spatial sampling of the open ocean based on tide gauge data alone is inadequate due to limited spatial distribution of tide gauges especially in the Southern Hemisphere. Satellite altimetry was developed to address the issue. SEASAT (1978) and GEOSAT (1985-1989) were the earliest satellites launched on altimetry mission. Data collected by these satellites, however, did not reveal the sea-level with sufficient accuracy due to errors in satellite altitude and obscuration of sea-level signal by measurement corrections. Technological advancement since then led to the success of the satellite TOPEX/Poseidon (T/P) which, launched in 1992, attained an accuracy of 2-3 cm in sea-level estimation. Satellites Jason-1 and Jason-2 were launched in 2001 and 2008 respectively following the mission of T/P and provided a wealth of data for monitoring the rates of sea-level change in the past two decades.

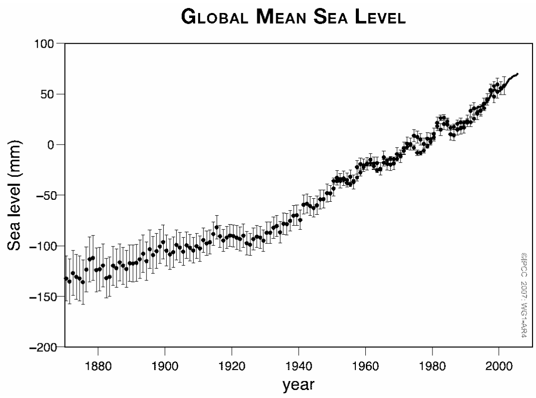

Figure 3 - Global mean sea-level relative to the average for 1961 to 1990 (IPCC 2007).

With accurate tide gauge and satellite altimetry data, the fourth assessment report (AR4) of the United Nations Intergovernmental Panel on Climate Change (IPCC) concluded that the global mean sea-level rose at a rate of 3.1±0.7 mm/yr for 1993-2003. This is similar to the observation taken in Hong Kong. During the period 1954 to 2009, the mean sea-level in the Victoria Harbour rose at an average rate of about 2.6±0.5 mm/yr (Figure 4) as measured by the tide gauges at North Point (1954-1985) and Quarry Bay (1986- present) and after removal of land subsidence effects.

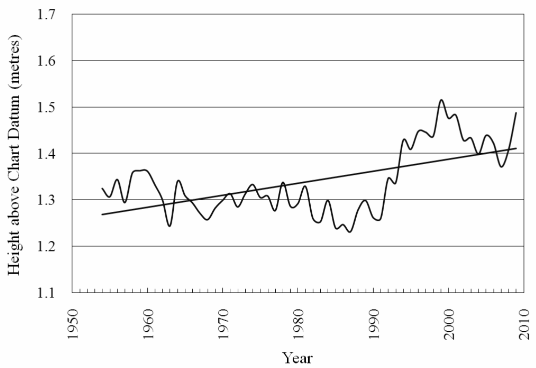

Figure 4 - Annual mean sea-level in Victoria Harbour

The tide gauge stations at North Point and Quarry Bay were built on reclaimed land where land subsidence was substantial during the first couple of decades of operation (Wong et al 2003). Civil Engineering and Development Department (CEDD) of the HKSAR government has conducted precision levelling measurement of the tide gauges at half yearly intervals to determine the rate of land subsidence. Tidal records were corrected for land subsidence before the mean sea-level was computed. In 2006, the Hong Kong Observatory (HKO) started to use continuous GPS stations to monitor crustal movement at Shek Pik and Tate's Cairn, and found that the mean vertical movement of the crust during 2006 to 2009 was small. A longer period of observation would be required to determine the trend of vertical movement of the crust at Hong Kong (Lau and Wong, 2010).

2. CAUSES

While mean sea-levels change naturally in the normal evolution of the Earth, anthropogenic global warming since the industrial revolution is probably the major cause of the accelerated sea-level change observed in the 20th century. Two primary physical processes are involved: (i) expansion of water volume in the global ocean when heated up; and (ii) transfer of water stored on land to the ocean due to increased melting of glaciers, ice caps and ice sheets.

