Sea Level Rise: Rates & Causes

Donald Bogard, Sept. 2018

Among the many concerns expressed by some about future global warming, perhaps the greatest concern is over future rising sea levels that would affect the whole globe and flood many populated areas. This report presents a broad overview of this issue and addresses the following. What are past rates of change in sea level; what variabilities exist among rise rates; what are the causes of sea level change; and what, if any, predictions can be made about future sea level.

Tidal Sea Level. Hundreds of tidal gauges are located at sea shores around the world, and many of these have collected data on local sea level for a century or more. Figure 1 gives examples of such tidal data for Key West, Florida, and Honolulu, Hawaii. The overall trend for both sites has been apparently constant rise rates (but see later) of ~2.37 & ~1.43 mm/yr. Local sea level changes on daily to yearly times scales, thus producing the "noise" obvious in the data. These changes are caused by e.g., tides, wind, air pressure, ocean currents, water temperature and salinity, etc. Consequently, tidal data must be available over several decades to ascertain the average sea rise at that site. Fig. 2 illustrates that sea level has risen continually since warming from the last stages of the Little Ice Age about year 1800.

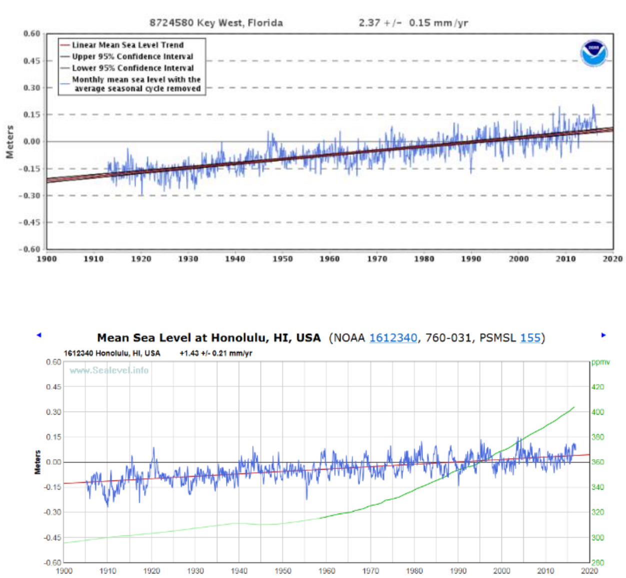

Fig. 1. Tidal sea level since 1912 at Key West, FL, and since 1905 at Honolulu, HI.

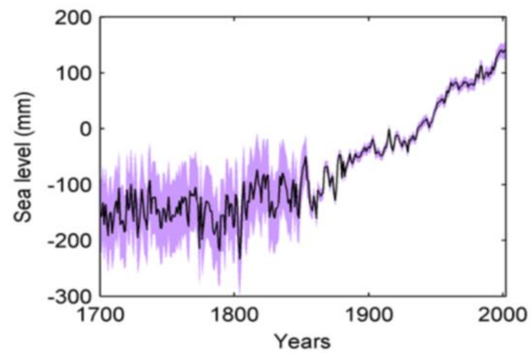

Fig. 2. Sea level since 1700.
https://www.psmsl.org/products/reconstructions/jevrejevaetal2008.php

Land Movement. Changes in sea level measured by tidal gauges are relative to the land surface at that site and often yield sea level changes quite different from one site to another. One important reason for such variations is vertical movement of the land surface that differs among sites. At some sites the land is sinking due to sediment compaction as water is excluded, or as underground water, oil, or gas is withdrawn. At Galveston, TX, the land is sinking at almost 5 mm/yr and even more at some other locations. Land surfaces also move both up and down from various tectonic causes, and especially from extra mass of glacial ice deposited on some surfaces in the last continental glaciation, followed by removal of that extra mass beginning ~15 kyr ago. Because continents are semi-rigid, recent land movements occur both where land ice has melted and some distance away, because of a tendency for continents to "tilt" under force applied to one side then released. Thus, the sea shores at some locations in northern Canada and Norway are rising at rates between 5 and 10 mm/yr.

