Update on the Role of the Oceans in Climate Extremes and Rising Sea Level

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Ocean processes are linked to many types of extreme weather and recent ocean studies are helping us understand the growing intensity of extreme weather events on land. Some of the observed changes in the ocean, which only a few decades ago were thought unimaginable in our lifetimes, are now occurring as result of human-caused climate change.

I. How We know that Earth is Warming Globally

Half a century ago many distinguished scientists pointed to new data that demonstrated changes in the carbon dioxide concentration of the atmosphere, and argued that if this trend continued over time it would have a global effect on Earth's

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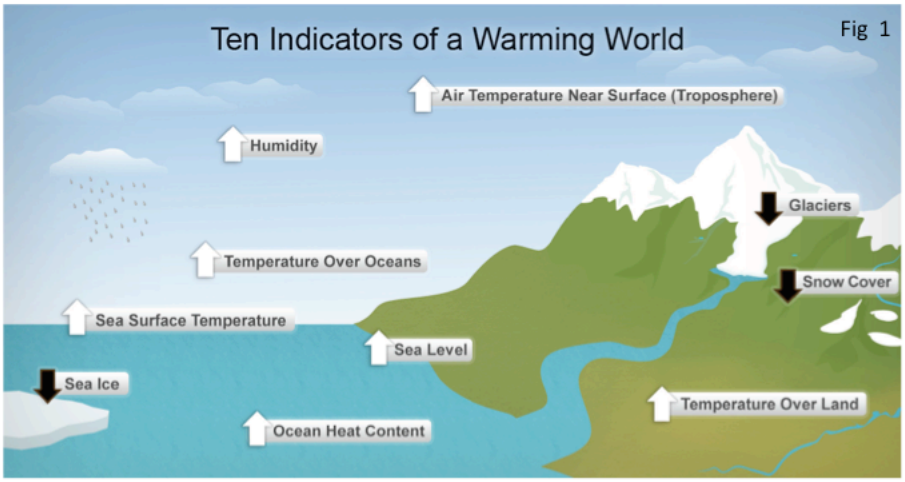
climate. One can imagine the check-list that would have been developed at the time – what you would want to be watching for to test the warming hypothesis – and the list would have looked something like the indictors in Fig. 1.



Consistent Trends in All these Indicators Over the Last Several Decades Provide Robust Evidence that Earth is Warming

NOAA/BAMS 2009

Many of these indicators could not, however, be measured well enough to discern trends before the 1980s, which is when Earth sensing satellites were first deployed. With variation from year to year, in Arctic sea ice, for example, it took time to know with confidence whether change was actually occurring. And initially some of the satellite data seemed to contradict land surface measurements, in surface temperature, for example. But with experience the new methods became reliable. For some indicators, such as sea level rise, satellite systems improved substantially the accuracy of the data.

Today there is widespread agreement among specialists who devote their careers to perfecting and deploying myriad systems that monitor the state of these indicators that trends for all of them point as would be expected if the Earth is warming. This clear global signal becomes stronger with every passing year.

II. Observed Changes in Ocean Temperature

As an oceanographer, I have a particular interest in one of the last pieces of evidence to fall in place among these indicators – the heat content of the ocean. In the early 1980s land surface data were beginning to indicate unusual warming, but a trend in warming or cooling of even the surface ocean would be much harder to detect - vast areas of the ocean were not regularly sampled.

And, just how much change in the ocean would a scientist expect to see over the course of a career in ocean science? Until a few decades ago, the guess would have been – not very much. The oceans have an average depth of more than 12,000 feet. It takes about a thousand years for ocean currents to fully mix the oceans, and most of the deep ocean is influenced only very slowly by what happens at the surface or in the atmosphere. But more significantly, we had decades, and in some cases more than a century, of data indicating relative constancy in deep ocean conditions.

