Sustainability Risks of Coastal Cities from Climate Change

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Abstract: Issues influencing the sustainability of coastal cities are assessed, reflecting the combination of impending sea level rise and storm surges, and increasing growth in populations in coastal cities. Geologic-time scales are utilized to draw parallels to characterize relevant historical occurrences that help to understand the context of projections of impending sea level rise issue to year 2100. Given that Antarctica holds sufficient water to raise global sea levels by 58 m if the ice were to melt, this indicates that even a small percentage of melting of the polar ice caps, should this occur, will have enormous implications to the sustainability of coastal cities which are projected to hold 12.4 percent of the world's population by 2060. The result is the combination of predicted sea level rise and associated storm surges indicate that drastic measures must be promoted to improve the sustainability of coastal cities.

Keywords: Climate change, sea level rise, population growth, sustainability, coastal cities.

INTRODUCTION

Awareness continues to grow that climate change has enormous implications to water supply security issues. Nowhere is this more relevant than in coastal cities. Increasing the concern is that the world's populations are dramatically increasing, and water-related disasters are occurring at unprecedented rates. The array of issues indicate that water security issues will be one of the most important challenges of the 21st Century [1].

Extensive writings are now acknowledging that current trends of water security are untenable. Most researchers are developing their arguments based on recent data records (e.g. [2-15], and many more). However, it is equally appropriate, as well as equally foreboding, to examine geologic timeframe information as it relates to water security issues [16]. In geologic-time dimensions, the assessments described in this paper are based in part on the information assembled from geologic-time data. As described in Clough [16], and expanded upon herein, the geologic-time inferences and data interpretations demonstrate important illustrative dimensions that help to explain the urgency and context of current climate change interpretations that influence the future sustainability of the world's coastal cities.

Due to projected sea level rise, storm surges and tsunamis, as well as issues arising from population growth in coastal cities, the sustainability implications for coastal cities are profound. This paper describes some of these important ramifications in terms of exposure risks that will dramatically influence the long-term sustainability of coastal cities.

SEQUENCE OF EVENTS OVER GEOLOGIC-TIME

The implications arising from the effects of both climate change and population growth exist with dimensions including, but not limited to, intensive rainfall events, rainfall-induced mudslides, decline of groundwater levels, drought, and onshore storm surges and tsunamis. In many respects, some climate change impacts have been evident for decades. However, as will be described below, impacts which are being reported in the media today can be paralleled to transformative events which have occurred over geologic-times measured in millions of years. In fact, these issues are now being demonstrated through elaborate and exhaustive explorations of events over geologic-time, and are being supported by increasing amounts of information which are providing awareness and understanding.

Although the impacts of climate change influence the entire world, climate change implications are particularly relevant to cities along the world's coastlines due to impacts that include, but are not limited to, flooding, hurricanes and storm surges, erosion, and saltwater intrusion. Approximately 40% of the world's population lives within 100 km of a coastline, in an area constituting just 10% of the earth's land surface [17, 18]. In 1998, over one-half the population of the planet (about 3.2 billion people) lived and worked in the coastal strip just 200 km wide while a full two-thirds, four billion, were found within 400 kilometers of an oceanic coast [19].

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An alternative means of identifying the magnitude of sustainability issues for coastal cities is to use the Low-Elevation Coastal Zone, or LECZ, as a metric defined as any contiguous and hydrologically connected zone of land along coastlines less than 10 m of elevation above current mean sea level [20]. Most of the world's megacities are located in the LECZ [21], and many are situated in large deltas. As Neuman *et al.* and Merkens *et al.* [22,23] have indicated, the populations of the LECZ are predicted to reach the proportions listed in Table **1**, such that large percentages, specifically 12.4%, of the world's population, is projected to be in the LECZ by 2060. More specifically, the most susceptible countries in terms of populations at risk include China, India, Bangladesh, Indonesia, Viet Nam, Egypt, Nigeria, and The Netherlands where, for example [22], Bangladesh has 40% of its population in the LECZ, and The Netherlands has 73% of its population in the LECZ.

Table 1: Populations of LECZ and of the World, with Time (as per [22])

Year	Population in the LECZ (in billions)	World Population (in billions)	Percentage of world population living in the LECZ
2000	0.63	6.1	10.3
2030	0.88-0.95	8.7	10.1-10.9
2060	1.4	11.3	12.4

Large percentages of the world's population live on, or near, coastlines for reasons including those of commerce, to facilitate the shipping of goods, tourism/recreation, and the supply of subsistence resources. With intensifying impacts arising from climate change (measured by rising ocean levels and stronger hurricanes/typhoons and severe storm surges), there are important implications to coastal cities as a result of their location. By gaining perspectives and understanding of historical events, improved understanding of ongoing issues influencing sustainability become more evident.