Vertical land surface movements are measured (generally to within a few tenths of a mm/yr) using the satellite global positioning system (GPS), which reflects radar off ground receivers and measures the transit time. Some 485 such GPS receivers are located within a short distance from a tidal sea level station, mainly around North America, around Europe and Australia, and the east coast of Asia (see Fig. 3). The majority of these co-located GPS-tidal stations document vertical land movement, both up and down, exceeding 0.5 mm/yr, and many indicate vertical land movement (up and down) between 0.5 and 2.0 mm/yr [Reference 1]. Most individual reported data on tidal sea levels (e.g., Fig. 1) do not have corrections applied for land movement. However, compilations of such individual data discussed later usually do have applied land movement corrections [Reference 2]

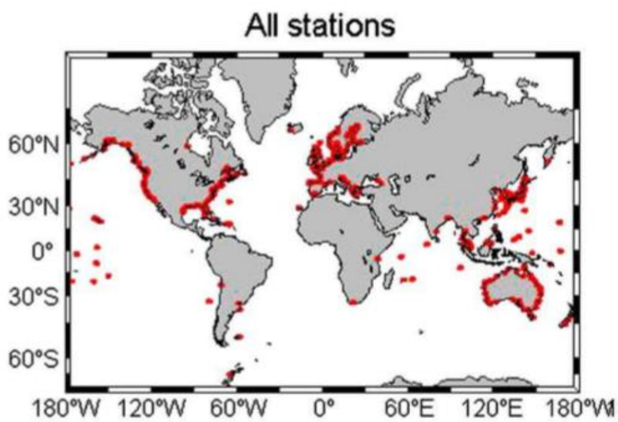

Fig. 3. 485 co-located GPS and tidal stations.

Correcting measured values of individual tidal sea level for land subsidence at each site often produces a significant change. Thus, the measured 2.37 mm/yr sea rise at Key West, when corrected for the GPS measured land subsidence of -1.01 mm/yr gives a real sea rise rate of 1.38 mm/yr. The measured 1.43 mm/yr at Honolulu, when corrected for land subsidence of -0.66 mm/yr, gives for the real sea rise a relatively low rate of 0.77 mm/yr. Correcting the measured sea rise rate since 1905 at Galveston of 6.47 mm/yr, when corrected for land subsidence of -4.76 mm/yr, gives a real sea rise of 1.71 mm/yr.

Another factor in measured sea rise rates is called glacial isostatic adjustment (GIA). When massive glacial loading caused continents to sink, deep mantle beneath those continents flowed out under the ocean basins and, because the oceans then contained less water mass, caused the ocean floor to rise. Since melting of that land ice and its return to the oceans, the ocean floor has been sinking. This affects all tidal gauge data the same, and individual reported tidal data do not contain such corrections. However, in compiled data and in evaluation of trends in global mean sea level, a 0.3 mm/yr GIA adjustment is applied to all tidal data.

Several studies have combined sea level data from many tidal stations (sometimes hundreds) and examined their combined long-term trend. The assumption is that averaging tidal sea level trends from many parts of the globe gives the global sea level trend. Fig. 4 [Ref 3] shows seven such tidal compilations. The data labeled "satellite" is discussed in the next section. The individual compilations of tidal data give slopes that define sea rise rates between ~1.3 and ~1.9 mm/yr, with an average of 1.7 mm/yr.

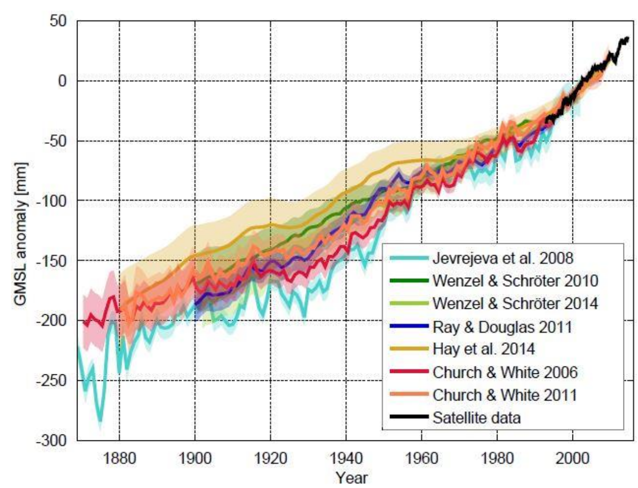

Fig. 4. Seven compilations of tidal sea level growth.

Sea Level by Satellite Altimetry. Beginning in 1993, a series of satellites used radar altimetry to measure time changes in the distance the beam travels to the open sea surface and back again. Sea height in the open ocean is quite variable over both time and the surface, so data is continually taken. Several altimetry satellites each collected data for a given time period (Figure 5).

