Central Coast Climate Science Education

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Lesson 9: Consequences of a Warming World Part 1: Physical Signs of a Warming World

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In this lesson of the tutorial we summarize the consequences of a warming world, as reflected in physical signs that can be measured by instruments on the ground and from satellites. In Lesson 10 we will discuss further consequences, including those that affect human society as well as the plant and animal life on our planet.

We have already begun to see some of these consequences. How much more severe they will become depends most of all on what action, if any, the nations of the world take to change the present "business as usual" trajectory of fossil fuel consumption. The last Lesson, Lesson 11, will describe the emissions reductions necessary to limit the amount of warming and the associated severity of these impacts, along with brief comments on the economic and political aspects of emissions reductions.

We now discuss some of the physical indicators that our world really is warming: snow cover, sea ice, ice sheets, mountain glaciers, sea level rise, and ocean temperatures.

Snow Cover Decline

A new analysis of snow cover in June (when melting is underway in the northern hemisphere) shows a rapid decline in snow cover in recent years: Here are some excerpts from a recent report (http://phys.org/news/2012-12-lows.html) as well as a plot (below) showing this decline:

> *A new analysis of snow cover observed by satellites shows record lows in Eurasia for June each year since 2008. In addition, three of the past five years have seen record low cover in North America. This is the lowest June snow extent since satellite observations began some 45 years ago. June snow cover is found to be falling much faster than expected from climate models, and is disappearing even quicker than summertime Arctic sea-ice.*

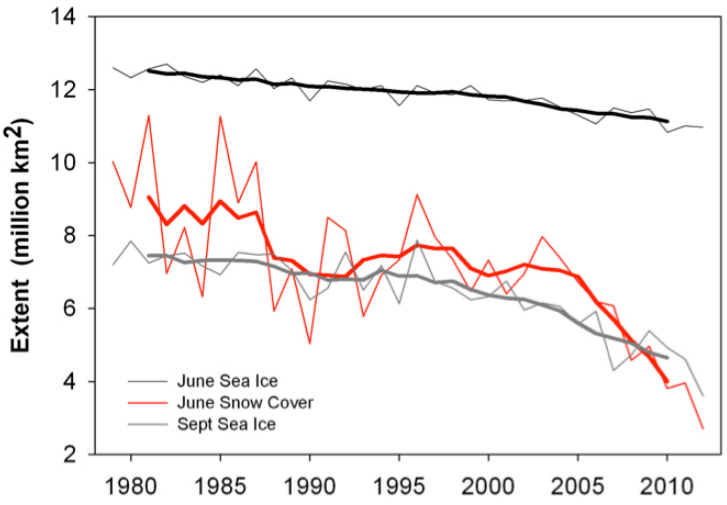

Figure 1.
The decline in June snow cover is shown yearly by the thin red line and the thick red line is a 5-year running mean. The other plots refer to arctic summer sea ice and are discussed below.

Arctic Summer Sea Ice Decline

The warming that is taking place is not uniform across the globe. As predicted by computer simulations, it is especially severe in the arctic. Of course it is still cold in the arctic during winter—very cold. So during the winter the Arctic Ocean freezes over but thaws during the summer with the area covered by sea ice reaching a minimum in September. This minimum has been declining dramatically over the last 34 years since satellites were launched that have the ability to accurately measure it. Figure 2 shows this decline. But even more dramatic has been the thinning of the ice and the reduction in its volume. "Old" ice, that ice that survives through one or two summers, is also rapidly declining. Estimates by polar experts over how long it will be before we have a summer with an ice free arctic ocean vary between a few years to a few decades, but most now expect it to be before 2050.

