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An Oceanographic Perspective

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I have spent my career trying to *understand* ocean processes such as waves, tides, tsunamis, ocean circulation, and climate. We have learned a lot, but we have a lot to learn. I will give a very abbreviated account of recent findings. The next step is to use our understanding (limited as it may be) to develop a sensible interaction with the planet and all its marine and terrestrial inhabitants; this is the more difficult task. An absolute prerequisite is for natural scientists to work together with those concerned with social sciences and ethics. I am grateful to the organizers of this conference for bringing these groups together.

1. History

Astronomers and Geophysicists began studying climate change long before the discovery of greenhouse gases. Newtonian perturbations in the orbits of Sun, Earth, and Moon are associated with severe, but somewhat predictable climate changes. From 20,000 to 10,000 years ago the Earth emerged from its last ice age. The transition consisted of melting continental ice sheets with an attendant global sea level rise (GSR) of 100 m in 100 centuries, followed by a current relatively stable epoch. By the 20th century GSR had slowed from 1 m/cy to 0.1 m/cy. When I first arrived at Scripps in 1939, the prevailing view was that the ice age cycle was coming to an end and that we were heading towards a new ice age; how clever of civilization to combat this danger by releasing a little CO_2 into the atmosphere... *or maybe not!*

2. Variability & Prediction

By the start of the 21st century, the GSR had doubled from 0.15 to 0.30 m/cy. The traditional GSR was based on the measurements from a global distribution of tide gauges. Tide gauge records are difficult to interpret as the gauges are attached to the "solid" earth which moves up and down nearly as much as the mean sea level. (In Venice, for example, the sinking of San Marco by 0.20 m/cy needs to be added to a global 0.30 m/cy for a total sea level rise of 0.5 m/cy; a serious consideration when evaluating the effectiveness of the Venice Gates).

By the end of the 20th century, the dependence on classical tide gauges was replaced by satellite altimeters that measure sea level relative to the center of the Earth. The observed doubling in GSR coincided with a transition of observing technique, very suspicious. Some years ago when oceanographers switched from Nansen bottles to bathythermographs for measuring temperature the ocean suddenly warmed! (It has since been proven by Australian oceanographer John Church that the 21st century GSR acceleration was real).

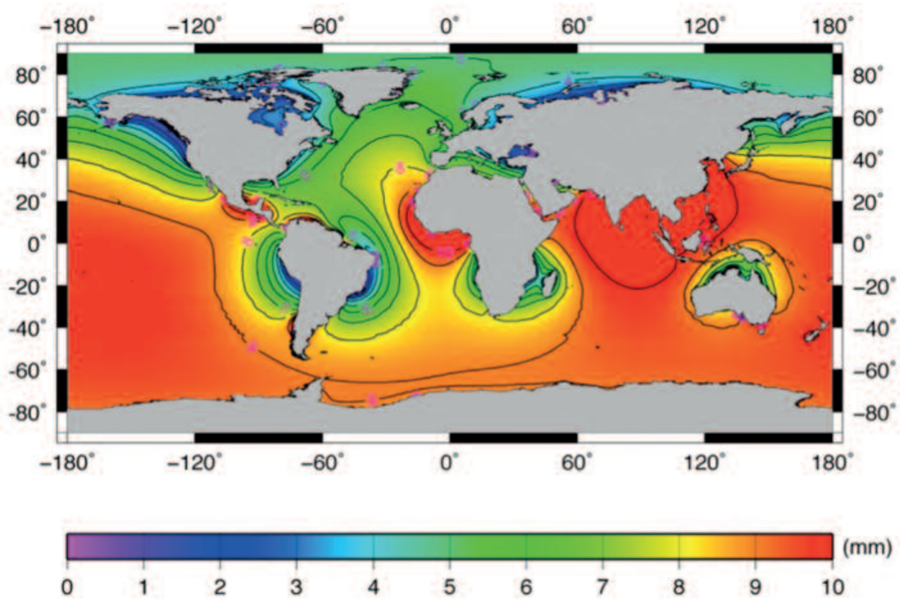

Figure 1. Annual Sea Level "Fingerprint" measured by the GRACE satellite mission (Velicogna personal communication). The removal of snow from Greenland is associated with an elastic rise in landmass, yielding low values in the *relative* rise of sea level in the area. (Courtesy of Isabella Velicogna).