Although Topex began acquiring data in 1993, multiple issues with early data collection have led most researchers to discount the first few years of data, and these are not shown. (Also note greater scatter of plotted Topex data.) The overall slope of altimetry data is not well defined, and gives a sea rise rate of about 3.2 mm/yr, almost twice the average, long-term rise rate from tidal gauges. The strong dip in the curve at ~2011 was probably caused by a strong la Nina, an ocean phenomenon that produces cooling of the tropical Pacific, and the small increase at 2015-16 is associated with an el Nino which caused Pacific warming.

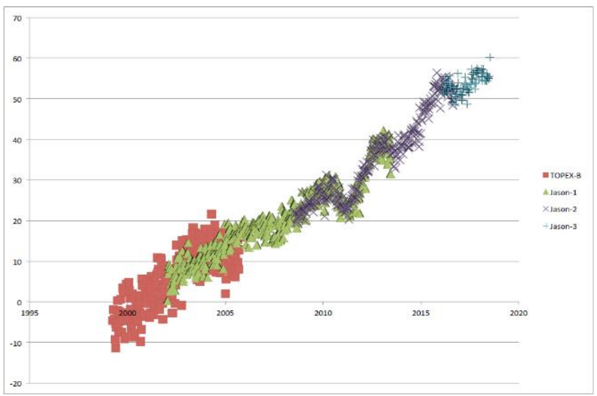

Fig. 5. Satellite altimetry of the global sea surface

There are two types of corrections that have to be applied to altimetry data to produce the results shown in Fig. 5. The first set of corrections includes factors like large biases and drifts in readings among the various satellites. A large correction is applied for Earth's shape, or geode. This correction is required because the Earth is not a sphere and the distance between satellite and sea surface varies during an orbit. A correction of 0.3 mm/yr is applied for isostatic sinking of the ocean basins following glacial melting (GIA discussed above). Investigators claim the uncertainty in satellite readings and applied corrections is about ±0.4%.

The second set of corrections applied to altimetry data is for various environmental factors that vary region by region and over time. These include things like character of the sea surface and atmosphere below. (Altitude for the Jason-3 satellite is above 1300 km.) Because these satellites pass over a region many times, there are many readings taken for a given location, and the sea surface and atmosphere conditions can be expected to vary across the monthly and yearly readings. The fact that the altimetry sea surface data cluster reasonably well to form a trend implies that these applied corrections are reasonably good. If they were not, more data scatter and an indistinct trend could be expected. This consideration and Fig. 5 imply that the altimetry sea rise rate has not changed appreciably over the time it was acquired.

Altimetry data measure the volume of the ocean and are sensitive to additions or subtractions of water, such as glacial melting. A second type of satellite data (GRACE) used to measure sea level is sensitive to ocean mass and thus is insensitive to changes in ocean volume caused by temperature. Sea rise rates involve merging gravity data from the GRACE satellite (acquired since 2003) and ocean temperatures obtained by ARGO floats to depths of 2,000 meters. GRACE measures the mass across a ~300 km diameter portion of the ocean beneath, a considerably larger footprint than altimetry data. ARGO temperature data are utilized to calculate the thermal expansion of the ocean caused by warming.

Sea level changes from 2005 to 2014 determined by the GRACE-ARGO technique are shown in Fig. 6 and compared to altimetry data [Ref. 4]. The effect of thermal expansion and of addition of water mass to sea rise are shown separately and summed, and are compared to data obtained by altimetry. The apparent effect of the 2011 la Nina appears in both data sets.

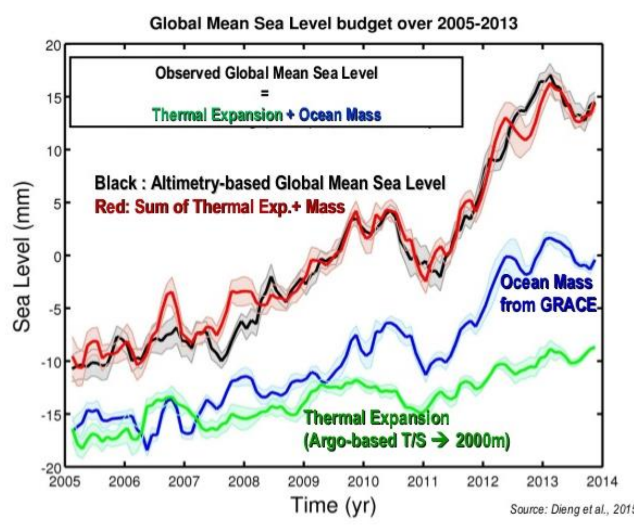

Fig. 6. Sea Rise from Altimetry & GRACE Satellites
https://www.slideshare.net/CFCC15/pre0082-cazenave-a