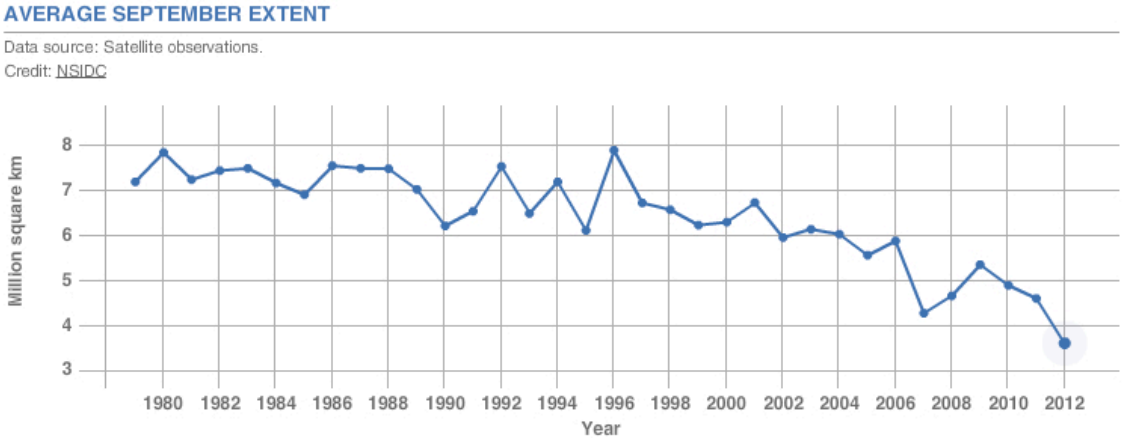

Figure 2.
The decline in arctic ice area at the September minimum.

One might ask whether the decline we are seeing is just something that occurs from time to time and is not something especially out of the ordinary. But a reconstruction based upon “proxies” for the arctic ice cover, shows how unprecedented this decline has been for almost 1 ½ thousand years. (Recall that “proxies” are indirect measures for various aspects of climate that are calibrated against recent direct measures in order to reconstruct past aspects of climate—in this case Arctic ice core, tree ring, and lake sediment data.)

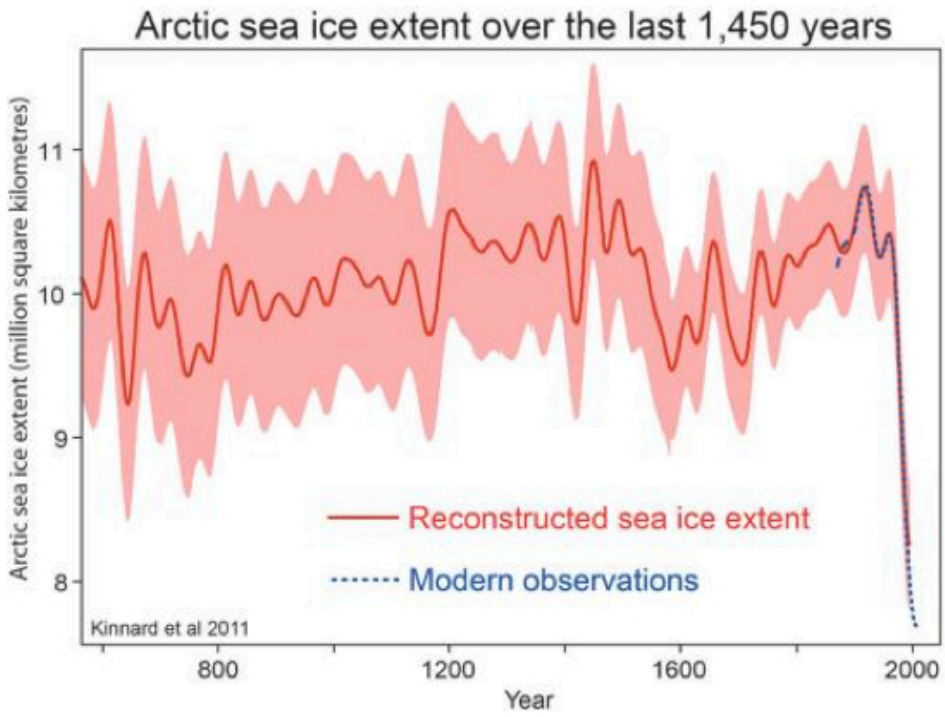

Figure 3.
Reconstruction of Arctic sea ice. The solid pink line is the 40-year running average and thus does not incorporate the most dramatic further recent drop of the year-by-year data shown in Figure 2.