The 20th century value of 0.15 m/cy was primarily due to the melting of glaciers and continental ice sheets. Would it approach the 1 m/cy rate experienced from 200 to 100 centuries ago? A major contribution to the acceleration comes from the melting of the Greenland icecap, with a total capacity of 10 m GSR (as compared to 100 m for the Antarctic). Monitoring the two icecaps has become a major issue. Fortunately the GRACE satellite configuration offers a timely and elegant solution for accurate measurements of the change in snow mass (Figure 1). Grace consists of two identical spacecraft flying in an identical polar orbit 500 km above the Earth, separated by 200 km, measuring changes in the distance between them to an accuracy of 0.01 mm. As the twin GRACE satellites circle the globe 15 times a day, they sense minute variations in Earth's gravitational pull. When the first satellite passes over a region of slightly stronger gravity, it is pulled slightly ahead of the trailing satellite. This causes the distance between the satellites to increase. The first spacecraft then passes the anomaly, and slows down; meanwhile the following spacecraft accelerates, then decelerates over the same point. By measuring the constantly changing distance between the two satellites and combining that data with precise GPS positioning one can construct a detailed map of Earth's mass anomalies.

GRACE measurements show a disturbing acceleration of Greenland glaciers melting. A linear extrapolation yields 1,850 and 1,000 gigatons/year loss for Greenland and Antarctica, respectively, by the end of this century. The corresponding values of global sea level rise are 0.52 and 0.28 mm/year for a total of 0.8 mm/years (0.8 m/century), close to the 1 m/century experienced at the end of the last ice age. But I cannot emphasize enough that there is no physical basis for assuming a uniform acceleration; it could be smaller, it could also be larger!

3. Feedback

The difficulty with predicting GSR is the expectation of powerful feedbacks (negative and positive) which may cancel (or double) GSR for decades at a time. The most immediate feedback is the polar floating ice field, which is rapidly shrinking, and one of these days will lead to an ice-free Arctic summer. When? Estimates vary between a few years (Peter Wadhams) and a few decades (Ola Johannessen). While the melting of FLOATING ice does not directly affect sea level (Archimedes Principle), it has a powerful effect on the albedo; ice is more reflective than water. The disappearance of the floating ice sheet is accompanied by rapid ocean warming and acceleration in the melting of adjacent Greenland glaciers previously discussed. On the other hand, a warmer ocean with enhanced evaporation is associated with increased cooling by increased cloudiness. These are conflicting feedbacks.

Then there is the problem of the melting of permafrost and the release of trapped methane. I would not be surprised if changes in wind stress lead to significant variations in the Gulf Stream, but I don't know whether these changes will be up or down. Changes in ocean circulation are associated with rapid changes in LOCAL sea level. A fair summary is that feedbacks are not well understood and can lead to some big surprises. Climate change and associated side effects are not smooth monotonic processes; their high variability makes it difficult to persuade society to take them as seriously as they must be taken.

4. Human Interference with Radiation Balance

There is a radical new development: humanity is not only the victim of climate change; we are the perpetrators (Paul Crutzen calls the present era the Anthropocene). As such, we have the ethical obligation to mitigate unfavorable climate change. The temperature of the planet is subject to a very sensitive balance between incoming and outgoing radiation. Disturbing the balance by just a few watts per square meters significantly changes the climate. This happens naturally by well-understood orbital perturbations. Human transgressions have now resulted in the uncontrolled release of greenhouse gases into the atmosphere, upsetting the critical radiation balance.

I think I express the view of the majority of experts who have studied this problem with the following statements:

- A generational transition from fossil energy to other energy sources (solar, wind, nuclear...) is within the technological competence of our civilization, and could go a long ways towards halting further imbalance of the planet radiation budget.
- To accomplish this will require international collaboration on an unprecedented scale.
- The restoration to pre-industrial standards and, thus, the sustainability of our planet, depends largely on ocean mixing, which has a millennium time scale.*

5. Closing With a Ray of Hope

I promised to end with a ray of hope. Will you permit me to speculate along lines where others in this audience have far more experience.

Brian Tucker was one of my Geophysics Ph.D. students at Scripps in 1975. Tucker has devoted his career to the reduction of casualties from natural disasters. His company *GeoHazards International* has worked for 23 years in 20 countries. I believe what he has learned is relevant to our task.

* The time scale for mixing the ocean is of the order L^2/Nu where L is the ocean mixing depth and Nu the turbulent diffusivity. For L = 1000m and Nu = $5x10^{-5}$ m^2/s the time scale is 700 years!