Consider geologic-time which stretches over a period of 4.6 billion years, since the formation of the Earth (as indicated by Windley, [24]). Sediment cores and isotope measures from the deep ocean horizons revealed a climate event 55 million years ago that is, in many ways, analogous to the current potential global warming circumstances. During this Eocene period, there were large releases of carbon dioxide, specifically during the Paleocene Eocene Thermal Maximum (PETM), wherein 4000 to 7000 billion tonnes of carbon were released into the atmosphere within a few millennia [25,26]. These emissions have been linked to a catastrophic release from sea-floor methane hydrate reservoirs [27]. The temperature and carbon isotope signals at the PETM may be explained by the rapid release of a large amount of isotopically light carbon to the atmosphere as CO_2 and CH_4, the oxidation of any CH_4 to CO_2, and the acidification of the ocean by CO_2. These events lowered the pH, increased dissolution of $CaCO_3$, and resulted in profound changes to both the carbon cycle and the acidity levels of oceans, causing large swathes of marine chalk to dissolve. Another possible explanation of the massive release of carbon is the oxidation of organic-rich sediments during the India-Asia collision that may also have acted as a driving mechanism for elevated CO_2 concentrations in the atmosphere [28].

In response to the carbon emissions during the PETM, atmospheric CO_2 levels increased and were in the range of 650-3500 ppm [29]. The result of these carbon dioxide releases to the atmosphere created atmospheric concentrations greater than 1000 ppm, which have been characterized as having led to an increase of global average temperatures of 5^{o} to 8^{o} C due to the large perturbation of the carbon cycle [25, 26, 30-34]. The CO_2 levels in the PETM are reported to have been followed by their gradual attenuation over several hundred thousand years [35].

For purposes of allowing comparisons with current times, the Anthropocene is a proposed epoch representing an era defined by timeframes in which humanity has significantly influenced the earth's geology and ecosystems. Alternative definitions of the starting point of the Anthropocene exist, but one is that the Anthropocene began about 1950 (see http://www.telegraph.co.uk/science/2016/08/29/earth-entered-new-anthropocene-epoch-in-1950-scientists-say/)). Other definitions for the start of the Anthropocene in approximately 1950 have been suggested as the time of nuclear weapons fallout (e.g. plutonium 239 used in 1945 in aboveground nuclear weapons tests [36]). As depicted in Figure **1**, on a timeline relevant to the Anthropocene, the dramatic, increasing human populations over time are clearly evident.

It follows that the human influence on the global hydrologic cycle is now considered the dominant force behind changes in water resource systems on a global scale, resulting in the Anthropocene as the new

