Rising Oceans: Economics and Science

Geoffrey Heal[1] and Marco Tedesco[2,3,3,4]

First Draft March 30 2018

Updated: April 16th, 2018

Abstract

We provide a non-technical review of the literature on the possible extent of sea level rise over the course of this century, and its economic consequences for the US. Sea level is likely to rise between two and fifteen feet, depending on the assumptions made about the progression of climate change and the method used to estimate sea level rise. The consequences for the value of coastal property and infrastructure will be immense, with losses in value of several trillion dollars in the worst-case scenarios and significant losses in even the most optimistic scenarios.

[1] Columbia Business School, gmh1@columbia.edu
[2] Lamont Doherty Earth Observatory, Columbia University, mtedesco@ldeo.columbia.edu
3 NASA Goddard Institute of Space Studies, NY
[3] We are grateful to Guido Cervone, Harrison Hong, Radley Horton, Garud Iyengar, Benjamin Keys, Christopher Mayer, Maureen Raymo, Craig Rye, Gavin Schmidt and Park Williams for valuable comments.
[4] Heal acknowledges financial support from the Dillon Fund via the Program on Fiscal Studies at Columbia Business School and Tedesco from the Director's Office of the Lamont Doherty Earth Observatory at Columbia University

Introduction

Of the many and varied consequences of climate change, sea level rise is one of the easiest to relate to and visualize: we have all seen examples of coastal flooding from storm surges through media and news. And this makes it straightforward to understand that sea level rise – and hence climate change – has harmful economic consequences. Cleary trillions of dollars of property and infrastructure are at risk.

Investors in residential and commercial real estate, and those in infrastructure, are potentially exposed to risks of flooding, droughts and forest fires as a consequence of the reverberations of climate change on environmental factors and weather. Such risks are higher for stakeholders with properties close to the coast or in regions where drought and forest fires are increasing (e.g., the Western U.S.). Because of this, the financial institutions that finance their purchases and hold their securities are also exposed to these risks. To date these risks have generally not been properly considered nor quantified, but since Hurricanes Katrina and Sandy this has been changing. 2017's hurricane and forest-fire seasons (with four major hurricanes landing over southeast U.S. and fires in northern California killing more than twenty people) will surely catalyze this change.

It is currently hard for investors to assess the risks that they now face, and will face in the future from climate change. Sea level will rise, according to some estimates, by as much as ten feet or more by the end of the century. This will lead to inundation and increase the severity of storm surges, also expected to increase due to the projected growing strength of hurricanes and greater rainfall. In this paper we are reviewing the economics and science of sea level rise with the intention of providing an analytical background for the assessment of the risks associated with rising seas.

Economic Consequences of Rising Seas

Sea level has been rising for decades now, as shown in figure 1,[5] and the rate of increase is itself increasing (the rate is accelerating), as this figure also shows. As we explain in

[5] From R. S. Nerem, B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters, G. T.Mitchum, Climate-change–driven accelerated sea-level rise, Proceedings of the National Academy of Sciences Feb 2018, 201717312; DOI:10.1073/pnas.1717312115.

the section on the science of sea level rise, we don't know exactly how much sea level will rise: despite estimates pointing to an increase in mass loss of both Greenland and Antarctica, there are large uncertainties about the rates at which this will develop in the future, and also uncertainties about the quantities of greenhouse gases humanity will emit or will be released by other anthropogenically-driven processes (e.g., permafrost thawing) over the coming decades. And it is these greenhouse gases that are driving the melting. Despite the uncertainties, there is general consensus that sea level will not rise by less than two feet by 2100, and could rise by as much as fifteen feet. Even the lower end of this wide range, two feet, is sufficient to alter coastlines substantially: an outcome at the upper end of the range would be totally transformative of the US's coast line, with massive implications for coastal property and infrastructure.