Sea level data obtained by GRACE-ARGO also require many of the corrections applied to altimetry data. GRACE data must be corrected for the Earth's geode. Calculations of thermal expansion are not straight-forward because the ocean temperature varies with depth and surface location and is often changing. Further, ocean thermal variations reflect measurements of temperature changes across the surface and appreciable changes with depth.

Comparison Tidal & Satellite Sea Rise. Figure 7 compares tidal sea rise compilations from several previous investigations, corrected for vertical land movement, for the period 1958-2014 [Ref. 5]. The trend for satellite altimetry data since 1993 is also shown. As apparent from Fig. 6 and from Fig. 4, land-corrected sea rise rates accelerated around the early 1990s, coincidentally about the time that satellite data first became available.

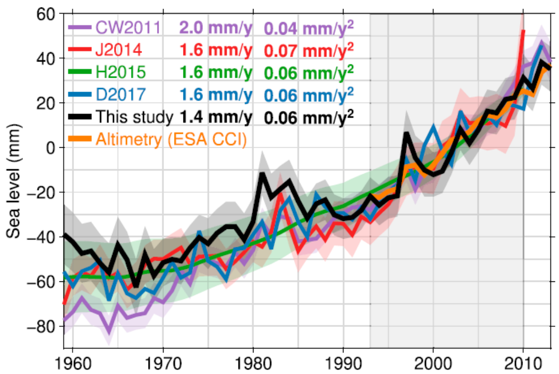

Fig. 7. Tidal & Altimetry Sea Rise Rates Compared

To gain understanding as to why sea level rise rates increased some 25 years ago, one must examine details in the tidal data. The Fig. 1 tidal data for Key West FL, shows apparent periodic changes in rise rates, e.g., negative rise ~1912-1928, positive rise after ~1928, and an even more positive rise after ~1998. Various researchers have examined such trends in defined time increments for compilations of tidal data. Fig. 8 examines the compiled tidal data of Fig. 4 in 15-year increments [Ref. 6]. Similar results (also using a time period of 15-years) were reported in a separate study, which concluded a sea rise trend of 1.1 ± 0.3 mm/yr (1σ) before 1990 and 3.1 ± 1.4 mm/yr from 1993 to 2012, consistent with independent estimates from satellite altimetry [Ref. 7]. This study also concluded that previous estimates of 20th century rise rates based on averages were too high. When examined in this way, not only do the rise rates of sea level change over time, but these variations resemble those for global temperature. (Global temperature decreased over 1880-1910, increased over 1910-1940, decreased over 1940-1970, and increased over 1970-2000.)

Because warming ocean temperature produces about half of total sea rise (discussed in later section), it is not surprising that sea rise mimics global temperature on shorter time scales. The slightly different shapes of the various compilation curves likely derive from the specific data and locations used, but the trend is quite similar for all. The average sea rise rate over short periods since 1900 varied between ~0.5 mm/yr and >3 mm/yr.

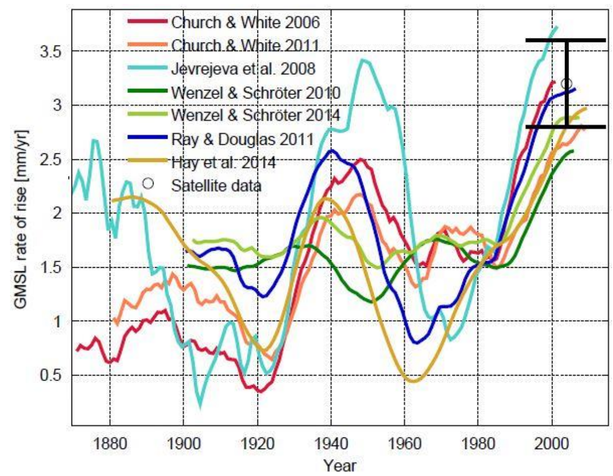

Fig. 8. Tidal Compilations in 15-yr Increments.