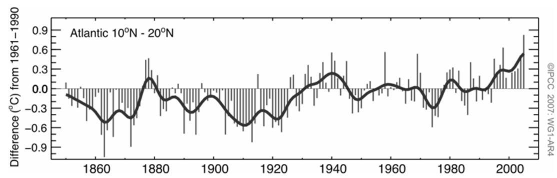

Figure 5 - Annual sea surface temperature anomalies (IPCC 2007)

Millions of sea profile measurements taken by the research community since 1955 indicated that the ocean had warmed in all basins down to 3000 m deep, with a higher warming rate in the upper 700 m. Calculation of thermal expansion of the ocean is complex as the thermal expansion coefficient of seawater varies strongly with salinity and temperature. To get a flavour of the magnitude, we may consider the tropical and mid-latitude ocean where the thermal expansion coefficient differs from 2.5×10^{-4} per °C by less than 50%. Using this value, a 1000-m layer of ocean will give rise to a raised sea-level of the order of 20 cm for a temperature change of 1°C. Results of detailed calculations revealed in IPCC's AR4 showed that thermal expansion of the ocean down to 3000 m made a contribution of 1.6±0.5 mm/yr during 1993 to 2003.

During the past century, widespread mass losses were observed in glaciers and ice caps (G&IC), and the Greenland and Antarctica ice sheets. IPCC's AR4 estimated that G&IC, Greenland, and Antarctica contributed 0.77±0.22, 0.21±0.07 and 0.21±0.35 mm/yr sea-level rise during 1993 to 2003.

The sum of these contributions, i.e. thermal expansion and melting of land ice, to sea-level rise for 1993-2003 was 2.8±0.7 mm/yr. This is in good agreement with the observed total sea-level rise of 3.1±0.7 mm/yr. These values also agree with the calculation based on climate modelling of thermal expansion and land ice melting which gives a rate of sea-level rise of 2.6±0.8 mm/yr during this period.

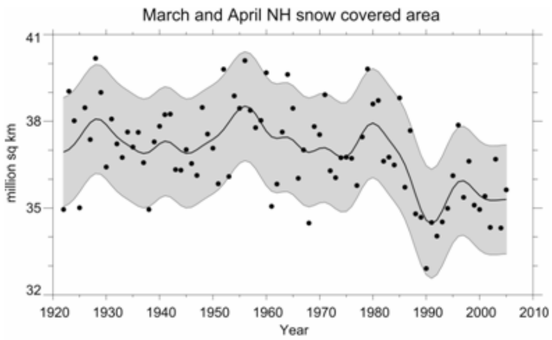

Figure 6 - Northern hemisphere snow cover during March – April (IPCC 2007)

With results from numerical climate modelling, IPCC's AR4 predicted that sea-level rise in the 21st century would range between 0.18 and 0.59 m compared with that at the end of the last century (IPCC, 2007) with contributions from thermal expansion up to 0.41 m, G&IC up to 0.17 m, Greenland up to 0.12 m, and negative contribution from Antarctic due to increased snowfall. A study released after IPCC's AR4 found that G&IC melting was accelerating (Meier *et al*., 2007) and suggested a sea-level rise of about 0.1 to 0.25 m in the 21st century due to G&IC alone.

In the past several years, increased ice loss was observed in Greenland and the West Antarctic Ice Sheet (WAIS) through ice sheet flow. Ice flow dynamics was, however, not included in the climate models used to project sea-level rise in IPCC's AR4 as the mechanism of these processes were not fully understood. Anyway, IPCC's AR4 estimated that if contributions due to increased ice flow were to grow linearly with the global average temperature change, the sea-level would rise by a further 0.1 to 0.2 m by the end of the 21st century.

There were attempts by climate researchers to predict the future sea-level rise by other methods. One such attempt was to establish an empirical relationship between global sea-level rises and mean surface temperatures. By applying such a relation to the projected warming by IPCC, a sea-level rise of 0.5 to 1.4 m by the end of the 21st century might be expected (Rahmstorf, 2007).