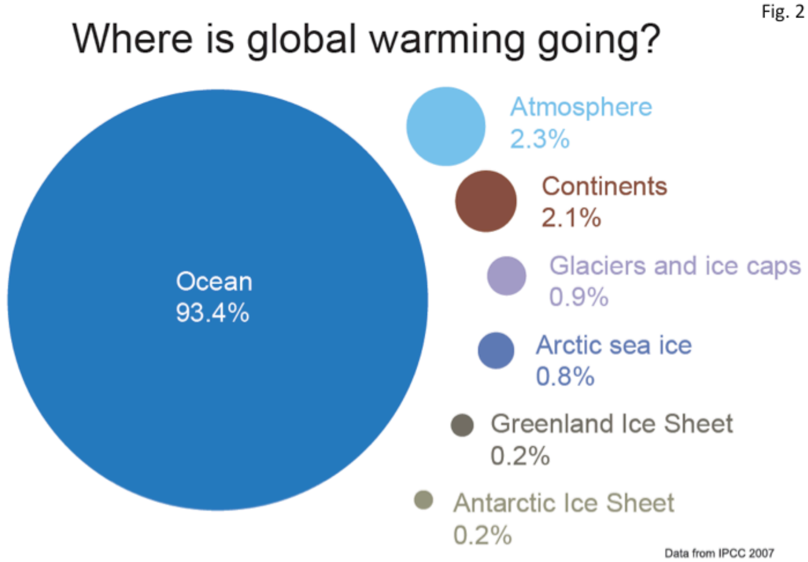
The oceans are an integral part of Earth's climate system and function as a grand flywheel. Their enormous mass and the high specific heat of water provide a steadying characteristic that helps to dampen rates of climate change. In a running engine, a spinning flywheel helps the running engine run steadily, as individual cylinders fire in sequence. If the engine stops running the inertia of the flywheel will keep it rotating albeit more slowly as energy is lost to friction. Similarly, the ocean helps to keep climate within bounds by absorbing and releasing heat slowly, and the range of these bounds guides us, as it did our ancestors, as we make decisions as to where to plant our important crops, were to develop our cities, where and how to position our key infrastructures, etc. Ocean conditions even far from land influence swings within these bounds. It's obvious that oceans influence climate in coastal regions, but changes in surface temperature in the central Pacific Ocean can influence weather patterns thousands of miles away in the Great Plains of the United States.

We now know that the ocean is changing more rapidly than was imagined likely just a few decades ago. The additional heat in the climate system caused by the greenhouse gases that we release with the burning of fossil fuels and land use practices is now penetrating deep within the oceans.

This means that the flywheel that has helped to keep climate extremes within bounds, bounds that we have assumed would remain steady, is now behaving differently. If these changes continue unabated we put at risk what many of us as individuals and societies hold dear – our investments in properties, commodities, and services.

With the findings of Levitus et al. (2000) and others who have confirmed these results, it is now clear that the ocean has absorbed more than 90% of the heat trapped over the past century by greenhouse gasses that have accumulated in Earth's atmosphere due to human activity (Fig. 2)

Fig. 2



NOAA/BAMS 2009

Confidence in these findings has been greatly strengthened with data from instrumented ocean buoys, known as Argo floats, that drift about the oceans at 3000 feet and every ten days descend to 6000 feet (Fig. 3). They then come to the surface and report via satellite their location, their trajectory over the prior nine days, and data for ocean temperature and salt content all along the way.

Fig. 3

Argo Drifting Floats Monitor Changes in
The Oceans' Heat Content – Initiated in the 2000s

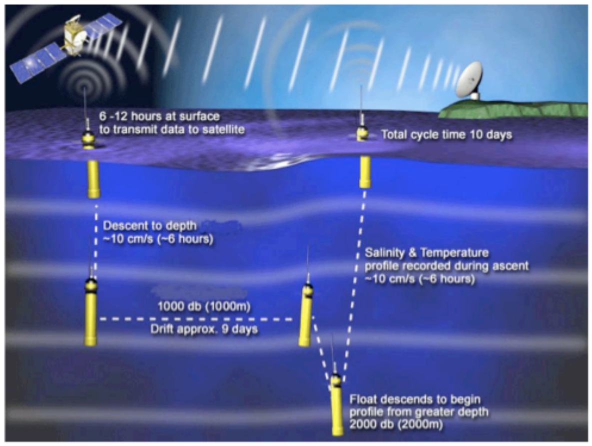
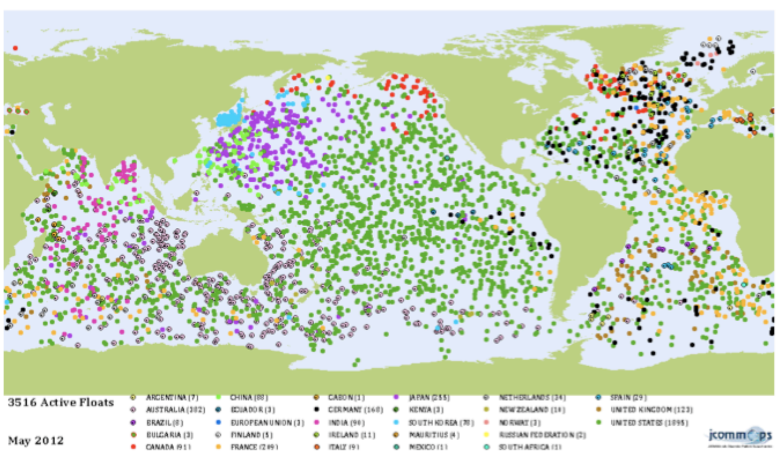