For an excellent discussion of the decline in arctic summer sea ice see http://www.skepticalscience.com/record-arctic-sea-ice-melt-to-levels-unseen-in-millennia.html. The paper from which Figure 3 is taken is from a paper in Nature Vol. 479, pp 509–512 (24 November 2011)

[Digression]
This discussion of arctic sea ice naturally raises the question of whether the same thing is happening in the Antarctic, and if not, why not. The difficulty in such a comparison is that the geography of these two polar regions are almost exact opposites of each other: The arctic consists of an ocean almost completely surrounded by land, while the Antarctic consists of a very large continent surrounded by a very large open ocean. This leads to very different types of behavior for sea ice through the course of the year: In the arctic, until recently, much of the sea ice survived through the summer minimum (September). In the Antarctic almost all the ice disappears at the end of the southern summer (March). As discussed above, the

arctic summer decline has been very dramatic—about a13% loss per decade over the satellite era. In the Antarctic the (southern) winter sea ice extent has shown a small growth—but at a very much smaller rate: about a 0.9% gain per decade. This slight winter growth is thought to be due to shifting wind circulation patterns involving a warmer ocean and the Antarctic ozone hole, whereas the vastly more rapid arctic summer decline is thought to result from generally warmer conditions associated with global warming. Because of the rapidity and cause of the arctic sea ice decline it has received much more publicity. A very recent and instructive comparison of arctic and Antarctic sea ice by experts at the National Snow and Ice Data Center is given here http://nsidc.org/arcticseaicenews/2012/10/poles-apart-a-record-breaking-summer-and-winter/ and a somewhat older but still interesting discussion is found here: http://nsidc.org/cryosphere/seaice/characteristics/difference.html

A short video about this topic is also highly recommended: http://www.youtube.com/watch?v=MPnj9eR7t0g&list=UUtZdUYUZr493AUh_EInBYxQ&index=3
(This is one of a series of videos from the Yale Forum on Climate Change and the media: see the post on this website under **Resources --> Video --> Yale Forum on Climate Change**)
[End of digression]

<u>The Greenland and Antarctic Ice Sheet Loss of Ice</u>

By far the largest amount of fresh water in the world is stored in the enormous sheet of ice covering most of the Antarctic continent. Much smaller, but still huge, is the ice sheet covering most of Greenland. Understanding how these ice sheets are responding to a warming world is extremely important for they are likely to play an increasingly important role in determining by how much and how fast sea levels will rise (see the sea level rise discussion below). The Greenland ice sheet alone contains enough ice to raise the current sea level by about 24 feet. (All the ice now on the Antarctic ice sheet would raise sea level by an enormous 230 additional feet.) But it needs to be emphasized right away that no glaciologist thinks even Greenland will lose all its ice before the next few hundred years, let alone Antarctica.

The “ice budget” (or “mass budget”) for these two huge ice masses depends upon the gain of mass from snowfall and the loss of the mass of ice as portions of the ice sheet slowly flow into the surrounding ocean. Determining this mass balance is very difficult and was especially so prior to the satellite era when on-the-ground surveys had to estimate gains and losses for these huge areas. With the satellite era two additional techniques have been used: a) altimetry measures to see whether the ice sheets are getting thicker or thinner and b) gravity measurements using the pair of GRACE satellites that measure a change in gravitational pull on the satellites by the ice sheets as their total ice masses change.

All of these 3 basic techniques have their own strengths and weaknesses and do not always agree with each other. Recently, however, a consortium of glaciologists got together to come up with the best possible estimates of the mass budgets of these two ice sheets. (There were 47 of the leading glaciologists in the world in this

consortium from 27 institutions and from 8 different countries (the U.S., United Kingdom, the Netherlands, Denmark, Germany, Austria, Canada and Australia). They published their conclusions in the magazine **Science**, Vol. 338, p. 1183 (30 November 2012).

The following plot (Figure 4) summarizes their conclusions:

