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STABILITY OF COASTAL ZONES

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Introduction

Throughout most of Earth's history, the coastline has been a very dynamic feature. Throughout most of human history as well, the coastline has been constantly shifting (Figure 1a). Only if we view sea level on the time scale corresponding to the rise of civilization has it been approximately stable (Figure 1b). It may not be that a stable shoreline was necessary for the flourishing of civilization, but the simple fact is that cities established themselves with firm roots on the edge of that steady shoreline, and to date have not had to accommodate the dramatic moves as have been the norm throughout most of geologic history.

Currently about 40 percent of the global population lives in the coastal zone,[1] with the proportion rising each year as society becomes more urban. This is the fraction of humanity at risk if sea level should rise dramatically and from hurricanes, storm surges, and other climate-related phenomena. The latest IPCC report on climate change impacts[2] places "death or harm from coastal flooding" as the number one risk from climate warming, and estimates that the current investment in adaptation to sea level rise is orders of magnitude less than what it needs to be to address the critical problem: a rapidly expanding population of poor living within reach of ever rising seas.

The future is uncertain if sea level departs dramatically from the current Holocene stable state, as is currently feared to be the case from anthropogenic release of CO_2. Throughout most of geologic history, sea level has been closely correlated with CO_2, which gives ample reason for concern.

Contributions to Sea Level Rise

A number of very different factors contribute to sea level rise (Figure 2). Two of the most important are the melting of grounded ice sheets, such as mountain glaciers and the ice sheets on Greenland and Antarctica, and thermal expansion of the ocean. Each of these two factors contributes nearly equally to the current observed rate of sea level rise. A third factor

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[1] Defined as living within 100 km of the shoreline, see http://sedac.ciesin.columbia.edu/es/papers/Coastal_Zone_Pop_Method.pdf

[2] Intergovernmental Panel on Climate Change, Working Group 2, *Climate Change 2014: Impacts, Adaptation, and Vulnerability*, http://www.ipcc.ch/report/ar5/wg2/

contributing to contemporary sea level rise is the depletion of aquifers that ultimately transfers that water from deep underground to the ocean. It is estimated that as much as 6 percent of the current sea level rise could be attributed to this effect,[3] and it would be larger if not for the effects of dams delaying that flow to the sea.

A number of other effects cause regional variability in sea level, and can locally have magnitudes just as large. One of the most important is dynamic ocean topography maintained by ocean currents. Climate change is expected to change land-sea thermal gradients, which in turn may intensify or weaken western boundary currents. For example, the Gulf Stream locally raises sea level by 2 meters in the western Atlantic. This effect is therefore especially important for any coastlines bordering major current systems, and can confound our ability to accurately predict the details of future sea level rise at any one location. The effect of changes in currents can make sea level rise much worse, or much less, than the global average.

Another significant effect is vertical tectonics. A number of coastlines, such as the US Pacific northwest, Japan, New Zealand, the west coast of South America, Indonesia, and portions of the Mediterranean, border active fault lines with a vertical component of slip on the faults. For example, the January 2010 earthquake in Haiti was responsible for co-seismic subsidence of the shoreline of one meter near Port au Prince (Figure 3). That is equivalent to more that 500 years of sea level rise at current rates happening in just a few seconds. Of course, there are other hazards associated with co-seismic slip such as falling buildings and tsunamis as well, and often these active margins produce net uplift of the coastal plain. Currently, however, we are unable to predict the tectonic component to sea level adjustment on human time scales with any certainty along these active margins.

Sedimentary processes are also important in understanding how a shoreline responds to sea level rise. If rivers can deliver an adequate supply of sediment to the coastal zone where the materials are distributed by alongshore currents, shore lines can under certain circumstances keep pace with sea level rise through aggradation (Figure 4). In far too many cases, these natural processes have been altered through construction of dams, sea walls, and other man-made structures which obstruct the nourishment of shorelines, leading to erosion and failure to keep pace with rising seas. As dams have become silted and have lost their original function of water storage,

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[3] Konikow, Contribution of global groundwater depletion since 1900 to sea-level rise, *Geophys. Res. Letts.* 38, 17, 2011 DOI: 10.1029/2011GL048604.

there has been a rising movement for dam removal to restore natural water flows with a number of benefits to wildlife and coastal protection through sediment supply to starved margins.