Fig. 4

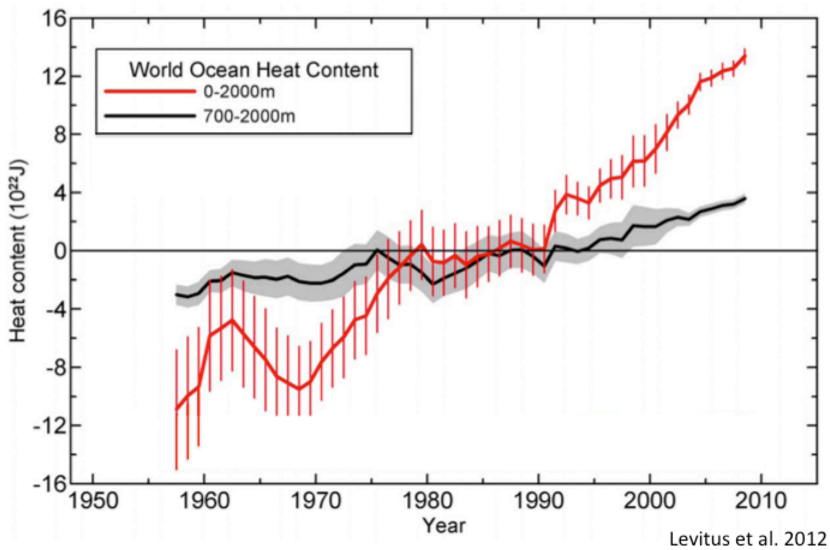
More than 3500 Drifting Argo Floats in Regular Operation
Profiling Ocean Temperature & Salinity to 2000 meters every 10 Days



This program ramped up rapidly during the 2000s, with about two-dozen nations sharing in the costs (Fig. 4). Now there are about 3500 of these floats providing data for large areas of the ocean that are rarely transited by ships. These new data have greatly improved precision in measurements of the oceans' heat content, and as can be seen in Fig. 5, the oceans have warmed steadily over recent decades.

The Deep Oceans are Warming at Great Depths

Fig. 5



Levitus et al. 2012

III. Observed Changes in Arctic Climate

A. The Arctic Ocean

A dozen years ago the news that Arctic sea ice was thinning and that during late summer there were large areas of open water in the central Arctic was surprising. Models had long projected that the Arctic would warm faster than other regions as atmospheric concentrations of greenhouse gases increased, but summer sea ice was being lost faster than the models projected. Part of the explanation may lie with the role of small soot particles from diesel combustion and fires that is blown north from lower latitudes. Though tiny, these dark particles increase the rate of snow and ice melt across the Arctic.

As is evident in Fig. 6, the summer extent of Arctic sea ice has declined since the satellite measurements for sea ice began in 1979, and it has thinned even more rapidly. Annually Arctic sea ice reaches its winter maximum in March and its minimum in September. As can be seen in Fig. 7, recent data indicate that new record lows for sea ice extent have been set during summer and autumn 2012.