3. IMPACTS

Rising sea-level may impact on islands and coastal populations via inundation, increased erosion, higher storm surge flooding, landward intrusion of seawater in estuaries, and changes in surface water quality and groundwater characteristics. With the anticipated range of sea-level rise in the 21st century, most of these phenomena would not be significant on normal days except during tropical cyclones in Hong Kong. Sea-level rise may increase the frequency and scale of sea flooding from storm surges brought by tropical cyclones.

Tropical cyclones approaching Hong Kong would raise the local sea-level by virtue of the low atmospheric pressure and high winds of the cyclone, a phenomenon called storm surge. Height of the surge depends on the strength of the tropical cyclone, its movement path and speed, and also its closest distance from Hong Kong. Typically, tropical cyclones that came close to Hong Kong would raise the sea-level by 0.5 to 1.0 m. In extreme cases in the past, the raised sea-level could exceed the normal tide level by more than 3 m, bringing serious sea flooding to coastal low-lying areas.

During the pre-Second World War period in the 20th century, severe storm surges have caused havoc in Hong Kong in 1906 and 1937. In the past 50 years, well-known cases of serious sea flooding due to storm surges include Typhoon Wanda in 1962 and Typhoon Ellen in 1983. The most recent cases of inundation due to storm surges were caused by Typhoon Hagupit and Typhoon Koppu in 2008 and 2009 respectively.

Figure 7 - Damage to a row of bungalows at Cheung Chau during Typhoon Hagupit in 2008.

Inundation of Tai O during the passage of Typhoon Hagupit in 2008 should still be fresh to the memory of many Hong Kong people. Hagupit was the strongest typhoon that affected Hong Kong in 2008. Amidst the gales in the night of the closest approach, Hagupit caused damages to a row of bungalows at seaside at Cheung Chau (Figure 7), and sea flooding to many coastal low-lying areas including Tai O village (Figure 8). At Tai O village, many residents had to move to the upper floor to take shelter.

At the Victoria Harbour, the highest storm surge during Typhoon Hagupit was 1.4 metres. Storm surge combined with normal astronomical tide resulted in a maximum sea-level of 3.53 metres above chart datum. This was the second highest sea-level recorded at the Victoria Harbour since the Second World War, after the record high of 3.96 metres during the passage of Typhoon Wanda in 1962.

Figure 8 - Sea flooding at Tai O during Typhoon Hagupit in 2008, photo courtesy of Television Broadcasts Ltd.

The maximum sea-level recorded during Typhoon Hagupit is an event with a return period of about 50 years based on statistical analysis. With a sea-level rise of 0.41 m due to thermal expansion of sea water by the end of the 21st century as predicted by IPCC's AR4, such a maximum sea-level would have a return period of 5 years. For the predicted sea-level rise of 0.59 m due to both thermal expansion and melting of land ice, this sea-level would have a return period of 2 years. The reason for increased occurrence follows from the fact that weak storm surges riding on a raised sea-level can reach a height previously caused by severe surges only. Hence, a rare sea flooding event occurring once in half a century on average in the past would become a biennial event.

In the case of the alternative prediction of 1.4 m by end of the 21st century as suggested by Rahmstorf, a maximum sea-level of 3.5 m could be reached even during ordinary spring tides (about 2.1 to 2.5 m above chart datum) which occur twice a month after new moon and full moon. A return of Wanda or Hagupit would be disastrous as the total sea-level would easily exceed 5 m, posing severe threats to the coastal low-lying areas.

Return period (years)	Extreme sea-levels (metres above chart datum) at Victoria Harbour			
	based on past data	after SLR of 0.41 m	after SLR of 0.59 m	after SLR of 1.4 m
2	2.9	3.3	3.5	4.3
5	3.1	3.5	3.7	4.5
10	3.3	3.7	3.8	4.7
20	3.4	3.8	4.0	4.8
50	3.5	4.0	4.1	4.9

Table 1: Magnitude of extreme sea levels at Victoria Harbour after projected sea-level rise (SLR).

IPCC has already started work on the preparation of a fifth assessment report (AR5) which should be finalised by 2013 to 2014. While some may like to wait for the outcome of AR5 on mitigation actions to be taken on sea-level change, early preparation may be relevant in projects and planning that take decades to complete.

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