As we explain below, the reason for this wide range of possible increases in sea level is that there are two different major approaches to estimating sea level rise and they yield different results. One approach models the contribution by the ice sheets and the thermal expansion of water, and extrapolates current and recent past trends: this approach yields estimates of an increase of a few feet. The other uses the historical record to assess how high the oceans were when the climate of the earth was last like it will be later this century, and finds that the oceans were then several meters above where they are today. This suggests that several meters of sea level rise have been the historical response to the conditions that we will encounter. It does not, however, provide an estimate of how rapidly this increase will occur – whether it will occur over decades or centuries.

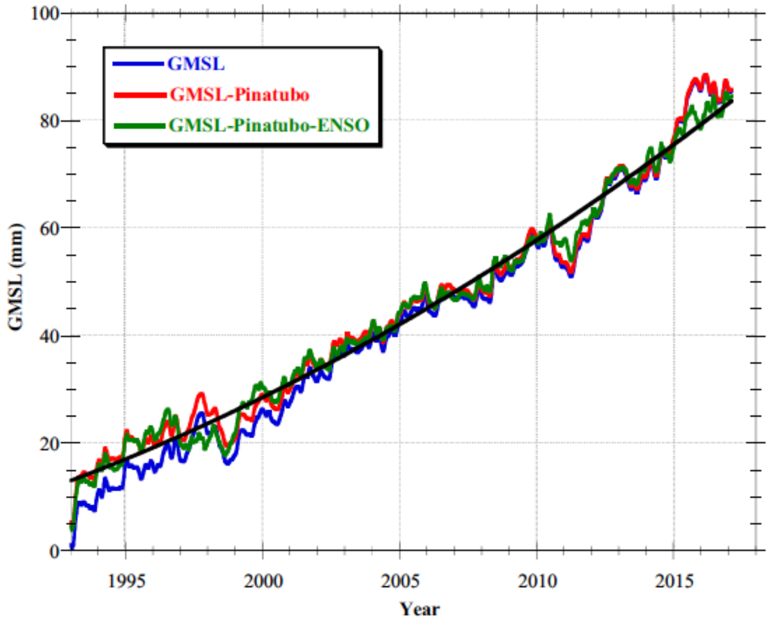

Fig. 1. GMSL from the adjusted processing of ref. 15 (blue) and after removing an estimate for the impacts of the eruption of Mount Pinatubo (12) (red), and after also removing the influence of ENSO (green), fit with a quadratic (black). The acceleration (0.084 mm/y^2) is twice the quadratic coefficient.

The consequences of higher oceans for business and the economy are far-reaching. Residential and commercial properties, agricultural land and infrastructure will all be affected. A very important point is that if a property is four feet above sea level now, and sea level rises three and a half feet, then this does not mean that it has escaped serious consequences. Property that is only a small height above sea level will be subject to flooding in storms and high tides to a degree that could greatly reduce its commercial value. Figure 2 shows possible historical flooding frequencies in Charleston SC and San Francisco and scenarios about how this frequency will increase over time as sea level rises, making relatively conservative assumptions about sea level rise and in particular assuming that both cities remain above sea level. Both cities could flood one hundred days a year or more by mid-century, independently on the CO2 emission scenario and clearly this is sufficient to disrupt business and daily life and greatly compromise property values, and can occur long before the area is submerged by the oceans. Flooding in Charleston has already increased from around two days per year in the 1970s to about ten events annually today, and the city could see a further increase of five to ten–fold by mid-century.