Fig 6

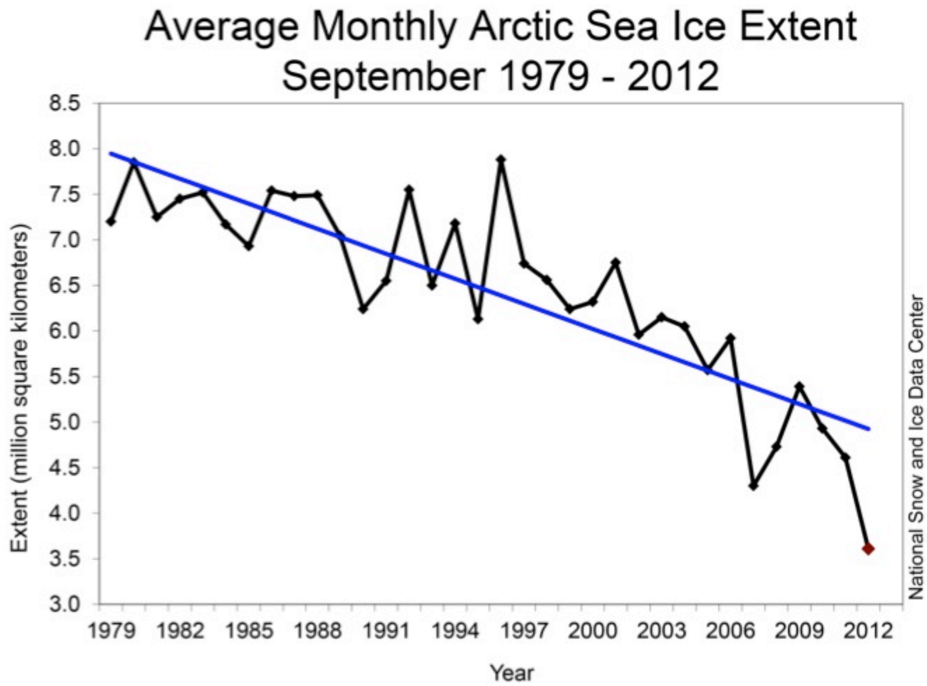
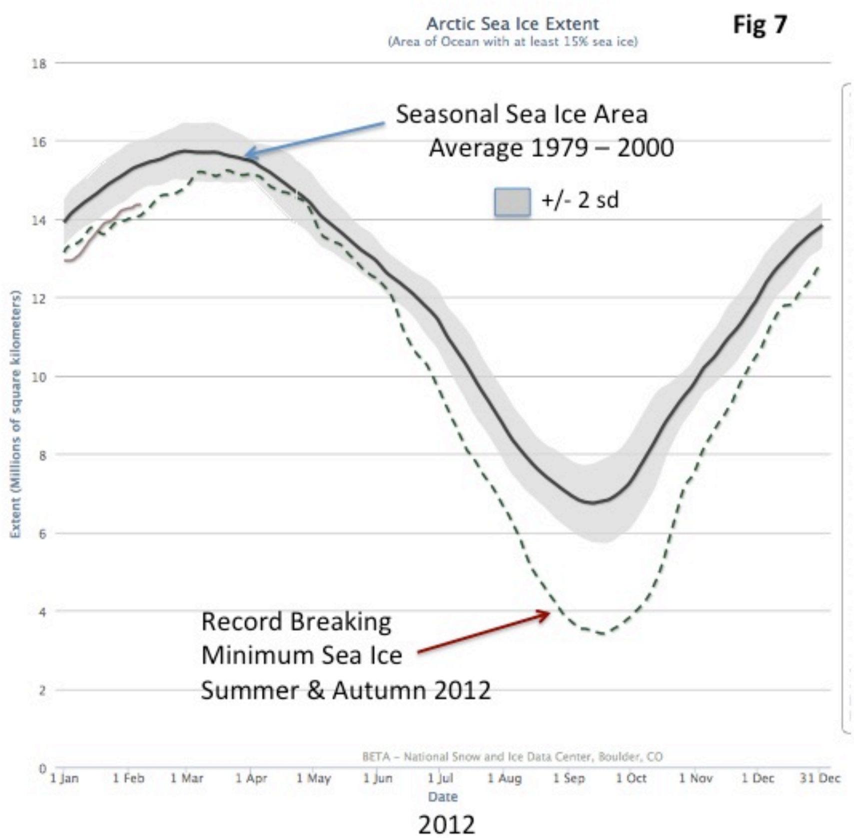

Average Monthly Arctic Sea Ice Extent
September 1979 - 2012
Extent (million square kilometers)
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
1979 1982 1985 1988 1991 1994 1997 2000 2003 2006 2009 2012
Year
National Snow and Ice Data Center

Fig 7


Arctic Sea Ice Extent
(Area of Ocean with at least 15% sea ice)
Seasonal Sea Ice Area
Average 1979 – 2000
+/- 2 sd
Record Breaking
Minimum Sea Ice
Summer & Autumn 2012
Extent (Millions of square kilometers)
18
16
14
12
10
8
6
4
2
0
1 Jan 1 Feb 1 Mar 1 Apr 1 May 1 Jun 1 Jul 1 Aug 1 Sep 1 Oct 1 Nov 1 Dec 31 Dec
Date
BETA – National Snow and Ice Data Center, Boulder, CO
2012