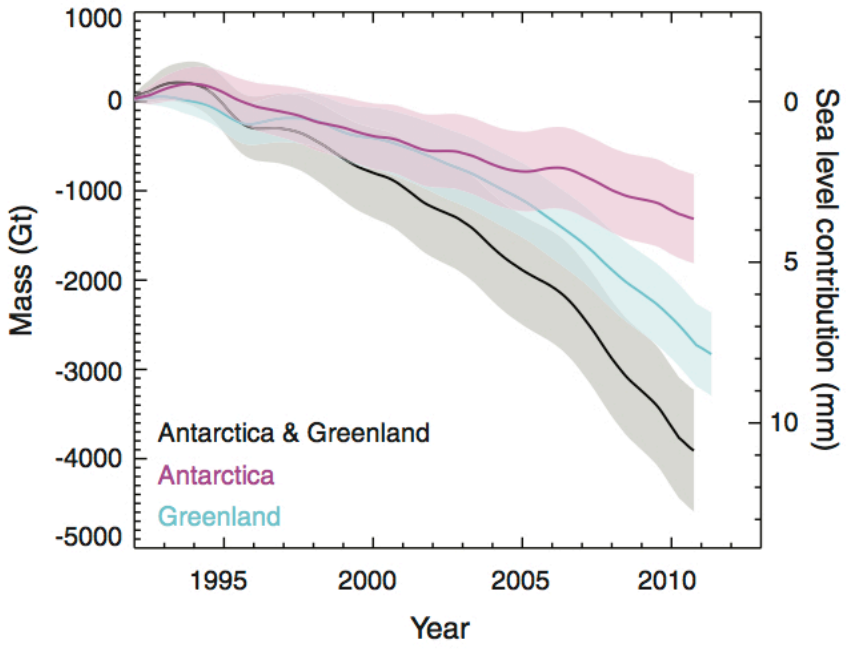

Figure 4.
Loss of mass (in 'gigatonnes') since 1992 from the Antarctic (pink), Greenland (blue) and combined (black) ice sheets. The scale on the right gives the equivalent resultant sea level rise.

Although it does not show up on the reproduction of this figure, the estimated uncertainty in the total loss of mass (or equivalently the ice sheets contribution to sea level rise) is a bit less then 20%. This diagram makes two things clear: a) ***both*** the Antarctic ***and*** Greenland ice sheets ***are*** losing mass, but the loss is currently more severe in Greenland than in Antarctica (the loss in Antarctica comes mostly from the west Antarctic ice sheet), b) the loss is not occurring at a constant rate, but the ***rate*** of loss is ***increasing***. How much more severe will this loss of mass be by, for example 2100? This is not known, and of course depends upon the future accumulation of CO_2 in the atmosphere. Reconstructions from the past cycles of ice ages show that there have been centuries, even decades, when these ice sheets lost mass very rapidly when temperatures were not very different from today's.

Loss of Ice from Glaciers

In addition to the ice stored in the Antarctic and Greenland ice sheets, a lot of ice resides in the glaciers that flow from mountain ranges. (More generally, "glaciers" in this accounting are considered to be ice in locations that are completely separated from the Greenland and Antarctic ice sheets.)

Recent work divided the glaciers of the world into 19 major regions and ***in each one*** of these regions the overall mass of ice stored in the glaciers of these regions is decreasing, though for a few individual glaciers increased snowfall has caused their mass to increase. The following graph shows the loss of mass from the world's glaciers in recent decades.

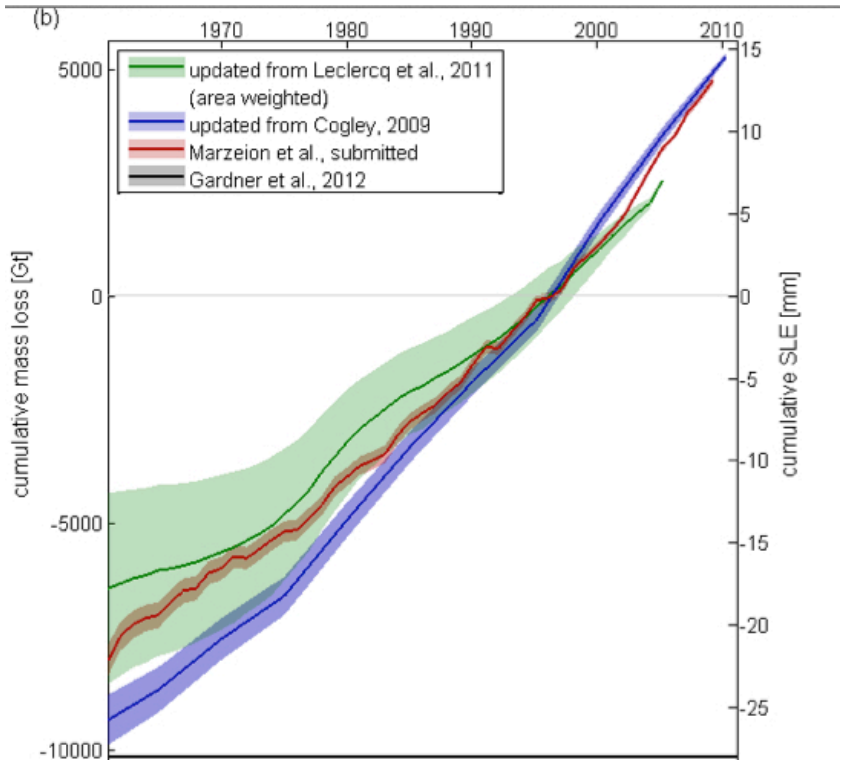

Figure 5.
Worldwide loss of mass from glaciers from three independent estimates. See the text for comments.