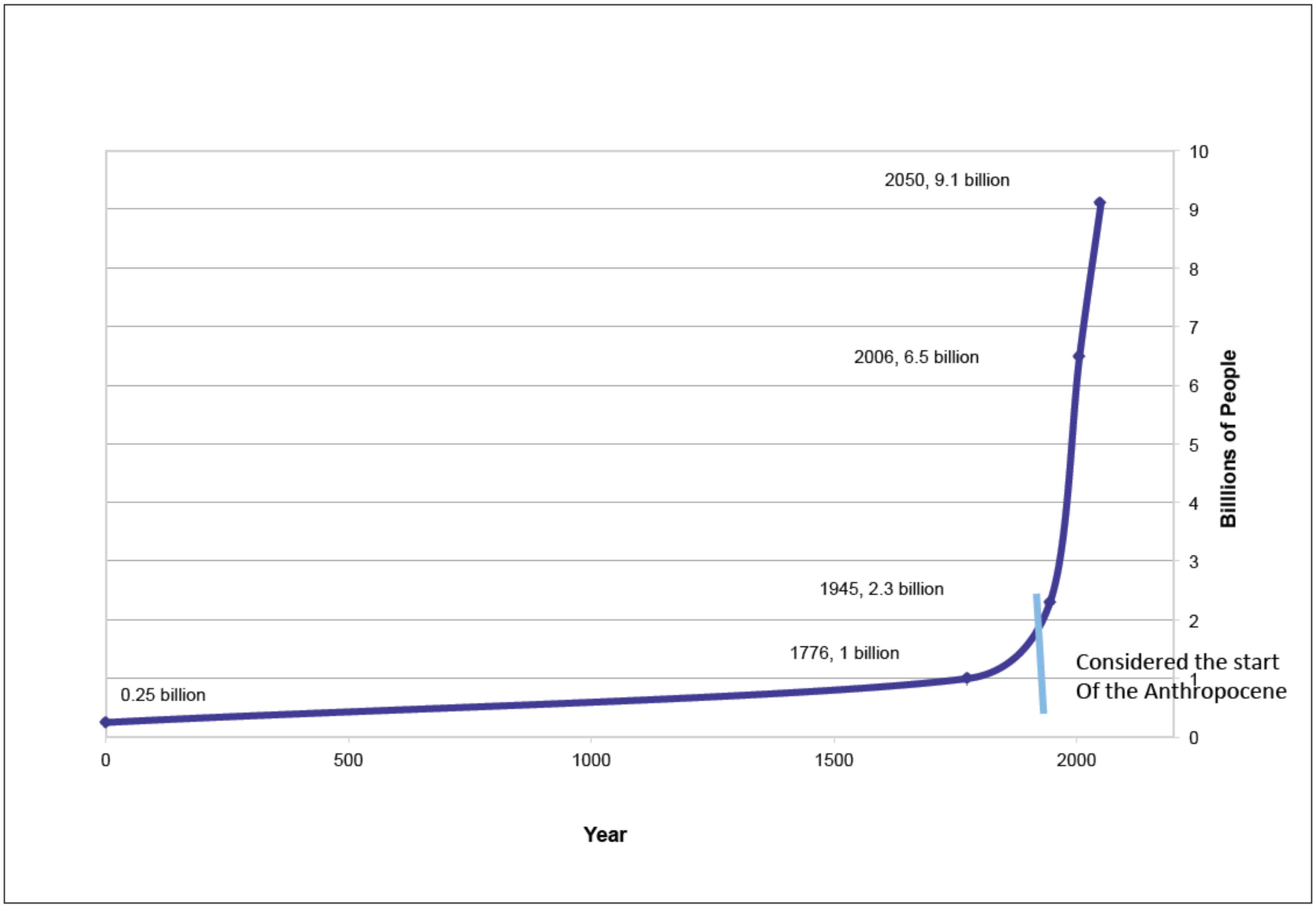


Figure 1: Population growth over time.

geological epoch. The potential ramifications of human input become clearer with recognition that current greenhouse gas emissions magnitudes are estimated as 35-40 billion tonnes/year or, equivalently, that collectively, the releases will approximately equal the total PETM releases in 100 to 175 years for carbon dioxide pumped into the atmosphere assuming they continue at their current rate. The current (2015) emissions are two-thirds larger than emissions in 1990, showing alarming increases over time [37].

Given the above, these PETM issues are useful in understanding how today's ongoing climate change may impact the sustainability of coastal cities:

1. **Example of Evolution of Continental Systems That Demonstrate Engineers Can Influence Nature, But Engineering Has Limitations** - Figure **2** depicts how North America would have looked 50 million years ago in the early Eocene (from Blakey [38]). The most important observations that differentiate the present-day North American landscape from that of the early Eocene, include: (i) Hudson's Bay did not yet exist, (ii) Florida was under water, and (iii) land access existed between Asia and North America, indicating the low sea level allowed human migration from Asia to the Americas [39].

2. Over the subsequent 50 million year period to present, surface water flows which were northward across North America (see Figure **2a** of [40]) in the Eocene evolved to the current situation (Figure **2b** of [40]) where the primary drainage now flows south via the Mississippi-Missouri River.

3. **Global Mean Temperatures Change Over Time** - The Global Mean Surface Temperatures from 1880 to present are illustrated in Figure **3** [41]. These results show the rapid increases in global temperatures that have occurred over the last 125 year period. Figure **3** demonstrates temperatures followed a steady increase in recent years, and that 2016 was the warmest year on record.

Figure 2: North America in eocene epoch [38].

4. **Atmospheric Carbon Dioxide Levels Are Increasing at an Unprecedented Rate** - Atmospheric CO_2 concentrations for the period from 45000 years ago to 15000 years ago hovered around 200 ppm CO_2 ppm; followed by a relatively rapid escalation to 260 and slower increases to 280 ppm CO_2 until about 1000 years ago; finally, very rapid increases from 280 to the current level of 365 ppm CO_2 in the last few hundred years [42]. Given the reference above to atmospheric carbon dioxide exceeding 1000 ppm, the rapid increases over the last 1000 years indicate that while CO_2 levels are currently only one-third those in the Eocene, the large magnitude and rate of increase of the CO_2 emissions in the Anthropocene is a major cause for concern.