Will someone who doesn't live in the Arctic be affected if the Arctic continues to warm and the area of sea ice continues to decrease during summer? New research shows links between the summer loss of Arctic sea ice and unusual extreme weather conditions across the temperate regions of North America and Eurasia (Overland et al. 2010). Ice atop water acts an insulator. Without an ice cover the surface ocean releases heat and water to the atmosphere. What most limits winter snowfall across much of North America is not temperature in winter, but rather availability of water vapor. It is often cold enough to snow but doesn't. More open water in the Arctic and in lakes increases the potential for snow across large continental regions.

New studies (Francis and Vavrus, 2012) show how warming in the Arctic can also influence the path of the upper atmospheric Jet Stream, creating higher amplitude waves, and in effect slow the propagation of weather patterns across the central North America. The result is that both warm periods and cold periods persist longer, potentially creating weather extremes on both ends of the scale. The authors suggest that this was in play during winter 2010-11, when record snow and cold occurred across parts of the central and eastern US just as record high temperatures were occurring across central Canada. During winter 2011-12 the La Niña also had a strong influence on the path of the Jet Stream – it was relatively flat rather than undulating – thus keeping cold air masses further north than usual.

It is also now well established that these changing ice conditions in the Arctic are affecting the exchanges of water between the Arctic Ocean and the north Atlantic Ocean in unusual ways (Speilhagen et al. 2012), and with unknown implications for future climate across regions bordering the North Atlantic.

B. Glacial ice melt

In July 2012 there was a lot of press coverage about an unusual Greenland melt event.. Even the highests of Greenland, nearly two miles above the sea, were melting. Ice core data indicate that this may have happened a handful of times in the last thousand years, but it hasn't occurred in the past hundred years . Greenland is covered by the most substantial mass of glacial ice in the northern hemisphere. It accounts for 10% of the surface fresh water on the planet. This ice cap is a broad flat dome that rises to about 10,500 feet, and were it all to melt global sea level would rise 22 feet. About a decade ago satellite images began to show that summer surface melting was occurring at increasing elevations and blue melt pools were beginning to appear above 6000 feet. These pools eventually drain through fissures in the ice, and probably speed the flow of glacial ice as it move along the solid bedrock. It is not terribly surprising that something like the recent July warm condition occurred. Figure 8 shows the cumulative number of days of melt during 2012. The number of melt days exceeded 120 for low elevation areas along the southwestern coast, and values above 100 days were seen in the far north and southeastern coastal areas as well. The extent and duration of summer Greenland melt was the largest since these satellite observations began in 1979. The melting period in 2012 lasted almost two months longer than the average for all years since the satellite observations began. *2012 was the first year in the satellite record that the entire ice sheet experienced melt at some point during the year*.

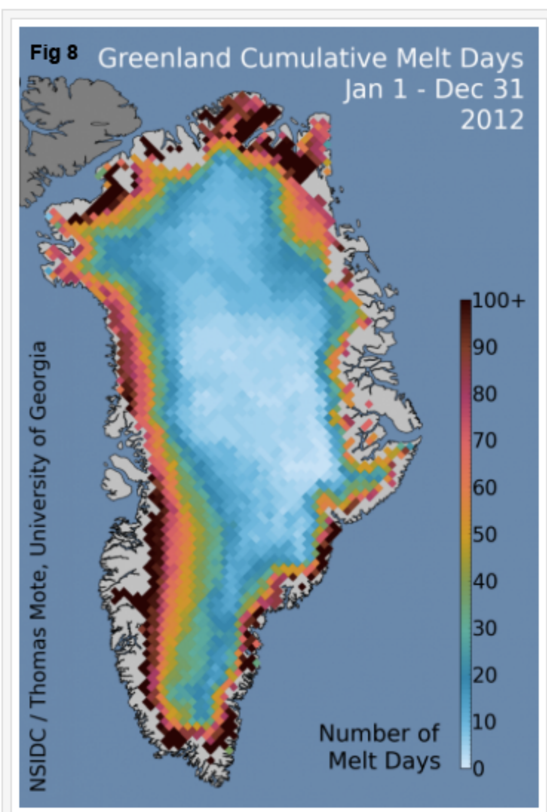


Fig 8. The number of melt days in 2012 on the Greenland Ice Sheet exceeded 120 for low elevation areas along the southwestern coast, and values above 100 days were seen in the far north and southeastern coastal areas. Data are from the Greenland Daily Surface Melt 25km EASE-Grid 2.0 Climate Data Record.

