Amplification of Relative Sea Level Rise by Land Subsidence

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Global mean sea level (GMSL) is currently measured from satellite observations of absolute sea level – the distance of the sea surface from the center of the earth.Eustatic sea level changes are global mean sea level changes related to changes in the volume of water in the ocean. These can be due to changes in the volume of glacial ice on land and thermal expansion of the water, both of which are affected by climate change (Risk Frontiers, 2023), GMSL can also be affected by changes in the shape of the seafloor caused by plate tectonic processes or subsidence of the seafloor under the weight of the extra water in the ocean basin that comes from melting glaciers and ice caps.

Rising sea levels are often attributed to climate change, but recent papers by Nicholls et al. (2021) and Wu et al. (2022) have revealed that, while much of sea level rise in coastal cities is indeed due to human activity, the main cause is land subsidence due to groundwater extraction, rather than human-induced global warming. Changes caused by local subsidence or uplift of the crust are called isostatic sea level changes.

Historically, global mean sea levels have been both lower and higher in the past than at present. Since the end of the last ice age, the average level has risen about 120 meters, tapering off to an almost constant level about 6,000 years ago, as shown on the left side of Figure 1. During the 20th century, the worldwide average sea level rise was about 15-18 cm, based on tide gauge measurements, as shown on the right side of Figure 1. As described by Webb (2023), anthropogenic climate change led to accelerating sea level rise starting around 1870. Since that time, the average rate has been 1.1 mm/year, but it has been gradually increasing. Studies estimate current GMSL rise to be between 2.5 and 3.5 mm/year in recent decades (Webb, 2023; Nicholls et al., 2021). Much of this is due to increased glacial melting as the global climate gets warmer, but a large part is due to thermal expansion of the water (Risk Frontiers, 2023).

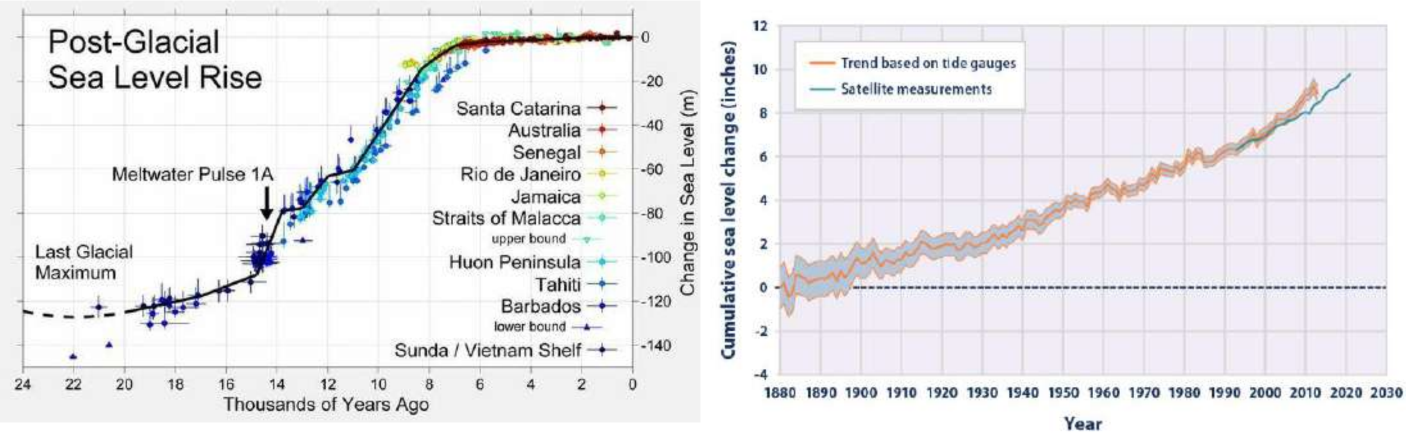

Figure 1. Left: Measurements of Global Mean Absolute Sea Level (GMSL) since the last glacial maximum. Source: Robert A. Rhode, Global Warming Art Project, Wikimedia Commons. Right: Global Mean Absolute Sea Level (GMSL) change, 1880–2021; the shaded band shows the likely range of values based on the number of tide gauge measurements collected and the precision of the methods used. Source: US EPA (Public domain), via Wikimedia Commons.

CITIES ARE SINKING WHILE SEA LEVEL IS RISING

Wu et al. (2022) measured subsidence rates in 99 coastal cities around the world between 2015 and 2020, using data from a pair of Europe's Sentinel-1 satellites. The subsidence rates for each city were calculated from satellite images taken once every two months during the observation period, which enabled the researchers to measure the height of the ground with millimetre accuracy.They found that in most cities, part of the city is sinking faster than 2 mm/yr. In 33 of the 99 cities, part of the city is sinking more than 10 mm/yr, three times faster than the current rate of global mean sea level (GMSL) rise. Cities with fast sinking regions are located throughout the world, including in Europe, North America, Africa, and Australia.The cities where subsidence has been the fastest (over 20 mm/yr) from 2015 to 2020 are in South, Southeast, and East Asia. The highest subsidence rates occur in Tianjin, Semarang, and Jakarta, where maximum rates exceed 30 mm/yr, about 10 times the rate of mean sea level rise. The maximum rates in Brisbane, Sydney, Melbourne, Adelaide, Perth and Christchurch lie between 5 and 10 mm/yr, and that in Auckland is between 10 and 20 mm/yr. Nicholls et al. (2021) similarly note that as coastal inhabitants are preferentially located in subsiding locations, they experience an average relative sea-level rise of 7.8 to 9.9 mm/yr, three to four times faster than GMSL.