Consequently, the question of what was the <u>average past rate of global sea rise cannot be answered without specifying a time interval</u>. The ~x2 higher sea rise rates since ~1990 and obtained by both satellites and land-corrected tidal gauges, when compared to earlier tidal records, strongly indicate that the recent greater rise in sea level has been produce by increased ocean warming. Ocean warming has been reported since about the 1970s to mid-1980s, depending on the source.

Are Satellite Data Reliable? Some have suggested that the significant increase in sea rise rates beginning about the time of the first satellite data (early 1990s) may not be real, but caused by errors in the various types of corrections and adjustments made to satellite sea level data. Some of these corrections have been large. Data for each instrument must be individual calibrated and over time adjusted for any drift. Initially there were large off-sets among the different altimetry satellites, and altimetry data prior to the late-1990s is sometimes omitted (e.g., Fig.5). All satellite data (including GPS) also must be corrected for Earth's geode (shape), for changing environmental factors, and for glacial isostatic adjustment. These corrections were discussed above.

Sea level data from GRACE-ARGO use GRACE satellite data to determine changes in the mass of the sea (e.g., glacier melting) and ARGO float data on vertical sea temperature to calculated the volume change in the ocean caused by thermal expansion. One might well question the accuracy of thermal expansion corrections based on ARGO and this dual, more complicated way to obtain sea level changes. However, the sea rise rates from GRACE-ARGO are similar to altimetry rise rates.

A common and powerful way to check the accuracy of measurement of some characteristic is by measuring it in different ways. If the methods agree, the implication is that uncertainties germane to only one of the techniques used do not affect the results. Not only do the altimetry sea rise data agree with the GRACE-ARGO data, but the tidal data, corrected for vertical land movements using GPS satellite data also generally agree over the past two decades or so. The only common parameter tidal data share with satellite data is the satellite correction for land movement. Any bias here would have to arise from corrections applied to all data sets. A possibility might be the geode shape correction applied to all satellite data. (This correction is relevant to only about 50-60% of the GRACE-ARGO sea rise; the other 40-50% of sea rise derives from ARGO expansion data.)

I suggest the fact that all three types of sea rise rate data – corrected compilations of tidal data, altimetry data from several satellites, and GRACE-ARGO – give very similar rise rates around 3 mm/yr over the past couple of decades (mid-90s for altimetry, 2002 for GRACE) constitutes a strong argument that this rise rate is near correct. IF there is a major bias in all three data sets, only the geode correction seems common to all three.

However, the satellite data discussed above comprise only the "official" US data set for sea level. Other satellite data were acquired, but are not generally included. The ERS-2 (European Remote Sensing) satellite had an operating radar altimeter over 1993-2002. The US Navy GFO mission (Geostat Follow-On) had an operating radar altimetry over 2000-2008. The European Space Agency Envisat satellite had an operating radar altimeter over 2004-2010. The sea level data acquired by these satellites are plotted in Figure 9 along with the TOPEX and Jason data of Fig. 5. Two of these three additional data sets are consistent with the TOPEX and Jason satellite data. Envisat data is not consistent and implies essentially no sea level rise over its measurement time. The sea rise rate shown in Fig. 9 of ~2.7 mm/yr does not include Jason data after 2011, which may explain it being slightly smaller. (Compare Fig. 5.) It is not clear whether the 0.3 mm/yr GIA correction has been applied in Fig. 9.

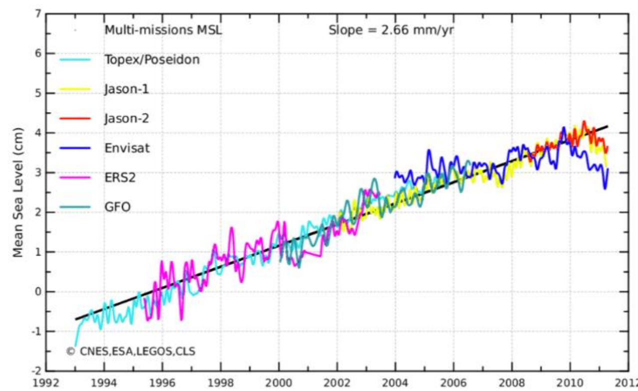

Fig. 9. Sea level acquired by ERS-2, GFO, and Envisat satellites compared to TOPEX and Jason data.

Causes of Sea Rise.