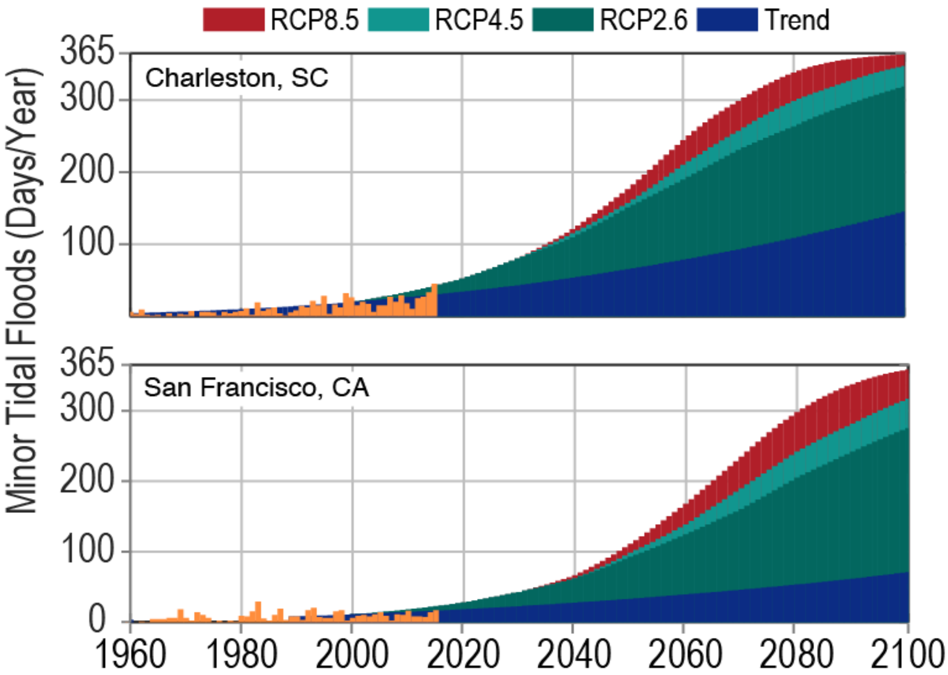

Figure 2: the frequency of flooding in Charleston SC and San Francisco in the future under various climate scenarios.[6]

Assets at Risk

Research by Climate Central (www.climatecentral.org, an independent organization of scientists and journalists) gives an estimate of the scale of the problem. A sea level rise of six feet would flood roughly 100,000 homes in New York City and would flood property in New York with a total value of $39 billion. A ten-foot rise would flood 300,000 homes and property with a value of almost $100 billion. The equivalent figures for Miami are 54,000 homes and property valued at $14 billion at risk with a six-foot rise and 130,000 homes and property valued at $32 billion for a ten-foot rise. By 2050 one billion dollars' worth of property would be at risk of regular flooding in Miami and ten billion dollars' worth in New York City. Table 1 summarizes this data.

[6] The different color bands correspond to different assumptions about future greenhouse gas emissions. These are the IPCC's Representative Concentration Pathways or RCPs. RCP 8.5 is a pessimistic scenario assuming that nothing is done to head off climate change, whereas RCP 2.6 is a very optimistic one assuming that the world moves away from fossil fuels completely by mid-century. This figure comes from https://science2017.globalchange.gov/chapter/12/

	New York City	Miami
6 foot rise	100,000/$39 billion	54,000/$14 billion
10 foot rise	300,000/$100 billion	130,000/$32 billion

Table 1: homes and property values at risk from flooding in NYC and Miami under 6 and 10 foot rises in sea level. Source: Climate Central

Figure 3 shows the possible property losses in the most exposed states of the US by 2050 and 2100, according to Hsiang at al. Note the huge increase between 2050 and 2100, and in particular the massive exposure in Florida, where one third of all housing is within ten feet of sea level.