According to NASA reports there is evidence in the ice core records of a strong warming event over Greenland in the 1880s. Data for global temperature show that the 1880s were unusually warm. As the Arctic continues to warm summer melting snow and ice at all elevations on Greenland is likely to become more common.

This past July Greenland was also in the news for the release of an iceberg roughly twice the size of Manhattan from the Petermann Glacier in NW Greenland. Satellite data now allow for very precise estimates of the mass of Greenland ice and changes in its outlet glaciers, which drain ice from the ice cap to lower elevations. Fig. 9 shows terminations of the major outlet glaciers, with black for those with land terminations and green for those with marine terminations, also known as tidewater glaciers.

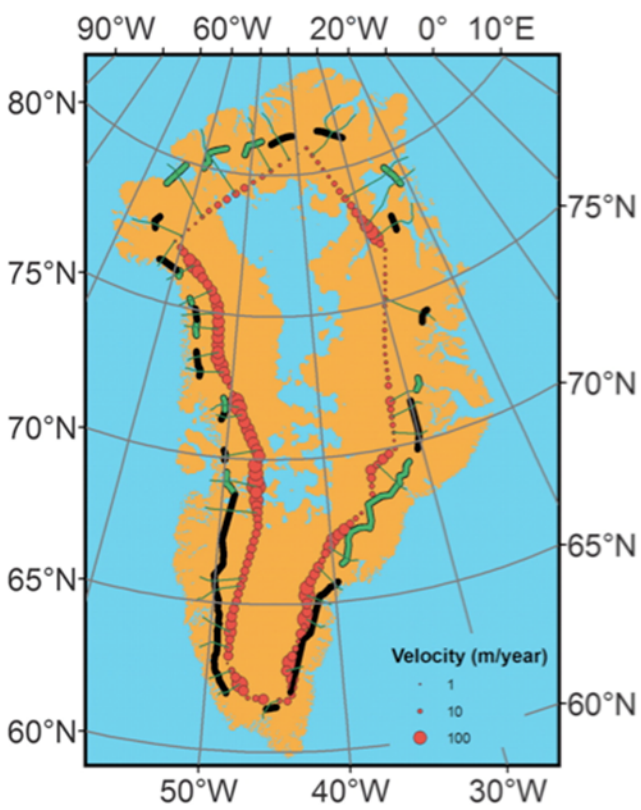


Fig 9

Rates of Glacial Motion and Locations of Greenland Outlet Glaciers with Terrestrial (black) and Marine (green) Terminations

"On the basis of calculations presented here, we suggest that an improved estimate of the range of sea level rise to 2100 including increased ice dynamics lies between 0.8 and 2.0 meters [31 – 78 inches]."

Pfeffer et al. 2008

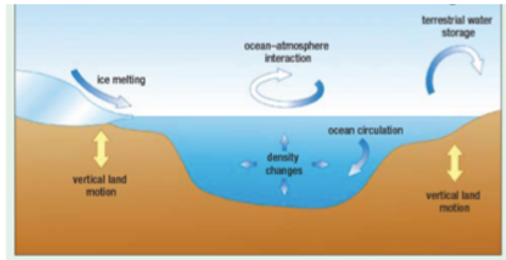
The greatest changes in Greenland glaciers over the past decades have been the rapid retreats of tidewater glaciers like Petermann. While conditions at higher elevation certainly affect glacial flow, the factor most likely responsible for the retreat and shedding of large icebergs by Greenland's tidewater glaciers is the warming of waters surrounding Greenland and their melting influence on the snouts of these glaciers. The string of red dots of varying sizes on Fig. 9 circumscribe the edges of the high ice cap and indicate, from satellite data, the best estimates for rates of glacial discharge (largest of the three sizes of red dot is 100 times faster than the smallest red dot). Note that the weight of this mass of ice depresses the center of Greenland below the sea level surrounding Greenland.