There are two major causes of sea level rise. Ocean warming produces thermal expansion of the ocean water, and melting of mountain glaciers and polar ice sheets adds more water to the oceans. The first increases ocean volume without increasing mass, and the second increases both volume and mass. Fig. 10 shows relative contributions of these sources since satellite data became available [Ref. 8].

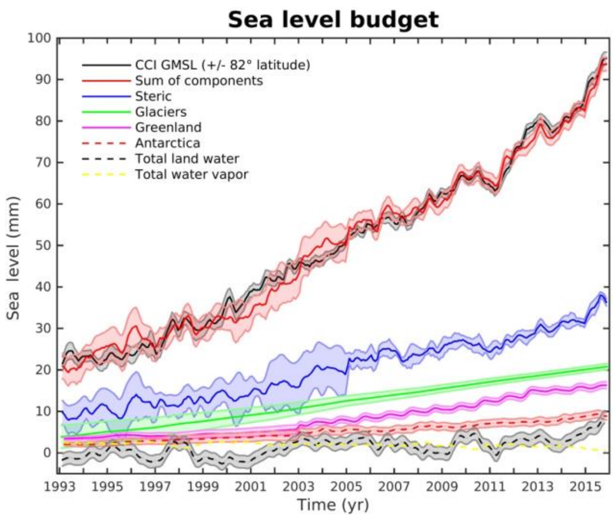

Fig. 10. Relative Contributions to Sea Rise.

The largest contributor (steric), about 40% of the total, arises from ocean warming. Melting of mountain glaciers is thought to be the second largest contributor (~25%) and add ~0.7 mm/yr to sea rise. Melting of Greenland ice is the third most important contributor (~20%). However, some estimates show melting of Greenland and mountain glacier ice to be more equal. Melting of west Antarctic ice (east Antarctic ice is generally increasing) is approximately half the melting rate on Greenland, depending on whether one considers increasing east Antarctic ice. (However, I found different estimates of the relative role for these parameters in producing sea rise.) The smallest sea rise factor shown in Fig. 9 is change in retention of water on land, which shows no net trend over time.

Earlier ocean heat content was estimated through temperature measurements of near-surface water by passing ships and floating buoys. Deployment of ARGO instruments to measure ocean temperature at depth, initially to 700 meters then later to 2,000 meters, began in the early 2000s. The ocean (average depth 3690 meters, deepest almost 11,000 meters) is known to undergo vertical mixing of both water and heat on an irregular time basis. Thus, to fully understand the degree ocean warming produces ocean expansion requires temperature measurements throughout. Different variations in ocean temperature occurs across regions. Further, in much of the ocean, the temperature increase over the past few decades is very small, and measurement uncertainties can be significant. Missing data for heat content often are estimated using models. I found considerable variation among graphical representations of ocean heat content with depth and the time when major heating began.

Because of their large number and small size relative to the ~300 km surface footprint of GRACE gravity measurements, determinations of the melting rate of mountain glaciers is uncertain. Different studies give somewhat different results. The mass of remaining mountain glacial ice is limited; one estimate deemed it capable of producing less than one meter of additional sea rise.

The following three graphs give estimates of the melting rate of the Greenland and Antarctic sheet ice, as measured by GRACE.

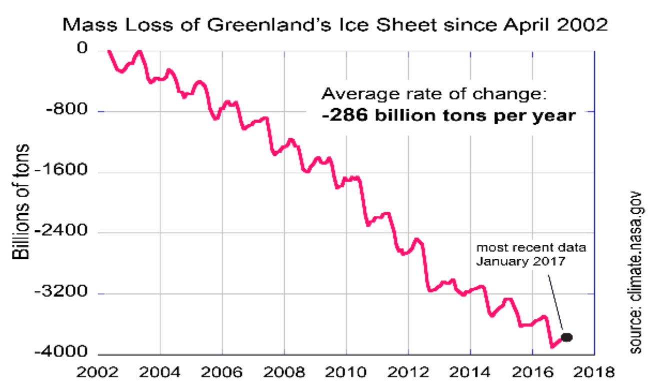

Fig. 11. NASA GRACE data on Greenland ice loss

The recent ice melting rates in Figs. 11 & 12 for Greenland are in agreement. Since 1979 the areas of GL exhibiting melting have been variable and working inland from coastal regions at a slightly increasing rate. The GL ice sheet is 2-3 km thick and spreads over 1.71 million km^2, or ~80% of the GL surface. The volume of the Greenland ice sheet is ~2.85 x10^6 km^3 (2.85 x10^{15} m^3) and its mass (glacial ice density =917 kg/m^3) is ~2.6 x10^{18} kg, or ~2.6 x10^{15} metric tons (~2.9 x10^{15} US tons). If melted, this Greenland ice would be about the same amount of water as in the Gulf of Mexico. At recent melting rates, it would require ~8,600 years for the ice on GL to entirely melt. Evidence from the last interglacial, when much of Greenland's ice melted, shows that temperature was a few degrees above that of today for ~10 kyr and above today's temperature for ~2 kyr before sea level then rose above today's.