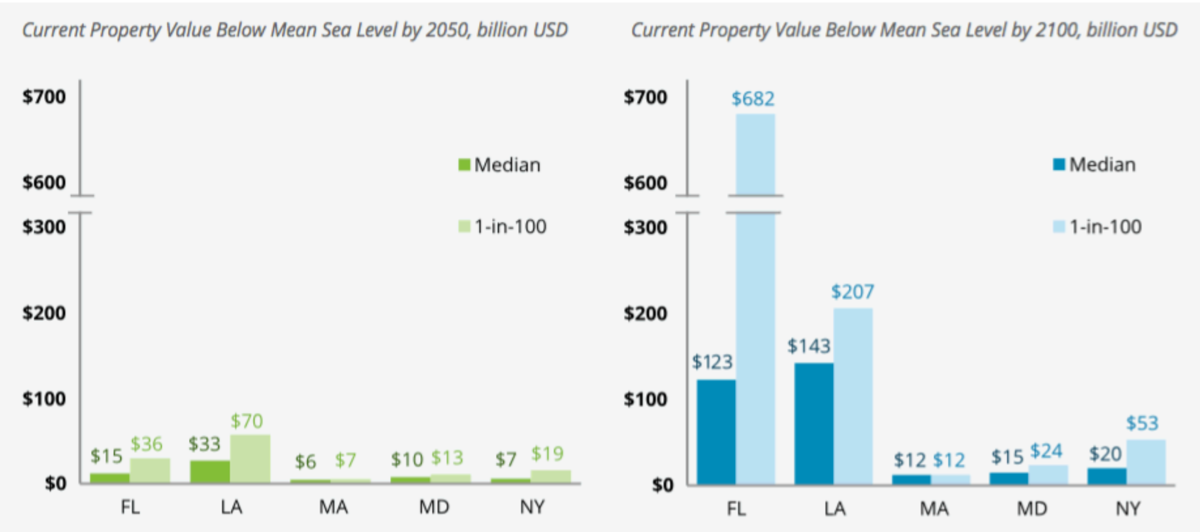

Figure 3: value of property at risk by state, 2050 and 2100. Source: Hsiang et al.

We have picked New York City and Miami because they are iconic cities, but they are no more exposed than other coastal cities: every coastal city or village in the world will be exposed to similar risks. A recent study by the World Banks ranked the world's cities according to their exposure to sea level rise, and found four US cities in the top ten in terms of expected annual average loss from flooding. The top ten cities are shown in Table 2.

Rank	City
1	Guangzhou
2	Miami
3	New York-Newark
4	New Orleans
5	Mumbai
6	Nagoya
7	Tampa-St Petersburg
8	Boston
9	Shenzen
10	Osaka-Kobe

Table 2: top ten cities in terms of expected annual average loss from sea level rise, from Hallegatte et al.

Coastal infrastructure also faces serious risks. During Hurricane Sandy, the three airports serving New York City were all flooded by the sea surge associated with the storm. In fact, many more major airports are vulnerable to a rise in sea level: according to the third US National Climate Assessment, twelve major airports have at least one runway within twelve feet of current sea level, meaning that with a sea level rise of only eight feet they could flood regularly. The airports at risk are listed in Table 3. This shows four airports within six feet of sea level and so especially vulnerable to flooding before the end of this century. The costs of moving an airport to higher ground are massive, and even the costs of hardening one against flooding are huge, assuming this is in fact feasible. Airports are of course not the only items of infrastructure at risk: another perhaps more important category is roads. Table 4 shows the miles of road within ten feet of sea level in the six most exposed states.

Airport Name/Location	Height above Sea Level [m]
Louis Armstrong/New Orleans	-1.7
Fort Lauderdale	5.2
San Francisco	5.4
Oakland	5.6
La Guardia	6.7
Isla Grande/San Juan Puerto Rico	6.8
Miami	7.4
Honolulu	7.7
Philadelphia	8.3
Newark	8.6
Ronald Reagan National/Washington DC	10.3
Tampa	10.6
JFK/New York	11.3

Table 3: Major Airports Vulnerable to Sea Level Rise. Source: Third National Climate Assessment, https://nca2014.globalchange.gov/report/sectors/transportation

State	Miles of road within 10 feet of sea level
Florida	10630
Texas	6136
North Carolina	3267
California	2634
New Jersey	2144
South Carolina	1872

Table 4: States with major exposure of roads to sea level rise: source Climate Central

Schools, ports, railroads and many other items of infrastructure are equally exposed to rising seas.