IV. Sea Level Rise

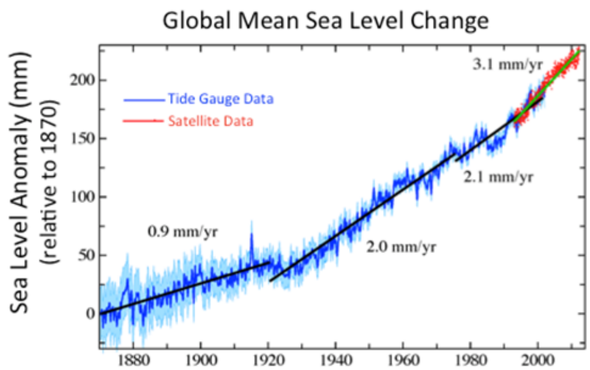
Sea level is influenced by several factors (Fig. 10). Globally the ocean's heat content and the amount of land ice are dominant factors. As the ocean warms, its volume increases and sea level rises. A warming atmosphere and ocean cause land ice to melt, and if this water reaches the ocean, it too contributes to sea level rise. Other factors, such as coastal uplifting or subsidence of the land will strongly affect local manifestations of sea level. Importantly, the rise of an ocean that is warming and receiving more water from ice melt on land isn't distributed uniformly across the world's oceans. I will return to this point shortly.

Fig 10

Contributing Components to Local and Global Sea Level



Tide Gauge and Satellite Data for Sea Level 1870 - 2012



The rate of sea level rise has increased in recent decades, and is today greater than the conservative projections made by the IPCC one or two decades ago, and it is now clear that changes in sea level are speeding up.

In 2001, the IPCC reported that "[w]ithin present uncertainties, observations and models are both consistent with a lack of significant acceleration of sea level rise during the 20th century" (IPCC 2001). But it is now evident (Rahmstorf *et al.* 2007) that sea-level rise has accelerated since 1990 (Fig. 10).

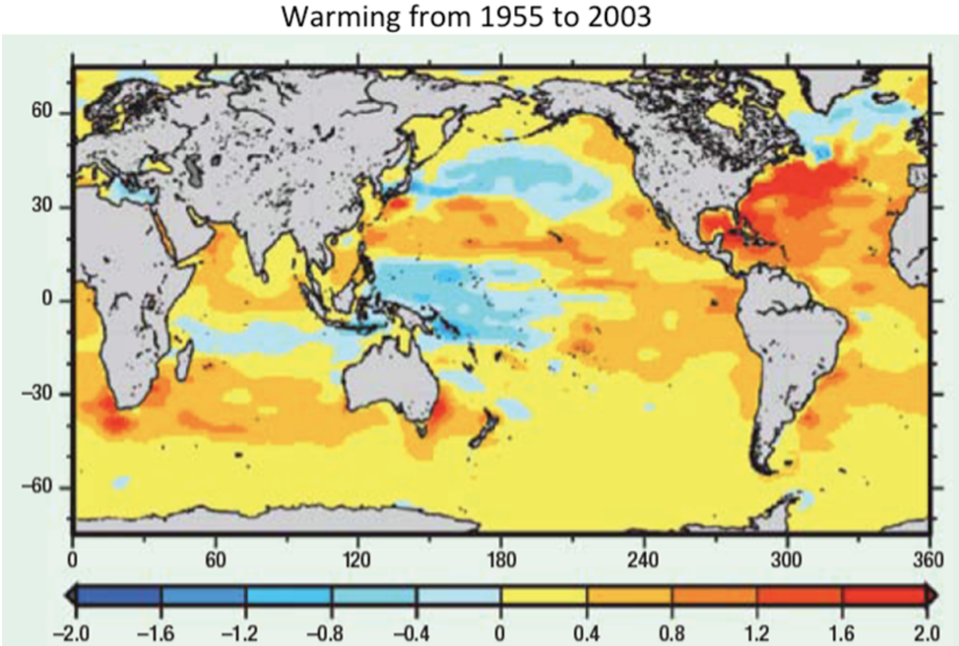
The 2007 IPCC report projected 12 – 24 inches of sea-level rise by 2100. These estimates did not preclude higher rates of rise due to increased rates of ice loss on Greenland and Antarctica. Although the IPCC authors were aware of publications relating to recent changes in Greenland and Antarctic ice, they lacked confidence that they could extrapolate meaningfully from these data to future sea-level rise. Rahmstorf (2007) used a semi-empirical relationship from 20th-century temperature and sea-level changes to project future sea-level rise from the IPCC scenarios for warming and derived an estimate of sea-level rise of about 2 – 4.5 feet for 2100 relative to the 1990 level. Using current outlet glacier discharge rates for Greenland to improve on the IPCC 2007 projections, Pfeffer *et al.* (2008) estimated a sea level rise between 2.5 and 6.5 feet by 2100 (Fig. 9).