Note that a ***loss*** of mass in Figure 5 is plotted ***upwards***, whereas in Figure 4, the **loss** of mass in the Greenland and Antarctic ice sheets is plotted ***downwards***. The shaded regions represent uncertainties in the estimates and since around 1990 the three estimates agree fairly well. Neither the left scale (in gigatonnes of ice) nor the right scale (the equivalent rise in sea level) are on an absolute scale but have an arbitrary zero point for the average of these three estimates between 1986 and 2005. So, for example, between 1990 and 2010 it is estimated about 5000 - (-2000) =7000 gigatonnes have been lost, contributing to a sea level rise of about (15 - (-4) = 19 mm of sea level rise. We will discuss sea level rise shortly.

While figures such as Figure's 4 and 5 convey in graphical quantitative form the loss of ice, pictures such as Figure 6 (below) of the astounding retreat of a glacier in Alaska make it easier to grasp the magnitude and severity of loss of ice. The two photographs in Figure 6 are taken from an atlas of Alaskan glaciers produced by the United States Geological Survey. Similar work has been produced in an ongoing

project of photographer James Balog to document retreating ice. A link to a talk he gave is here:
http://ed.ted.com/lessons/james-balog-time-lapse-proof-of-extreme-ice-loss
but, to experience the full impact of his work readers are urged to see on a wide screen his most recent documentary "Chasing Ice". (See on this website my comments on "Chasing Ice": ***Tutorial and Essays --> Essays --> Communicating Climate Science and Story Telling: Five Examples***, then scroll to **"Chasing Ice": James Balog Documentary**

Figure 6.
Two photographs of the Muir/Riggs glaciers in Alaska from a USGS publication. The black and white photograph was taken in 1941 and the color photograph in 2004. The white streak in the background of the 2004 photo marks the height of the glacier in 1941.

Ocean Heat Content and Atmospheric Temperatures

As we saw in Lesson 5, (see in particular Figure 7) the amount of heat in the ocean has been steadily rising for the last several decades and shows no signs of ceasing to do so. The same is true for the air temperature when smoothed over periods of time that average out the short term El Nino and La Nina variations. This is true whether measured over the ocean or over the land, and is true whether measured near the Earth's surface from weather stations or away from the surface via satellites.

Sea Level Rise

Basic laws of physics demand that the loss of ice from the great ice sheets of Greenland and Antarctica and the glaciers of the world, together with the warming waters of the ocean, must lead to the average sea level of the ocean increasing, since the volume of ocean water expands as it warms. And indeed measurements confirm this. Here are two records of sea level, one going back to 1870, based on tidal gauge records. The more recent and far more accurate one is from a series of NASA satellites, dating from 1993.

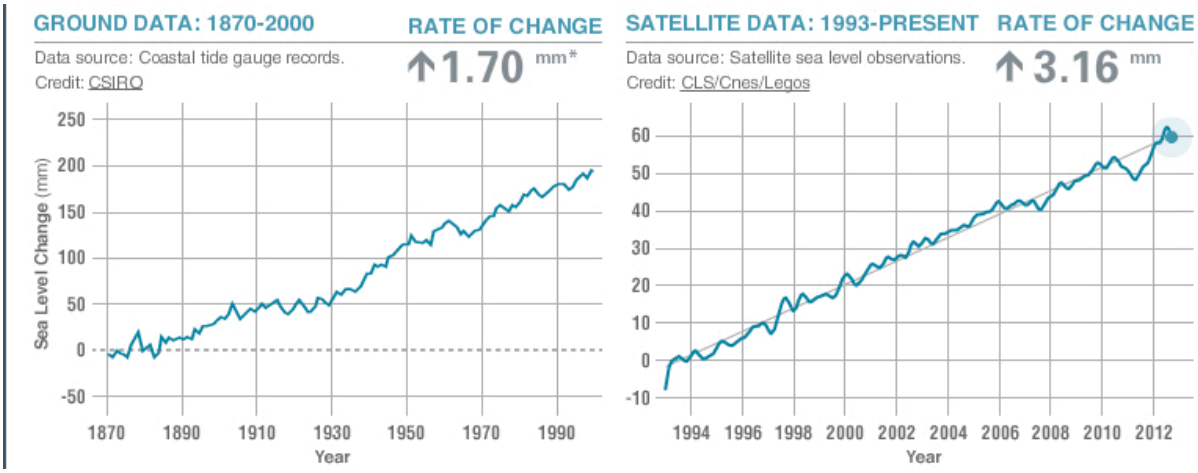

Figure 7.
Sea level changes since 1870.