Locally in ice covered areas a rather large effect that must be accounted for is rebound from the removal of the ice. For example, the shoreline of Greenland, rather than being inundated, will actually emerge from the ocean should the Greenland ice cap melt, on account of isostatic rebound of Earth's solid surface in response to the unloading of the weight of the ice. The flow of rock in the solid state deep in Earth's asthenosphere toward the uplifting region produces a further subsidence in the region peripheral to the rebounding area, actually accelerating sea level rise in areas adjacent to the former glaciated areas. This phenomenon has been well documented and calibrated from the retreat of the Wisconsin glaciers, and is expected to be noticeable should the Greenland icecap melt as accelerated rates of sea level rise over the global average in Europe and North America.

Finally, many ocean islands are underlain by volcanic pedestals built on subsiding seafloor as tectonic plates age and thermally contract. Although the rate of thermal contraction of the seafloor is slow on human time scales (maximum rates of 0.04 cm/year) and small relative to the other effects discussed (cumulatively currently 0.30 cm/year as an average globally),[4] it adds to the other causes of sea level rise mentioned above, making ocean islands particularly susceptible.

Challenges in Predicting Future Sea Level Rise

While the past correlation between CO_2 in Earth's atmosphere and sea level appears compelling, predicting the details of future sea level rise on human time scales is particularly challenging. With the number of people potentially at risk, and the amount of the coastal plain that could be inundated in the next century or two, it is desirable to know how fast one might need to retreat from the shoreline. If the predictions of future sea level rise err on the side of being too fast, then one may abandon shoreline-dependent facilities before it is necessary to do so. If one errs on the side of predicting a sea level rise that is too slow, then one may not have planned a retreat that is fast enough, such that facilities are hastily abandoned when they still have useful life.

The difficulty with predicting sea level rise is that, to begin with, locally it is the sum of the many effects discussed above, not all of which can be

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[4] http://oceanservice.noaa.gov/facts/sealevel.html

predicted with some or any certainty (e.g., where future earthquakes will occur, what the details of future ocean circulation will be). Another challenge is that sea level rise is a derived quantity from climate predictions of temperature, and even the projections for temperature have uncertainties which are difficult to quantify.[5] For example, the current predictions of future temperature rise are an "envelope" of what the various models project, from the most optimistic to the most pessimistic, not formal error bounds on any one much less the ensemble of all of the models. The models themselves are unlikely to be completely independent, having had at least some aspects of their codes in common over the decades that they have been developed. They all depend on assumptions on Earth's albedo and cloud physics, two of the most uncertain elements of radiative forcing. The codes themselves tend to be only approximations of the true physics: they include parameters such as "eddy viscosity" which aren't real, but are designed to make the model ocean behave as is observed. In addition, to make the models more efficient, approximations are made to some of the calculations – representing them as smooth functions rather than computing each grid point individually.

All in all, the known physics of the green house effect coupled with the long-term observed rise in atmospheric CO_2 correlated with rates of fossil fuel use means that there is very high confidence that global temperatures will surely rise in the coming decades. But exactly how fast is difficult to predict because the net carbon budget is a small difference between very large sources and sinks. Even attempting to predict the temperature trend over the last decade or two has uncovered some surprises, such as the recent "pause" in warming attributed to oceanic absorption of heat.[6]

"No Regrets" Actions

Estimates are that even with a commitment so far not evident to decarbonizing the energy system, it would take several decades to transform the global complex energy delivery network from one based on fossil fuels to one based on renewable and other forms of non-CO_2 emitting energy

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[5] Bader, David; Covey, Curt; Gutowski, William; Held, Isaac; Kunkel, Kenneth; Miller, Ronald; Tokmakian, Robin; and Zhang, Minghua, *Climate Models: An Assessment of Strengths and Limitations* (2008). US Department of Energy Publications. Paper 8. http://digitalcommons.unl.edu/usdoepub/8

[6] England *et al.*, Recent intensification of wind-driven circulation in the Pacific and the ongoing warming hiatus, *Nature Climate Change*, 4, 222–227 (2014) doi:10.1038/nclimate2106

sources. Given that reality, it appears that the world is destined to experience some appreciable amount of sea level rise, and must be preparing now for that eventuality. There are three basic strategies for approaching this problem:

1. Plan an organized retreat from the sea where inundation is inevitable;
2. Fortify high-value investments that cannot quickly retreat to buy time;
3. Restore natural processes to allow shorelines to keep pace with sea level rise.