Financial Risks

These extensive risks to real property and infrastructure have financial counterparts. Much of this physical capital is financed by capital markets, with homes and commercial property funded by mortgages and public infrastructure by bonds, issued either by municipalities or by agencies such as the Port Authority of New York and New Jersey, the Metropolitan Transit Authority, etc. These mortgages and bonds are financial assets widely traded on capital markets, and a sudden drop in their value as a result of flooding could have repercussions throughout the financial system. The financial crisis of 2007-9 resulted from a sudden realization that some components of mortgage pools were much less valuable than had previously been believed, and its costs to the world economy were devastating, unprecedented (other than in wars) since the great depression of the 1930s. Assets at risk of abrupt revaluation due to recognition of sea level risks may be as extensive as the pool of sub-prime mortgages in 2007.

Closely related to the financial risks posed by non-performing property and infrastructure loans, is the risk of a collapse of a regional housing market. If it becomes clear that some property in a region is unsaleable because of flooding risks, there is a chance of contagion leading to an entire regional housing market freezing up. Buyers will stay out of a market where the risk of property loss seems real. In this they may be hastened by banks or insurance companies. Banks looking at financing coastal property may at some point decide that they can no longer give thirty year mortgages on the most exposed properties, and insurance companies may decide to stop covering property from storm and sea damage once the risk of this becomes great enough. The inability to finance or to insure (or re-insure) property could be enough to precipitate a collapse of the local market. Freddie Mac's recent publication[7] raises exactly this question:

"One challenge for housing economists is predicting the time path of house prices in areas likely to be impacted by climate change. Consider an expensive beachfront house that is

[7] See Freddie Mac, Life's A Beach

highly likely to be submerged eventually, although "eventually" is difficult to pin down and may be a long way off. ***Will the value of the house decline gradually as the expected life of the house becomes shorter? Or, alternatively, will the value of the house—and all the houses around it—plunge the first time a lender refuses to make a mortgage on a nearby house or an insurer refuses to issue a homeowner's policy?*** *Or will the trigger be one or two homeowners who decide to sell defensively?"*

Such a collapse seems a possibility in southern Florida, and possibly in some other east coast markets particularly exposed to sea-related risks. It would lead to huge financial losses for local property owners, households and businesses, and could have macroeconomic implications as those affected retrench to try to compensate for their losses. Some studies indicate that prices of homes in areas liable to increasing flood risks because of rising seas are already beginning to fall away from the mainstream, so far only by of the order of 5%, but another major storm could readily accelerate this.

These financial risks pose complex policy problems. Would governments feel obliged to compensate families who lose homes – generally their main asset – because of rising seas? Or to compensate those who suffer great financial losses even if their homes remain useable? A managed retreat from the coast seems a sensible response to these risks, but will no doubt be politically unpopular and hugely costly.

The Science of Rising Oceans

Sea levels are rising for two reasons. One is that water, like many materials, expands as it heats up. So the water column in the oceans grows taller as the oceans heat up. The second driver of rising seas is of course the melting of ground-based ice, such as glaciers and the Greenland and Antarctic ice sheets. If all ground-based ice on Earth were to melt, oceans would rise by over 200 feet, revolutionizing the coastlines of the world and destroying huge areas of human settlement.

It is easy to predict the thermal expansion of water, but sadly this represents only half of current sea level increase. On the other hand, it is extraordinarily hard to predict how fast ice sheets will melt, and this will be the main driver of future sea level rise. Hence the large margin of uncertainty in predictions of future sea level rise. There are two approaches to predicting how fast oceans will rise as a result of the melting of ground-based ice. One is to develop computer models of the dynamics of sheets and use these to extrapolate from recent history, and the other is to look at the historical record – the paleoclimate record – and use this to assess how high the oceans were at past times when climatic conditions such as temperature and greenhouse gas concentrations were similar to todays. In general studies of the historical climate record suggest much greater increases in sea level than modeling ice sheet dynamics or extrapolating the trends of the last few decades.