1. Tucker (2013) has considered the history of three severe earthquakes in developed vs. developing countries.

	Chile (developed)	**Haiti** (developing)
1960	M(9.5): severe casualties	
2010	M(8.8): 0.1% casualties	M(7.0): 11% casualties

After a magnitude 9.5 earthquake in 1960, Chile embarked on a robust earthquake safety program, developing and enforcing modern building codes. During the same period, Haiti, lulled by two centuries of seismic quiescence and hampered by poverty, disregarded earthquake risk.

In 2010 large earthquakes struck both countries. How did the resulting losses compare?

- 0.1% of Chilean citizens who experienced severe shaking died.
- 11% of Haitian citizens who had experienced equivalent shaking died.

The Chilean effort had been enormously successful: their buildings were 100 times less lethal than the Haitian buildings.

2. Tucker evaluated Chile's safety program and determined:

- The cost of PREPAREDNESS and PREVENTION was one twentieth the cost of RESPONSE, RECOVERY and RECONSTRUCTION for somewhat equivalent results:

A shilling of PP is worth a pound of RRR

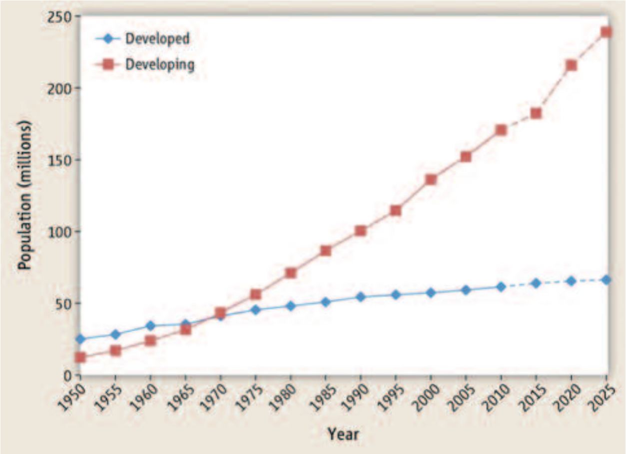

Figure 2. Increasing urban earthquake risk for developed and developing countries (Tucker 2013). Fifty-year increase in the population of the 25 most populous cities that are within 100 km of a seismic fault capable of generating a Mag 7 earthquake (Courtesy *Science* Magazine).

Figure 3. Coastal housing in Port-au-Prince, Haiti, a developing country.

3. Figure 2 shows the total population since 1950 of "developing" and "developed" cities, selected from the world's 50 most populous cities that are located within 100 km of a fault capable of generating an earthquake with $M \geq 7$. Over the past 60 years, the number of people exposed to strong earthquake shaking in cities in developed countries has grown from 25 to 70 million, in developing countries from 15 to 240 million! Accounting for changes in both population and the quality of seismic-resistant construction suggests that over this period, the relative earthquake risk for cities in developing countries, compared to that of cities in developed countries, has increased by 2 to 3 orders of magnitude. Figure 3 (Port-au-Prince) is an example of such a megacity in a developing country.

Figures 4 and 5 depict two selected sites at LOW and HIGH TIDES

The tidal rise in sea level is well predicted, providing a six-hour window for a leisurely evacuation.

Large tsunamis can be of equivalent amplitude, but they are not yet predictable and the time for evacuation is short. Think of the dry and flooded coastlines pictured above as being separated by an interval of only 15 minutes! We need to make progress in earthquake and tsunami predictions and develop tsunami-warning systems with designated escape routes. Some low-lying areas are building mounds to which people can more readily escape.

LOW TIDE at 1 P.M. **HIGH TIDE at 5:50 P.M.**

Figure 4. St. Mary's Lighthouse, Whitley Bay, Northumberland, 17 and 20 September 2008 (Photos by Michael Marten).

LOW TIDE at 12 Noon **HIGH TIDE at 8 P.M.**

Figure 5. Perranporth, Cornwall, 29 and 30 August 2007 (Photos by Michael Marten).

At the opposite extreme is an equivalent rise in sea level associated with global warming. The evacuation time is now measured in centuries, giving adequate opportunity for an orderly and fiscally responsible transition. Low lying areas should be converted from dense housing to parklands with flood-resistant vegetation.

Multimega coastal cities in developing nations are a disaster waiting to happen. Here again, Preparedness and Prevention are far more effective and affordable than emergency response.

References

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