An average sea-level rise of even 2.5 feet during this century would be of enormous consequence for lives, livelihoods, and property in coastal regions across the globe. Major cities, large portions of nations, indeed entire island nations will be affected. But for any specific locality future sea level will also be influenced by changes in currents and winds, proximity to the mass of melting ice sheets, and on the vertical movements of the land due to geological processes.

For example, a 2-foot rise in global sea level by the end of this century would result in a relative sea-level rise of 2.3 feet at New York City, 2.9 feet at Hampton Roads, Virginia, 3.5 feet at Galveston, Texas, and 1 foot at Neah Bay in Washington State (Karl et al. 2009). The SW and eastern coasts of the US have already experienced greater than average rates of increase over the last half-century (Fig. 11).

Trends in Sea- Level Change (mm/yr) due to Warming from 1955 to 2003

Fig 11



Milne 2008

In the Gulf Coast area alone, an estimated 2,400 miles of major roadway and 246 miles of freight rail lines are at risk of permanent flooding within 50 to 100 years as global warming and land subsidence (sinking). Seven of the 10 largest ports (by tons of traffic) are located on the Gulf Coast.(Karl et al. 2009) The US Navy estimates that $100 billion of Navy installations would be at risk with a sea level rise of about 3 ft. (NRC 2011)

For many of us in ocean science the compelling evidence for human-caused climate change came with the observations of deep ocean warming, the ice core data that demonstrate linkages between Earth's past temperature and atmospheric greenhouse gas content, the acceleration in sea level rise, the abrupt melting of land ice and ice shelves that had been in place for many thousands of years, and global changes in ocean chemistry. Such changes in these phenomena can only be consistently explained by an unusual rate of greenhouse gas release to the atmosphere.

The idea that greenhouse gases from fossil fuel combustion affect climate, which was studied by Arrhenius more than a century ago and developed further by Calendar a half century later, is correct. Interestingly, Arrhenius did not anticipate the rapid growth in human population during the 20th century and our increasing demands for energy - he thought that it would take millennia rather than a just a century to double the pre-industrial atmospheric CO_2 concentration.

State of the art fully coupled climate models can now simulate the natural processes that affect climate (solar cycles, volcanoes, and internal cycles such as the El Niño – Southern Oscillation) and the human-caused processes that affect climate (greenhouse gases and aerosols) to show the relative importance of each of these components in the climate of the past and present. Using assumptions about trends in population, type of energy used, etc. these same models can make projections about future climate. One very clear finding from these studies is that one of the largest uncertainties about future climate relates to the choices that we and our children will make regarding energy use. The more dependent we are on CO_2-emitting sources of energy, the more Earth's climate will change.

The decisions we make today will affect future generations and should motivate us to wisely use knowledge from climate science to reduce risks of harm from unnecessarily disruptive climate.

Thank you for inviting me to contribute to this discussion.

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References

BAMS/ NOAA (2009) http://www.ncdc.noaa.gov/bams-state-of-the-climate/

Frances, J.A. and S.J. Varvus (2012) *Geophys. Res. Lett.* 39, L06801

IPCC (2001) Working Group 1, Summary for Policy Makers. http://www.ipcc.ch/

Karl, T. R., J.M. Melillo, T.C. Paterson (eds.) (2009), *Global Climate Change Impacts in the United States*. Cambridge University Press.

Lean, J.L., D.H. Rind (2009) *Geophys. Res. Lett.* 36, L1570

Levitus, S., J. Antonov, T.P. Boyer, C. Stephens (2000), *Science* **287**, 2225.

NRC (2011) Naval Studies Board, Natl Acad Press

Overland, J.E. and M. Wang (2010) *Tellus 62A, 1–9*

Pfeffer, W.T., J. T. Harper, S. O'Neel (2008), *Science* **321**, 1340.

Pritchard, H.D., R. J. Arthern, D. G. Vaughan, L. A. Edwards (2009), *Nature* **461**, 971.

Rahmstorf, S. et al.(2007), *Science* **316**, 709..

Rahmstorf, S. (2007), *Science* **315**, 368.

Speilhagen, R.F. et al. (2012) *Science* **331**, 450