One example of a planned retreat is the current project at Alligator River National Wildlife Refuge (Figure 5) in North Carolina. Over one million acres will be inundated over the next few centuries as sea level rises over this low-lying coastal plain. The project, which involves the Nature Conservancy, US Fish and Wildlife Service, and other partners, provides natural baffling ability of oyster reefs to reduce the amount of energy reaching the shoreline and to promote sediment accretion behind the reef. There will also be wildlife corridors to allow an orderly migration inland of endangered species such as the red wolf.

The communities that commit to long-term planning and zoning taking into account sea level rise will avoid unnecessary costs and high-value losses from inappropriate location of expensive infrastructure, such as airports and hospitals. For example, selective conversion of coastal property to parks and open space as parcels become available for purchase (especially after natural disasters such as hurricanes) can be an effective way to retreat from rising seas.

There will be some high-value investments that will need protection. It is up to society to say what is worth armoring against rising seas. Certain cultural icons will likely make the list, such as the Statue of Liberty. But what about low-lying areas of cities, such as the SOMA area of San Francisco (Figure Z)? Virtually the entire city of New Orleans?

Finally, we need to restore coastal processes. Free-flowing rivers deliver sediment to the coast, which then gets redistributed to shorelines by along-shore currents. Under some conditions shorelines can build to keep pace with rising seas. However, we have drastically reduced the sediment load to the coastal zone by building dams, and altered along-shore transport by building jetties and sea walls. The Elwha Dam in the Pacific Northwest of the US is an example of a dam that had become silted up and outlived it usefulness for water storage. It is now in the process of being dismantled to restore the natural flow of the river sediment to the coastline. This dam removal project is being closely monitored both in the near term as the pulse of sediment which was stored behind the dam arrives and in the long term as the river regains steady state.

Concluding Thoughts

Experts who study the psychology of threats, such as Dan Gilbert from Harvard, point out the reasons why humans are too slow to react to the threat of climate change:[7]

- Climate change lacks a human face: there is no "bad guy" to which we can direct our attack;
- It doesn't violate our moral sensibilities: CO_2 is an odorless, tasteless gas;
- It is not perceived as an immediate threat: the problem is still too far in the future, even though in truth we must start taking action today;
- Climate change proceeds at a slow rate: as a species our senses are not attuned to gradual changes.

For this reason, public education for all who live in the coastal zone of the risks and the actions needed to build resiliency are badly needed. Shoreline-dependent facilities, such as sea terminals, should be designed with rising seas and planned obsolescence, and inland migration in mind. Young children should begin from the time they are small to view the shoreline as a place they visit for recreation, camping, and for viewing wildlife, but not a place to put down deep roots.

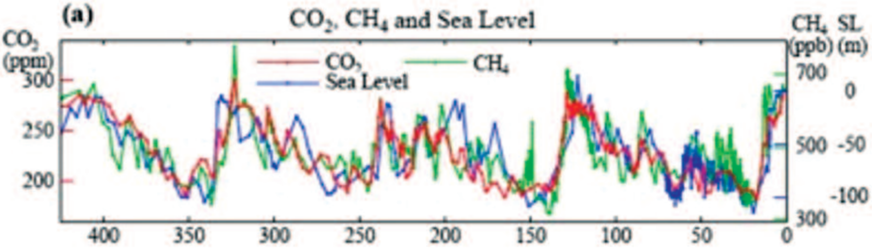

Figure 1. (a) Relationship between carbon dioxide (CO_2, methane (CH_4), and sea level for the Cenozoic (from Hansen *et al.*).[8] For comparison, Neanderthals lived 200 to 300 thousand years ago. Homo sapiens emerged as a species ~400 to 250 thousand years ago. (b) Detail of Holocene sea level. Data from Fleming *et al.*,[9] Fleming,[10] and Milne *et al.*[11] For context, the Great Pyramides were built 2470 BC, the city of Babylon flourished about the same time. By 8000-7000 BC, farming was firmly established in Mesopotamia.