5. **Sea Level Changes Over Time Have Been Large** - The global average absolute sea level changes over the period 1880 to 2015 have risen by 9 cm (3.5 in) in the last 130 years [43]. In the longer, historical context as depicted in Figure **4**, sea levels have risen by 122 m (400 ft) over the last 18000 years as a result of the post-glacial sea level rise as reported in Titus *et al.* [44]. Added to the abscissae of Figure **4** are the times of the Holocene and the age of industrialization to provide context. With the onset of deglaciation, rapid changes in sea level occurred, culminating in responses due to major ice-loss events related to ice sheet collapse (in particular, occurring in Antarctica) [45-47].

The above indicate changes in temperature, carbon dioxide, and sea levels that have occurred. During the last glacial period, the most recent "Glacial period" that took place from circa 110,000 to approximately 8,000

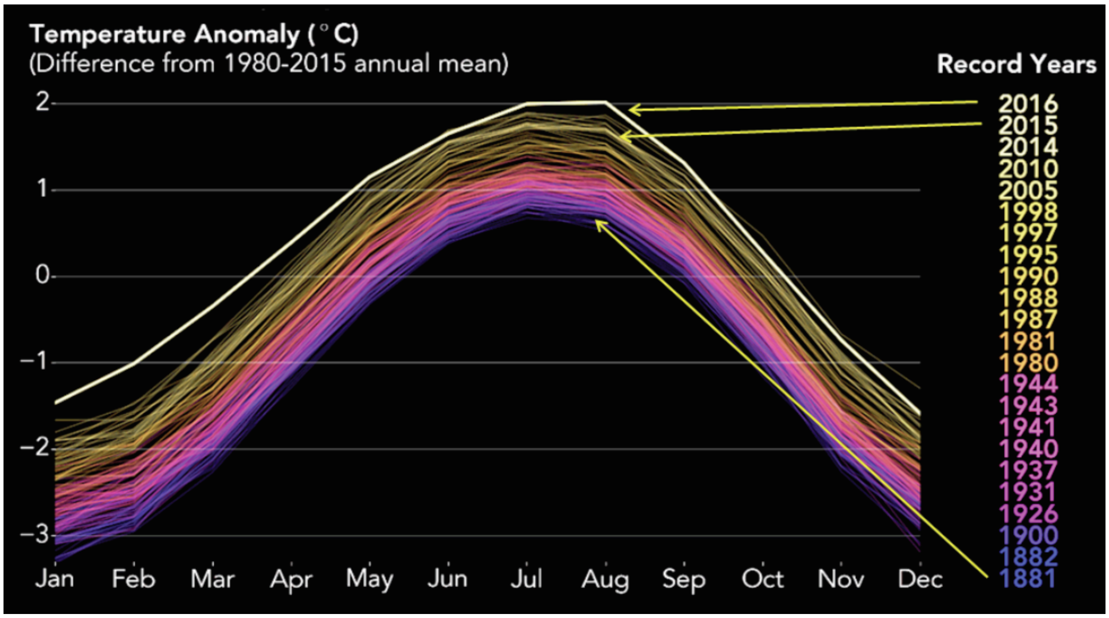
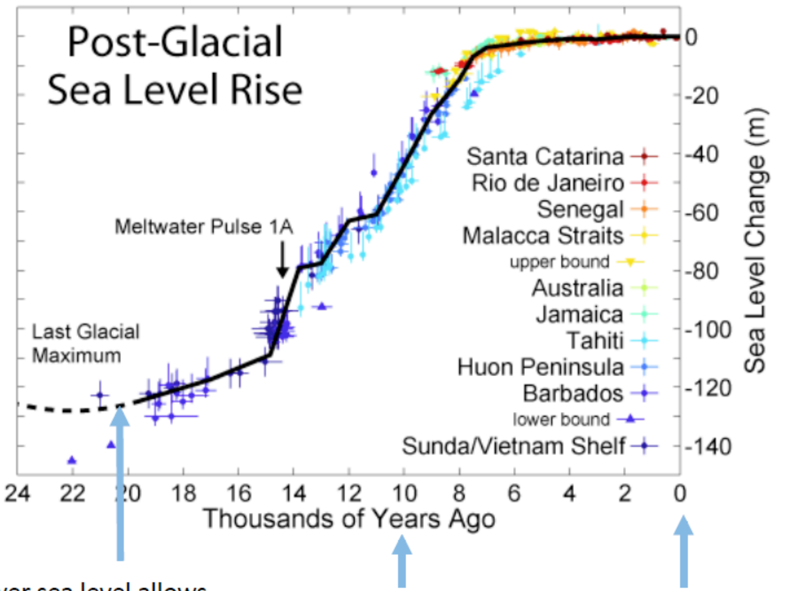


Figure 3: Temperature differences from 1980-2015 mean (after NASA, 2017).



