21W.034 – Professor Taft

Scientific American Update: Sea-Level Rise and Its Potential Impacts

It is a normal weekday in Miami at high tide, and traffic is backed up down Main Street. There's n congestion, crowded intersections, or traffic accidents. Instead, the streets are crowded with water that has come up through the sewers and flooded any low areas. One side of the road is completely impassable, and cars wait to use the one passable lane. This scene is depicted in *South Florida's Rising Seas*, a documentary directed by Kate MacMillin and Juliet Pinto. In interviews, many long-time residents of Miami say that used to think the flooding was due to burst pipes, and some wondered whether the water was safe to be in contact with. This type of flooding is now a common occurrence, and Southern Floridians are starting to understand that it is caused not by problems with infrastructure, but by the rising seas, which are proving to be more and more of a threat to everyday life on the coasts.

Southern Florida is one region already coming face to face with the dangers of sea-level rise, and many other coastal cities worldwide have already felt its impacts. Those located near river deltas or coastal wetlands like saltmarshes and mangroves will see more extreme impacts. In a 2010 review article from Science Magazine, Robert Nicholls and Anny Cazenave found that in the Eastern Hemisphere, tide levels have already risen considerably: the sea has risen and engulfed five meters of coastline in Tokyo, three meters in Shanghai, and two meters in Bangkok. Nicholls and Cazenave also found that in Southern Bangkok, extreme coastal subsidence has led to loss of more than one kilometer of coastline, causing entire developments to be washed out to sea. Because many of our largest cities and most densely populated areas lie on the coasts, sea-level rise poses a huge risk to many people worldwide, and will prove to be a crucial problem for the future of global infrastructure. Currently, models of sea-level rise vary widely in their estimates and the issue is still not fully understood by climate scientists. However, recent findings have supported that sea levels will undoubtedly continue to rise, and likely accelerate into future centuries.

The two primary causes for sea-level rise currently are melting of the polar ice sheets and thermal expansion of the ocean (which happens when rising ocean temperatures cause expansion of ocean water). About 10 percent of sea-level rise can be attributed to changes in land water storage, both by natural water cycles and by human factors like underground water mining, irrigation, deforestation, and the building and removal of dams. In their review, Nicholls and Cazenave note that since 1960, thermal expansion has accounted for 25 percent of sea-level rise, and 50 percent from 1993 to 2003. However, in the most recent decade, thermal expansion accounts for only a third of sea level rise. Thermal effects themselves have not decreased, but instead have been overshadowed by a rapid increase in the rate of glacier melting. On this subject, Nicholls and Cazenave found that from 1993 to 2003, less than 15 percent of sea level rise was due to melting of the ice sheets, but in the period from 1993 to 2009, more than 6 percent of the rate of sea level rise could be attributed to total ice mass loss. This drastic jump is a very startling indication of the melting that is now occurring in the Polar Regions, which scientists are trying to understand in greater depth.

Since the 1990's, new instrumentation has allowed scientists to better understand this ice mass loss. Nicholls and Cazenave describe several of these methods, including Satellite radar and laser altimetry, and the Gravity Recovery and Climate Experiment (GRACE) mission, which have provided highly accurate data on the mass balance of the ice sheets. Nicholls and Cazenave also found that in general, these models have agreed that ice loss in Greenland and West Antarctica is accelerating, nearly doubling its contribution alone in the time period from 2003 onward. Additionally, in a recent 2014 New York Times article, Coral Davenport writes that the summer melt season in Greenland now lasts 70 days longer than it did in 1972, as reconstructed from satellite observations. This marks a large change from conclusions made in the late 1990's, when scientists had limited methods for observing polar ice dynamics. In 1997, a Scientific American article, "The Rising Seas," discussed this topic, and its author David Schneider concludes that scientists then were actually not sure as to whether the polar ice sheets were growing or shrinking.

In their review, Nicholls and Cazenave note that rapid outlet glacier flow and iceberg discharge into the surrounding ocean can explain the majority of this ice loss. Especially in West Antarctica, where large ice sheets are being discharged into the sea, this sort of ice dynamics accounts for nearly all ice loss. However, according to Nicholls and Cazenave, in Greenland a significant cause of ice loss is the larger rate of surface melting in comparison to snow accumulation. They also discuss the idea that polar melting is linked to rising ocean temperatures, so as ocean temperatures increase with global climate change, this will trigger further ice discharge. Similarly, ice reflects solar radiation, while the ocean absorbs it, so as the area of the ice caps shrink, more sunlight will be absorbed and warm the ocean, which further contributes to this negative cycle.

Most models, although they rely on a variety of techniques, have agreed that since 1950 sea levels have been rising steadily by approximately two millimeters per year. In the 1997 Scientific American article, Schneider concluded that this rate is consistent over several studies. However, more recently, Nicholls and Cazenave report that between the years of 1993 and 2009, sea levels have risen 3.3 millimeters per year, with an uncertainty of about .4 millimeters per year. This point clearly shows that sea level rise will not only continue, but accelerate into the coming centuries.

Se levels have been difficult to measure for scientists because they vary significantly, not only regionally but with variation in natural processes. In areas like the West Pacific, sea levels have risen up to three times faster than the global mean due to regional variation in ocean temperature and salinity. Nicholls and Cazenave discuss additional factors like the uplifting of various parts of the ocean floor due to tectonic action, that make some areas appear to have sea level changes several times higher than actual rates. Scientists have developed ways to compensate for these effects by essentially "subtracting" the effects of plate shifting. Additionally, perturbations in natural ocean cycles such as ocean currents, which are affected by ice melt and freshwater runoff, change sea level measurements over scales of decades, which can skew data and make forming conclusions on sea level trends difficult.