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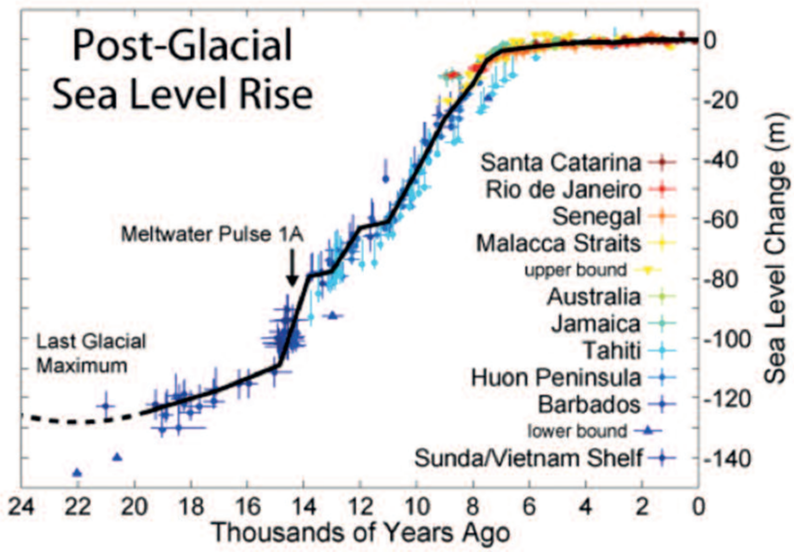
[7] Presentation at Pop!Tech 2007, see http://www.peopleandplace.net/media_library/video/2009/3/23/responding_to_the_threat_of_climate_change

[8] Hansen, J. *et al.*, Target CO2: Where should humanity aim? http://www.columbia.edu/~jeh1/2008/TargetCO2_20080407.pdf

[9] Fleming, K., P. Johnston, D. Zwartz, Y. Yokoyama, K. Lambeck and J. Chappell (1998). "Refining the eustatic sea-level curve since the Last Glacial Maximum using far-

Thousands of years before present

(b)



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and intermediate-field sites". *Earth Planet. Sci. Lett.* 163 (1-4): 327-342. DOI:10.1016/S0012-821X(98)00198-8

[10] Fleming, K. (2000). *Glacial Rebound and Sea-level Change Constraints on the Greenland Ice Sheet*. Australian National University. PhD Thesis.

[11] Milne, G., A. Long and S. Bassett (2005). "Modelling Holocene relative sea-level observations from the Caribbean and South America". *Quat. Sci. Rev.* 24 (10-11): 1183-1202. DOI:10.1016/j.quascirev.2004.10.005

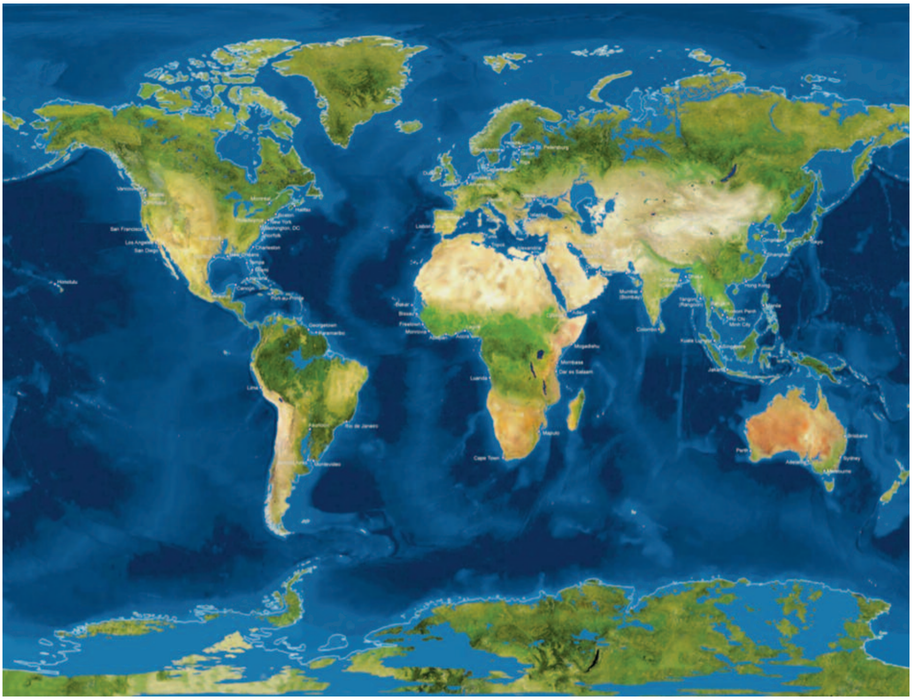

Figure 2. National Geographic's "If All the Ice Melted",[12] while raising awareness to the threats of sea level rise, contains a large number of inaccuracies concerning the details of what actually would happen. It is a "fill up the bathtub" model of melting ice, and does not account for first-order effects such as thermal expansion of the ocean and rebound of formerly ice-covered regions.