Lower sea level allows
Migration to Americas

Age of Holocene
4-5 million humans

1800 – Age of Industrialization
~1 billion people

Figure 4: Post – Glacial Sea Level Rise. *Reference*: Adapted from Wikipedia. Sea Level Rise, accessed Nov 8, 2016 – This figure was prepared by Robert A. Rohde from published data, and is incorporated into the Global Warming Art project.

years ago. These dimensions of fluctuations [48], showing escalation of both CO_2 and sea level changes over time indicate some of the context of evolution to where the world is today.

WATER EQUIVALENTS IN THE ANTARCTIC AND ARCTIC OF POLAR REGIONS

Investigation of the potential for sea level rise in the future must include the implications of the melting of ice in the polar regions. The Greenland and Antarctic ice sheets combined hold 99% of the world's fresh water. Although Antarctica and Greenland are deserts (with about 8 mm/yr liquid equivalent of precipitation), there are such enormous quantities of water in these polar regions that even a minor fraction of melting has important implications to sea levels for low-lying lands (and hence, the environment of the earth's population living in the LECZ) as described below.

The area of Antarctica is 14×10^6 km^2 or approximately twice the size of Australia or continental US. There is, on average, 2750 m (9000 ft) of ice and 15 m (500 ft) of land above current sea level in Antarctica. At the South Pole, ice thickness peaks at 4776 meters [45]. As a result of these enormous volumes of ice, Antarctica holds sufficient water to raise global sea levels by 58 m if all of the ice melted [45]. It is noted that although the melting of the Antarctica ice will be at a slow rate (potentially requiring approximately 1500 years), even small percentages of polar ice cap melting will have enormous implications to sea level rise as melting continues. Even a two percent melting of Antarctica will translate to a 1.2 m change in the mean sea level. From available evidence, there is likely to be a continued melting in both polar regions with no replacement of ice mass due to the abovementioned desert conditions.

IMPLICATIONS OF SEA LEVEL RISE COMBINED WITH POPULATION INCREASES

Even today, groundwater is a primary source of drinking water in many coastal areas. An example of the existing precarious issues of security of water is from Lacombe and Carleton and Barlow and Reichard [49, 50] who have shown that groundwater withdrawals have lowered groundwater levels by 30 m, and are below existing sea levels, resulting in intrusion of salinity into the groundwater aquifer. As sea levels rise, onshore storm surges intensify, and as populations increase, salinity intrusion issues will intensify.

Onshore storms also highly influence the sustainability of coastal cities. Hurricane Katrina in 2005 generated an 8.47 m surge [51] which claimed more than 1800 lives in Mississippi and Louisiana. Meteorologic, oceanographic and geographic factors influence the extent of impact of storm surges and hence, the magnitudes are location-specific, but the result of the above is that our abilities to protect coastal regions are limited. When the storm surge magnitude of 8.47 m is combined with sea level rise of approximately 1 m by 2100, the LECZ definition of 12.4% of the projected world's population by 2060 at risk indicates the challenge.

Sea level rise as relevant to current times is being estimated as between 2.6 to 2.9 mm/year since 1993 (Watson et al., 2015) [52]. For the period 1870 to 2004, global average sea levels are estimated to have risen a total of 195 mm [53]. Given the above circumstances, and indication of the implications of these changes and where people live, the 20 coastal cities at greatest risk in the world according to Nicholls *et al.* [54] are indicated in Figure **5** are at greatest risk due to coastal flooding. As climate changes, larger cyclonic storm surges are occurring. Flood exposures are increasing in coastal cities owing to increasing populations and assets/infrastructure. Compounding the effect is that in China, the world's most populous country, migration is causing the growth of populations in coastal areas to be at three times the country's natural rate of population growth [22]. From cities illustrated in Figure **5**, logic demonstrates the economic threats (population levels and level of commerce and trade activity) from rising seas are enormous.