Since the beginning of the twentieth century, the global mean sea level (GMSL) has been rising at a mean rate of 1.7 ± 0.3 mm/year, according to data collected by in situ tide gauges,[8] Starting in 1993, satellite altimeter data has also allowed us to study the spatial distribution of sea level rise and provide improved estimates that don't rely purely on coastal data, as does that collected by tide gauges. Spaceborne altimeter data have measured a rise in global GMSL of 2.9 ± 0.4 mm/year starting in 1993 (through 2017) and is pointing to an 'acceleration' of GMSL of 0.084±0.025 mm/yr^2 (see Nerem et al). The acceleration component is extremely important as it indicates that not only is GMSL increasing but it is also doing so at a faster pace every year. Neglecting the acceleration term has large impact on the GMSL estimates: such a term, indeed, adds 56.4 cm to the 23.7 cm obtained from the linear term (2.9 mm/yr) during the 82 years until 2100. To put things in context, the contribution to GMSL due to the acceleration is of the same order of the SLR projected by 2100 under the RCP 8.5 scenario. Satellite altimeter data has also shown the spatial distribution of SLR, which is not uniform over the earth. This unevenness of SLR is due, among other things, to the thermal expansion of the ocean (which is uneven as different parts of the oceans heat by different amounts) and] to the changes in the gravitational field of the Earth associated with the mass losses from the Greenland and Antarctic ice sheets. The maps of sea level rise points to a larger increase along the east coasts of the United States and within the Gulf of Mexico, two areas that have already been experiencing recent floods and inundations.

Using the historical record to reconstruct GMSL from past eras can provide information on the total GMSL that we should expect to be associated with current and future

---

[8] e.g., Church and White, 2006; Bindoff et al., 2007

climate conditions. We use observational evidence of historical sea levels, and ice-sheet reconstructions through models. Studying the periods when SLR and GHG concentrations were similar to today can offer precious insights into how the Earth responded then to a changing climate and how the ice sheets responded. Scientists have identified three periods when GMSL was higher than today. (see Dutton et al) The first period, mid-Pliocene warm period (MPWP) occurred about ~3 million years ago (mya). During this period, CO_2 levels were similar to today's (ranging between 350 and 450 parts per million, ppm) with peak global modeled temperatures being on average 1.9° to 3.6°C warmer than preindustrial era.[9] For this period, ice sheet models simulate an increase in GMSL due to melting in Greenland and Antarctica of, respectively, ~ 7 and 6 meters for a total of 13 meters or 39 feet. The second period (denoted as MIS 11) occurs around 400,000 years ago (kya), when temperatures are estimated to be ~2.6°C warmer than preindustrial and reconstructed GMSL higher than present, with several records documenting at least partial retreat of the Greenland Ice Sheet. The third period (denoted as MIS 5e) occurred around 125kya and contains the best record. Recent studies accounting for the geographic distribution provided by a compilation of local sea level rise indicate that GMSL during this period was in the range of ~ 6 – 9 m (18-27 feet) above present, the Greenland Ice Sheet was smaller than present and undergoing substantial, though incomplete, retreat of the southern sector at the time when GMSL was peaking.