Note that the rate of sea level rise between1870 and about 2000 has averaged about 1.7 mm per year, but this rate has accelerated and is currently about 3.16 mm per year averaged between 1993 and 2012. Note also the large “hole” in the right hand plot in 2011. This was caused by a strong La Nina pattern that shifted rainfall patterns world wide, especially in Australia. Evaporation from the ocean that normally falls back as rain in the ocean (and thus has no effect on sea level) fell instead on land, and thus caused a temporary drop in sea level. But this water eventually worked its way back to the ocean within a year or so and the sea level rise continues.

Oceanographers and glaciologists have examined the “sea level rise budget” to compare the observed rate of rise with that calculated from the observed warming of the ocean and the observed rates of ice loss from the glaciers and ice sheets. (There are also small contributions to sea level change due to other human activities: namely, withdrawing ground water, some of which finally ends up in the ocean, and retention of rainfall that ends up in reservoirs.) We can get an estimate of the main contributors between about 1995 and 2010 by ignoring these smaller effects. From Figure 4, the loss from the ice sheets during these 15 years is about 11mm, and from Figure 5 that from the glaciers is a bit larger, 15 mm. The total rise during this interval has been about 47 mm, and the expansion of the ocean due its increasing temperature makes up for the rest—about 21 mm.

What is in store for the future and what can we learn from the past? Attempts to reconstruct sea level rise during the past show that sea level rose dramatically from the depths of the last ice age about 22,000 years ago as the enormous ice sheets covering large parts of the northern hemisphere slowly retreated. This is shown in Figure 8. Since that time the sea level has risen by about 120 meters or nearly 400 feet! But most of this increase took place over 7000 years ago and in fact for the last 2000 years it has been quite stable with gentle increases and decreases—until the warming brought about by increasing CO_2 levels caused it to start increasing again. This is shown in Figure 9. The bottom panel of Figure 9 shows a reconstruction of sea level rise near the North Carolina coast. There was a slight rise during the medieval warm period around 800-1200 AD followed by a slight fall

during the “little ice age” from about 1600-1850. This is then followed by a steeper rise that is ongoing and, as shown in Figure 7, accelerating. The top panel of Figure 9 is a reconstruction of global surface temperatures, and shows that the rise in global temperature is coincident with the upturn in sea level.

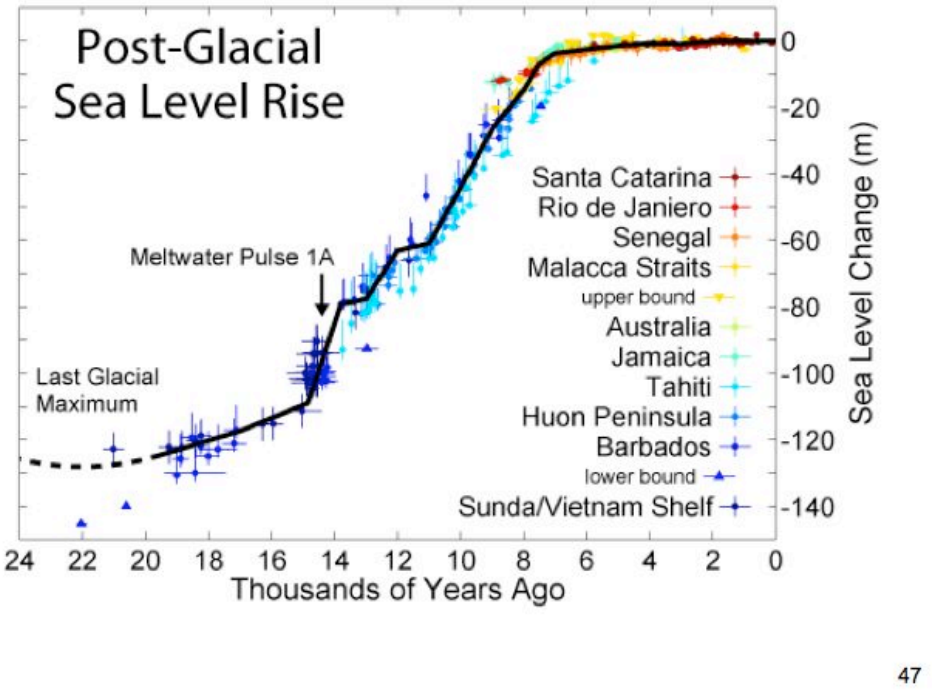

Figure 8.
Sea level rise since the end of the last ice age.