Sea level rise predictions indicate that a 400 mm (15 in) rise would result in 7 to 10 million refugees in Bangladesh alone, and a rise of 200 mm (8 in) would create 740 thousand climate refugees in Nigeria [48]. Sea level rise is one of the lines of evidence that supports the awareness that global climate is warming (e.g. see https://blogs.scientificamerican.com/news-blog/maldives-drowning-carbon-neutral-by-2009-03-16/).

A sea level rise of between 0.3 m to 1.22 m from current conditions is predicted by 2100 (which is not infeasible when viewed in the context of Antarctica melt, as referred to above). This prediction includes the effects of thermal expansion of water and the progressive melting of major ice sheets and glaciers (IPCC, 2013) [48].

Further magnifying the sea level impacts to coastal cities are storm surges. However, the magnitude of greatest interest is not sea level alone but the elevation above mean sea level, namely the storm tide. For example, a 6 m storm surge would result in a 7 m storm tide if the surge happened at a high tide of 1 m. However, waves on the top of the storm tide break when they reach shallow water, resulting in an external 'high water mark'. The result, in Biloxi, Mississippi, for example, was a high tide of .3 m, and 3.7 m high waves on top of the 7.3 m storm surge (at Biloxi) in Hurricane Katrina; the result was a high water mark of 11.4 m [55].

The inundation, flooding, coastal erosion and saltwater intrusion associated with the sea level rise and storm tide will result in enormous issues for sustainability of coastal cities. The inundation, flooding, coastal erosion, and saltwater intrusion will be severely impacting the sustainability of coastal cities. Storm surges and the associated salinity intrusion, are

Figure 5: The top 20 cities exposed to coastal flooding [54].

worsened by extreme events such as hurricane/ typhoon storm surges. 'Once in a century' storm surges may become 'once in a decade surges' [56]. People are becoming increasingly hesitant; even now, real estate buyers are not asking how close a home is to the water's edge but instead, "how far back it is from the waterline. How many meters above sea level? Is the unit fortified against storm surges? Does it have emergency power and sump pumps?" [57].

Even a relatively small sea level change may result in large changes in risk because people and infrastructure aren't prepared to deal with the effects of ocean level rise. In some locations, developments have moved back further from the shore (e.g. in Texas, due to recurring hurricanes) whereas in many other locations, such adjustments are not evident.

Sustainable measures to adapt to climate change are necessary. Coastal adaptation measures need to reflect changes in storm tide in addition to sea level rise. Indications of needs include:

1. Avoid attracting populations and assets by constructing coastal defences which are intended to protect them for today's risks, but may fail in future events;
2. Use an 'ecosystems approach' which can lead to more sustainable solutions by taking into account the value of ecosystems such as those which support food, recreation and water purification;
3. Broaden efforts to protect people and property by considering conservation and restoration of marshes, seagrass beds, coastal forests and coral reefs that help to buffer coastlines from waves and storm surge along with the engineering solutions and provide collateral benefits to people;
4. Include consideration of options such as prevent backflow by pumps at wastewater outlets, and adopt stormwater valves to address more frequent and intense flooding;
5. Relocate facilities to higher elevations including wastewater treatment plants; and,
6. Develop crisis management and contingency plans to include early warning systems and evacuation plans. Water rises quickly (e.g. 2 to 3 m in just minutes), and the storm surge has sufficient power to sweep a car away and citizens must be made aware of these circumstances.

The above are but a few of the approaches that need to be considered, to improve the sustainability of coastal cities.

CONCLUSIONS

With the increasing understanding of geologic-time features related to sea level, the evidence is becoming increasingly clear that climate, and in particular, sea level rise and increased storm surges, support the argument that these issues will be increasingly challenging the sustainability of coastal cities. Given the magnitudes of current greenhouse emissions in comparison with CO_2 concentrations estimated as a result of PETM CO_2 emissions, global warming is clearly supportable. As well, with the magnitudes of water in the polar ice caps such that even a small increase in melting, the basis exists to support increases in mean sea level rise having enormous impacts to coastal cities. As a consequence, projections indicate that approximately 12 percent of the world's population (those residing in the LECZ by the year 2060) will be severely impacted in coastal cities. The combination of an approximate 1 m rise in sea levels and the concomitant storm surges (e.g. such as the 8.7 storm surge in the case of Hurricane Katrina in 2005) will greatly impact the sustainability of these coastal cities.

Resilience and sustainability of coastal cities in response to rising sea levels and population growth are clearly at risk.

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