Unfortunately rates of sea-level change for previous warm periods when sea level was higher than present are at best highly uncertain. Yet understanding the SLR in the past is key for predicting and adapting to future sea-level change, as the reconstruction of historical GMSL offers a window into the potential maximum sea level (and associated rates of change) that can be eventually reached in the future. However, the past record might not be a perfect guide to the future: changes observed in the past occurred under different conditions than the ones occurring today. For example, in the case of the MIS 11 and MIS5e, warm climates and higher GMSL were largely driven by changes in the intensity of solar radiation at high latitudes, associated with changes in the earth's orbit. Beside quantitative differences in the drivers forcing the change, changes in solar radiation because of orbital changes act differently from the relatively more uniform

[9] Today we are about 1C above the pre-industrial era.

global warming associated with increased atmospheric CO_2 that will influence future sea levels. So although we can reconstruct sea levels associated with past eras when the climate was similar to where we are now or soon will be, these are not necessarily good predictors of where our sea levels are going. However, they represent our best information on what is the potential maximum sea level that can be reached during similar temperatures and CO_2 concentration conditions. Although these approaches give us a sense of what increases in sea level are possible given the climate changes that are coming, they do not tell us how fast these increases will occur. They do not enable us to determine the rates of change of sea level in the distant past, so we cannot deduce whether the massive increase in sea levels occurred over decades or centuries or millennia.

Conclusions

Oceans have risen and are continuing to rise, and are doing so at an increasing rate. It is not clear how far they will rise by benchmarks such as 2050 or 2100: estimates for 2100 range from two to three feet to fifteen to twenty feet. We have explained why there is such a broad range of estimates: we can think of these as upper and lower bounds to the rise that might actually occur.

It is very clear that even a small increase in sea level will impose substantial economic costs on the US, and in particular on vulnerable states such as those on the East Coast and the Gulf of Mexico. They face loss of housing and loss of infrastructure, including such expensive and hard-to-replace items as airports. And as figure 2 shows, there may be substantial impairment of economic value long before an area is actually below sea level.

These costs will fall on households, municipalities and states, with many households at risk of losing their main assets, namely their homes. And the drop in value of physical assets can lead to corresponding decreases in the values of the financial assets that are secured on them, such as mortgages and bonds. This can move the pain from coastal communities to the entire country. A similar set of costs will occur worldwide, as the impacts of sea level rise will clearly not be confined to the US: indeed many countries are more vulnerable than the US. We could therefor see significant disruption of the global economy.

References

R. S. Nerem, B. D. Beckley, J. T. Fasullo, B. D. Hamlington, D. Masters, and G. T. Mitchum *Climate-change–driven accelerated sea-level rise detected in the altimeter era*, **Proceedings of the National Academy of Sciences,** www.pnas.org/cgi/doi/10.1073/pnas.1717312115

Houser, Trevor, Solomon Hsiang, Robert Kopp, Kate Larsen, Michael Delgado, Amir Jina, Michael Mastrandrea, Shashank Mohan, Robert Muir-Wood, D. J. Rasmussen, James Rising, Paul Wilson. **Economic Risks of Climate Change: An American Prospectus**, Columbia University Press, 2015.

Hallegatte, Stephane, Colin Green, Robert J. Nicholls and Jan Corfee-Morlot *Future flood losses in major coastal cities*, **Nature Climate Change**, Vol 3, September 2013.

National Climate Assessment: Climate Change Impacts in the United States, at

https://nca2014.globalchange.gov

Freddie Mac: *Life's A Beach*, at

http://www.freddiemac.com/research/insight/20160426_lifes_a_beach.html

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, **Geophys. Res. Lett.**, 33, L01602, doi:10.1029/2005GL024826.

Bindoff, N.L., J. Willebrand, V. Artale, A, Cazenave, J. Gregory, S. Gulev, K. Hanawa, C. Le Quéré, S. Levitus, Y. Nojiri, C.K. Shum, L.D. Talley and A. Unnikrishnan, 2007: *Observations: Oceanic Climate Change and Sea Level.* In: **Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change** [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Dutton, A, A. E. Carlson, A.J. Long, G.A. Milne, P.U. Clark, R. Deconto, B.P. Horton, S. Rahmsdorf, M.E. Raymo. Sea-level rise due to polar ice-sheet mass loss during past warm periods **Science 10 July 2015**