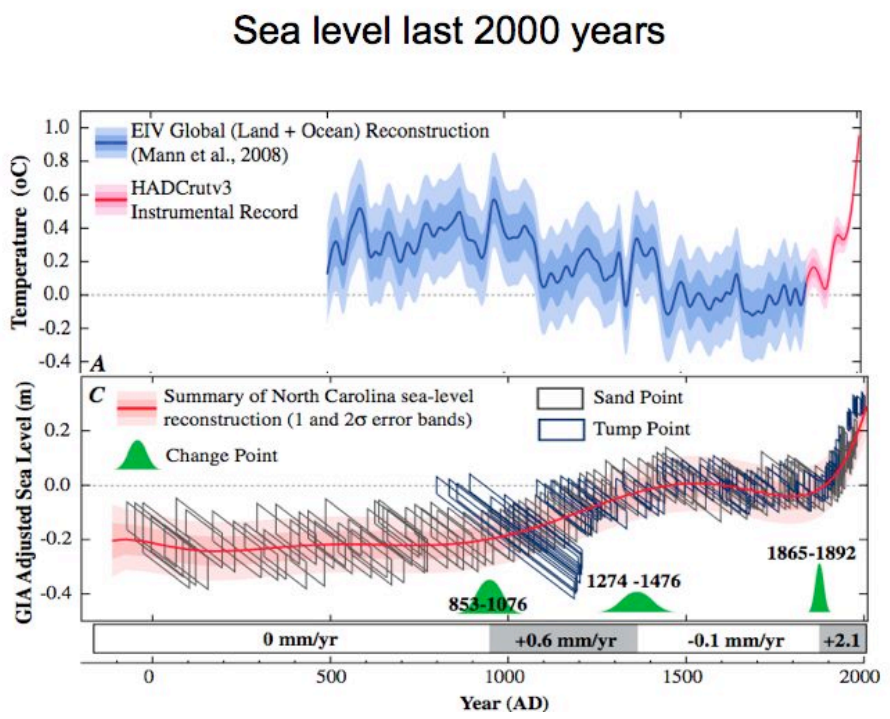

Figure 9.
Sea level and Global Temperatures over the last 2000 years.

By how much and how fast will the sea level continue to rise? As we have repeatedly stated, all such projections depend upon which emissions scenario the world adopts over the next several decades. But even for a given scenario the understanding of the processes governing how the Antarctic and Greenland ice sheet respond to increasing global temperatures are not well enough understood to project with any certainty the sea level rise by 2100, but about 3 feet seems fairly likely. This is an average over the globe. With respect to the center of the Earth, some parts of the land are rising, some falling. Ocean and wind currents are likely to shift as well, so that the actual sea level rise in a given location may be significantly above or below this value. As will be discussed in Lesson 10, a rise of just 3 feet would be devastating to a large segment of the world's population.

Summary:

In this Lesson we have summarized some of the observed evidence for a warming world: Decreasing snow cover, loss of arctic sea ice, loss of ice from the Greenland and Antarctic ice sheets, and loss of ice from most of the world's glaciers. Together with the increasing heat in the ocean (Figure's 2 and 7 in Lesson 5), the loss of ice from glaciers and ice sheets is causing sea levels to increase. For a very recent summary of some of this evidence directly from some of the scientists who are doing the research, see the following video:
http://www.youtube.com/watch?v=SWDWYgc496M&list=UUtZdUYUZr493AUh_EInBYxQ&index=1. The video

features interviews with 8 leading climate scientists taken during the annual meeting of the American Geophysical Union in December 2012. This video is yet another in the excellent series from the Yale Forum on Climate Change and the media: see the post on this website under **Resources -->Video --> Yale Forum on Climate Change**.

All this evidence is now so compelling that the word frequently used in reviews of the evidence for a warming world by scientific organizations is: ***"unequivocal".***