The subsidence measured by Wu et al. (2021) and Nicholls et al (2021) causes the Relative Sea Level (RSL) as measured by tide gauges to diverge from the satellite GMSL values on the right side of Figure 1. Subsidence of the land independently of GMSL sea level amplifies the RSL rise and causes it to be higher than the GMSL value.However, it is the tide gauge measurements of RSL, not GMSL, that matter to the local community and its engineers and planners. Whether or not tidal cycles or storms cause flooding of critical coastal structures depends on the RSL measured at that location. Adaptation needs to be based on RSL, not GMSL sea levels determined by satellite.

MECHANISMS OF LAND SUBSIDENCE

Several different processes can affect subsidence or uplift of land. Tectonic movement affects areas with active faults in both a steady manner (gradual pre-seismic and post-seismic deformation) and a transient manner (when earthquakes occur).This mainly occurs along coastlines where plate tectonic subduction is occurring around the margins of the Pacific Ocean, and generally causes coastal uplift. Long-term glacial rebound following melting of the last ice age's heavy ice sheets is causing land to rise in high northern latitudes.This is occurring at a slow and steady rate of a few mm/yr. However, in many regions, the ground is sinking because of sediment settling and aquifer compaction. Although these can happen naturally, they can be greatly accelerated by human activities, including ground water extraction related to rapid urbanization and population growth, oil and gas production, and the weight of buildings in cities.

To estimate the effect of the weight of buildings in New York City, Parsons et al. (2023) calculated the subsidence from the cumulative mass and downward pressure exerted by the built environment in historical time.The results depend on near surface geology as well as the underlying bedrock, which influence the severity and longevity of subsidence. The surface geology of New York City is a complex glacial terrane, requiring the use of different rheologic soil profiles ranging from nonlinear soils, linear elastic soil, to linear elastic bedrock.Clay rich soils and artificial fill were found to be especially prone to significant building settlement, with subsidence ranging from 75 to 600 mm since measurements began.The nonlinear elastic models have a subsidence range between 25 and 425 mm, the elastic soil models range between 25 and 375 mm, and the linear elastic bedrock models have subsidence levels that range from 0 to 5 mm. Straus et al. (2021) found that their estimates of total climate-linked sea level rise in New York at the time of Hurricane Sandy in 2012 are 24 to 48 mm lower than observed values, suggesting that this may be due to land subsidence.

UNDERSTANDING THE CAUSES OF LAND SUBSIDENCE

Erkens et al. (2015) compared the state of subsidence research and policy development in five cities: Jakarta, Ho Chi Minh City, Dhaka, New Orleans and Bangkok.
They sought insight into the processes causing subsidence in the urban environment that could be used to identify best practice cases. The left side of Figure 2 shows that land subsidence rates vary widely from city to city; a more recent figure showing similar data for eight Asian deltaic cities can be found in Figure 2 of Cao et al. (2021). Subsidence can differ considerably within a city area, depending on groundwater levels and subsurface characteristics. Values provided on the left side of Figure 2 represent an average for the local subsidence hotspots, with values as high as 4m. Some cities are currently experiencing an acceleration of subsidence resulting from economic growth in recent decades.

Erkens et al. (2015) found that in many cases, the underlying processes and the relative contribution of the different drivers is not well understood. Similarly, they found that the level of technical understanding, policy formulation and governmental engagement in cities is diverse. Whereas some cities are in an early state of research and policy development on land subsidence, others have already implemented measures mitigating subsidence and the resulting damage. Erkens et al. (2015) find that the different stages of development indicate that cities can learn from each other, thereby avoiding mistakes made by others. Cities that actively pursue a policy on subsidence have valuable experiences to share with cities that have just started to address their subsidence. Tokyo stands out as an example where subsidence has stopped after successful mitigation measures were implemented.