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[12] http://ngm.nationalgeographic.com/2013/09/rising-seas/if-ice-melted-map

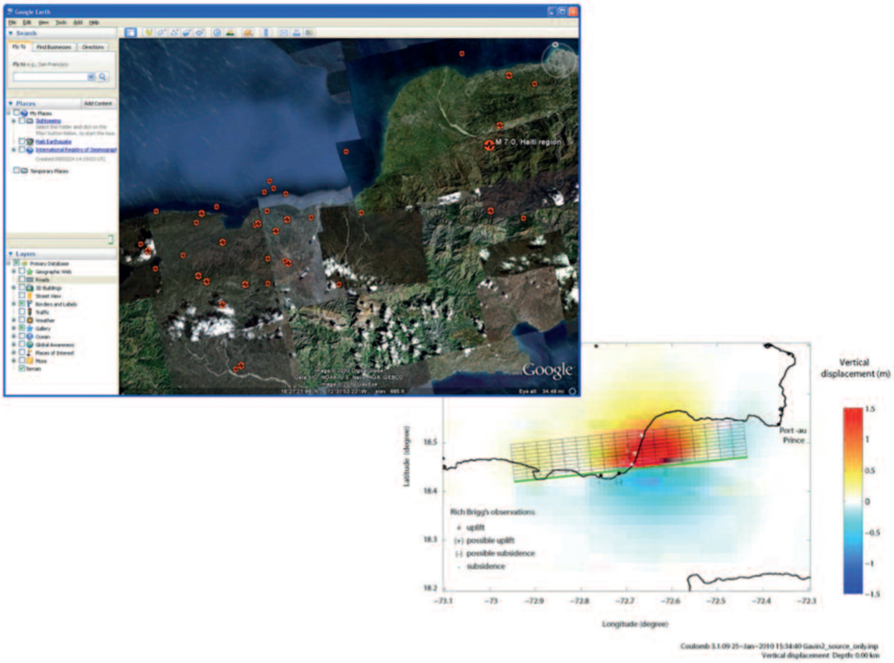

Figure 3. Revised source model from Gavin Hayes (USGS – National Earthquake Information Center) matches the imagery-based observations of coastal uplift and subsidence by Rich Briggs (also USGS-NEIC). The figure is from Ross Stein (USGS-Menlo Park). The image is a screen capture from Google Earth, which has an imbedded layer pulling in USGS earthquake locations updated every 5 minutes, part of an ongoing partnership with Google out of Menlo Park. Co-seismic displacement was shoreline near Port au Prince subsiding more than 1 m relative to the ocean. Figure courtesy of David Applegate, USGS-Reston.

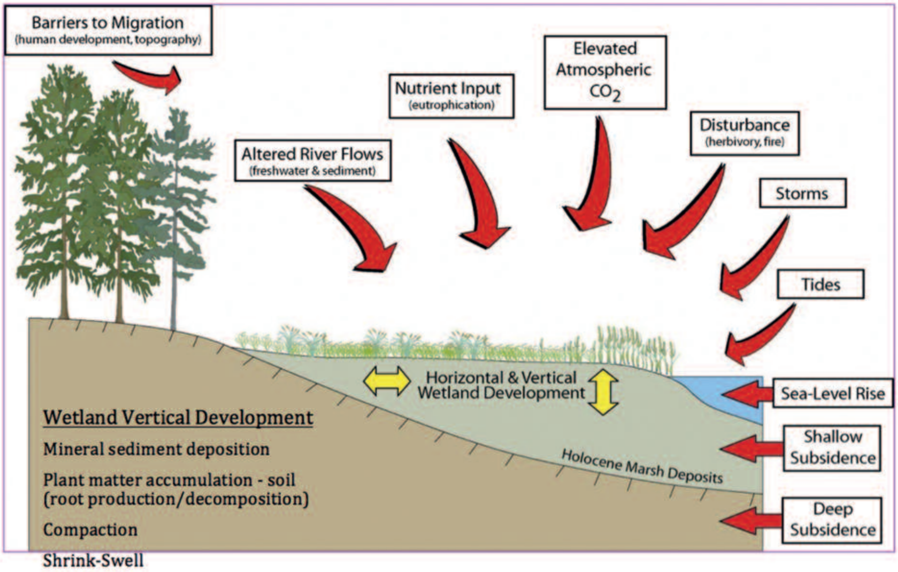

Figure 4. Cartoon illustrating horizontal and vertical wetland growth (yellow arrows) in response to coastal processes. Red arrows show threats to shoreline aggradation.

(a)

(b)

Figure 5. The Alligator River, NC project. (a) Location of wildlife refuge along the Atlantic coast of North Carolina. (b) Planned interventions to facilitate an orderly retreat from the rising sea.