As of today, model predictions range between 30 and 180 centimeters of sea-level rise by the year 2100. According to Nicholls and Cazenave, 3 centimeters essentially marks a continuation of current rates of sea level rise into the next century, while 180 centimeters would be the result of an extreme acceleration in sea levels caused by rapid ice melt. The largest unknown factor driving these models is the future behavior of the polar ice sheets and large glacial areas in the Antarctic, which has long been an area of debate for climate scientists. As recently as in Schneider's 1997 article, the scientists' results varied but all came to the general consensus that the polar ice sheets were relatively stable. Recent rates of melting in the Polar Regions recorded through satellite methods have suggested, however, that the ice sheets respond much more quickly to temperature changes than previously anticipated.

In a recent research study, "Timescales for Detecting a Significant Acceleration in Sea Level Rise," Ivan Haigh and his team explore various methods for analyzing historical sea level data to predict future accelerations in sea level. In the first method, historical data is analyzed and fit to a quadratic least-squares regression, which fits the data points to a curve to calculate their acceleration. Within this method, two data sets were used: one using tide gauge measurements from ten different coastal locations (coastal mean sea level or CMSL), and one averaged over many locations globally (global mean sea level or GMSL). For both models, when periods shorter than 90 years at a time were studied, the accelerations were not consistent and there was large variability in sea level over decades. However, Haigh found that in longer periods in the GMSL, consistently positive accelerations were present, which are predicted to increase and become more noticeable in tide gauge records in the 2030s.

In the second method, Haigh broke up the tide gauge data into shorter overlapping time periods, and for each found a line that best fit the data, comparing the slopes (the rates of sea-level rise) for each period. Again the model used data from CMSL (Coastal Mean Sea Level) and the GMSL (Global Mean Sea Level), showing that for 40-year overlapping periods both models predict rates of sea level rise in the late 2010s and early 2020s that are significantly higher than past rates (the CMSL data showing delays up to 5 years as compared to the GMSL). In both projection strategies, Haigh found that accelerations greater than the current rates of .1 millimeters per year are not projected to occur until the end of this decade into the next decades. This idea challenges arguments that increased rates would have been already detected for high-projection pathways (those with u to two or three meters by 2100, such as those predicted by the International Panel of Climate Change, or IPCC). Haigh's data strongly suggests that these types of rates are still entirely possible.

Perhaps the most pressing issue posed by sea-level rise today is its potential impacts on coastal regions, and the ways in which these regions will choose to adapt to the rising seas. Currently, research has shown that although sea level rises between two and three feet are predicted globally by 2100, this number could surge up to six feet on the East Coast, making many cities vulnerable to flooding. In her *New York Times* article, Davenport writes that only 1.5 feet of sea level rise would endanger six trillion dollars of property around Baltimore, Boston, New York, Philadelphia and Providence, R.I. Hurricane Sandy, which struck the East Coast in 2012, provided warning of dangers to come. Many cities experienced major flooding, including New York City, where the subway system was shut down due to flooding for several days. New York declared a state of emergency for every county, as many in Midtown Manhattan were evacuated and many more in suburban communities lost their homes to flooding.

In the southern East Coast, the city of Miami sits on a large bed of limestone, making the city even more vulnerable to flood damage because limestone deteriorates in the presence of salt water.

Davenport also references the Southeast Florida Regional Climate Change Compact (SFRCCC), which reports that sea levels in Miami could rise more than 24 inches by 2060. It also explains that this amount of sea-level rise would damage most small roads within the next 35 years, and destroy their highways by the year 2050.

Not only will many East Coast cities be in danger, but many island nations are already experiencing flooding events in their villages and fear they will soon lose their entire islands to the ocean. Davenport references findings of the Smithsonian Tropical Research Institute, where scientists have predicted that the islands of the San Blas archipelago, home to the indigenous Kuna people, will be underwater in the next 20 to 30 years. The government of Panama has already begun planning to relocate its people; some have agreed to the plan, while others have not and resist moving from their homeland. Davenport also writes that the low-lying islands of Kiribati, as well as other islands states like the Maldives and Tuvalu, will likely be forced to flee as well as a result of sea-level rise. The article also quotes President Anote Tong of Kiribati, who stated that sea water has already infiltrated fresh water sources and ruined crops, and predicts that the island will be completely uninhabitable in the next 30-60 years.

In planning for future sea-level rise, many coastal areas like these islands will soon need to decide (or have already decided) whether to attempt to build seawalls and dams as protection against the sea, or allow rising sea levels to overtake city areas and cause a widespread retreat from the shores. This decision ultimately relies on various social, economic, and political factors for individual regions. Davenport discusses some national and regional development plans that have already been made, such as in the Netherlands, where the government is planning to provide greater protection against sea level rise and greater level of safety for coastal development. The Netherlands is a very experienced country with the issue, and has been building dikes and levees to combat sea-level rise ever since the country experienced a flood in the early 20$^{th}$ century that took the lives of many Dutch civilians. However, adaptation in developing regions will be more complicated, as the country faces more limits to adaptation due to cost and other socioeconomic factors. Although the future of sea level rise is still unknown, the ways in which our societies choose to adapt will be crucial in the coming centuries, and will play a key role in its eventual impacts on life on the coasts.

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