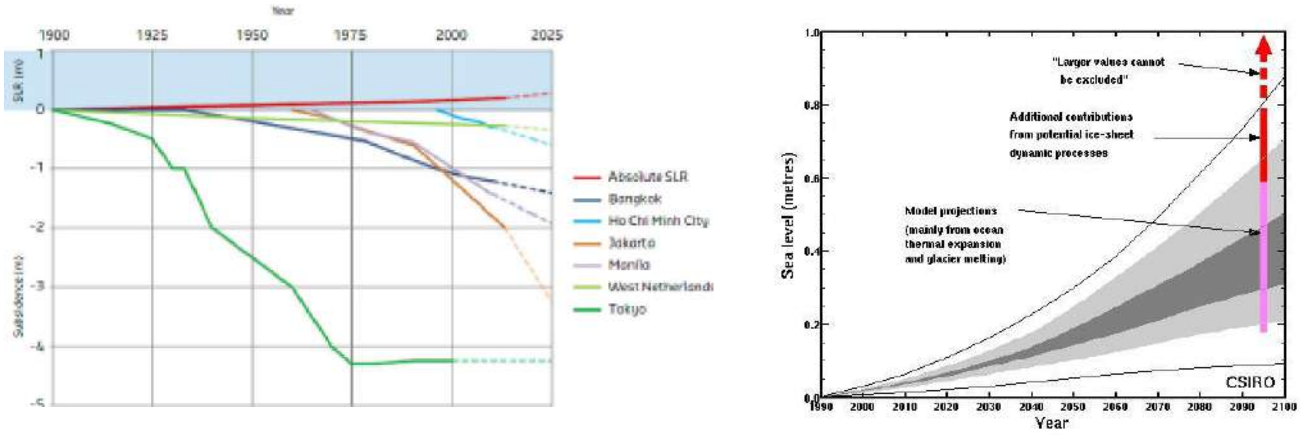

Figure 2. Left: Cumulative subsidence history in five coastal cities around the world. Absolute sea level rise is depicted as reference. Source: Erkens et al. (2015). Right: Future sea level projections to 2100 from the IPCC. Source: CSIRO, Creative Commons.

IMPACTS AND DAMAGE FROM LAND SUBSIDENCE

Erkens et al. (2015) identified two different types of damage caused by coastal subsidence. The first is increased flood risk (due to increased flood frequency, floodwater depth, and duration of inundation resulting from sea level rise and storm surge) and more frequent rainfall-induced floods due to ineffective drainage systems. This is mainly the result of non-differential subsidence, which is characteristic for large subsidence bowls that exist when groundwater or hydrocarbons at greater depth are extracted. Examples of cities that have increased flood risk due to subsidence include

Jakarta, Ho-Chi-Minh and Bangkok.
The second type of damage affects buildings, foundations, infrastructure (roads, bridges, dikes), and subsurface structures (drainage, sewerage, and gas pipelines). This is the result of differential subsidence. This commonly happens when earthquake faulting occurs, or when the subsidence is the result of shallow processes such as loading or drainage of soft soils. Examples of cities in which structures are damaged include New Orleans, Venice and Amsterdam. Over the longer term, however, cumulative subsidence of soft soils may also increase flood risk as for instance happened in the Netherlands (subsidence over the last ~ 1000 years) and in New Orleans (subsidence over the last ~ 150 years). The extent of the damage is different in the two cases: increased flood risk usually applies to a larger area than structural damage that applies to single structures or parts of a network.

MITIGATION AND ADAPTATION STRATEGIES

Future sea level projections to 2100 from the IPCC are shown on the right side of Figure 2; these may not account for accelerating Greenland and Antarctic ice sheet melting and sea level rise (Risk Frontiers, 2023). Major cities around the world are expected to grow disproportionately relative to rural areas, with a projected 70% of the world's population living in cities by 2050 (United Nations, 2019).As coastal cities grow globally, the combination of groundwater extraction, construction densification and sea level rise imply increasing inundation hazard. As these trends continue it will be important to develop mitigation and adaptation strategies to address inundation in growing coastal cities. Mitigation only works for human-induced subsidence. While subsidence is a large threat to the global environment, it can be remediated far more easily than climate change.

Erkens et al. (2015) note that monitoring of land level and groundwater extraction are important for understanding the cause of the subsidence so that effective mitigation measures can be designed. Typical mitigation measures include restrictions of groundwater extraction, artificial recharging aquifers, or raising phreatic water levels. Technologies such as satellites and radar can quickly identify areas of subsidence, while simple policies and tools can be used by local authorities to efficiently combat the problem. As shown on the left side of Figure 2, implementation of groundwater regulations in 1975 abruptly solved the problem in Tokyo. Other solutions to subsidence include finding alternative water sources, practicing efficient agriculture to use as little water as possible, and injecting water back into aquifers.

Cao et al. (2021) describe adaptation pathways for eight Asian deltaic megacities under sea level rise and land subsidence, including Tokyo, Jakarta, Manila, and Ho Chi Minh City. They found a common pattern of engineering-based countermeasures being implemented by the government after informal adaptation efforts by residents, characterised by reactive approaches that solve problems as they arise, and a decoupling of formal and informal adaptation strategies.

In order to improve the long-term sustainability and resilience of these cities, Cao et al. (2021) suggest that formal and informal adaptation should be synchronized and complementary, with adaptation governance aiming to include residents in decision-making processes to avoid social conflict and the creation of additional problems that could hinder the development of coastal cities. They suggest that future research should focus on the limits of the current adaptation pathways, as sea level rise will continue beyond 2100.

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