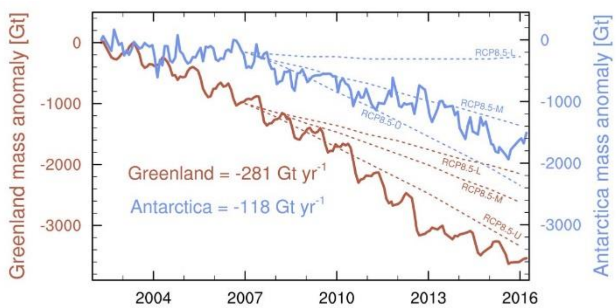

Fig. 12. Melting Rates Greenland & Antarctic Ice
https://globalchange.umich.edu/globalchange1/current/lectures/dangerous_climate/dangerous_climate.html

Melting rates of ice on Antarctica shown in Figs. 12 & 13 appear to differ. The rate of 118 Gt/yr in Fig 12 is higher than the total Antarctica melting rate in Fig 13, but lower than the West Antarctica rate. East Antarctica has been gaining ice. The difference in melting rates between Figs 12 & 13 may be a matter of what portions of the continent are included. The rate of ice melting on both Greenland and West Antarctica have been slowly increasing.

A Perspective. Measurements of sea level rise using tidal gauge data versus satellite data monitor different things. Tidal sea rise is relative to the local seashore. Land at that seashore commonly is rising or falling, and sometimes this dominates over the real sea rise. Further, changes in ocean level near a specific seashore may be quite different from that at other tidal gauges located some distance away, independent of local land movement. This occurs because of variations in mean ocean height around the globe. These variations are caused by influences of many regional factors (ocean currents, tides, winds, temperature, salinity, etc). The net

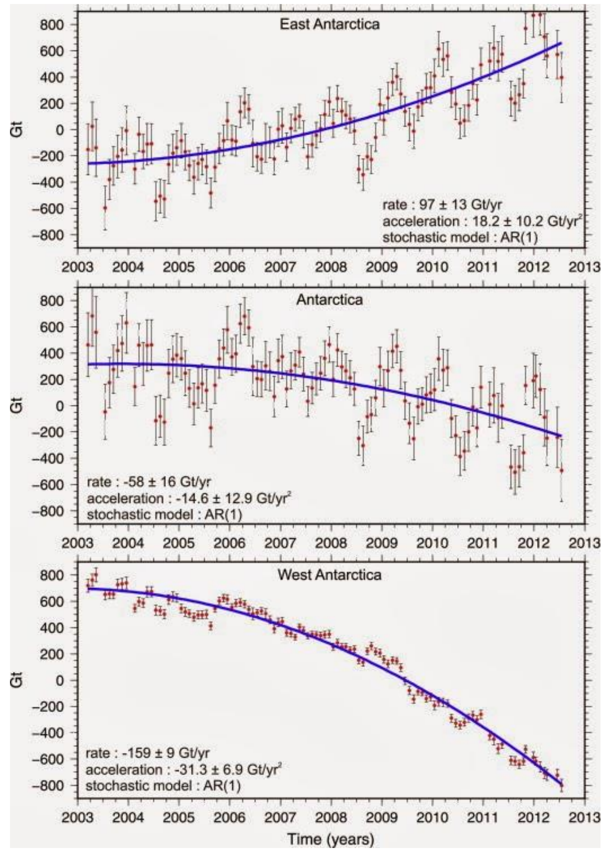

Fig. 13. Ice Melting Rates On Antarctica.
https://www.sciencedirect.com/science/article/pii/S0012821X13005797

rate of sea rise measured by local tidal gauges, not global sea rise, is the value of greatest interest to the population and infrastructure located near a particular seashore.

Satellite measurement of sea rise differs from tidal data in that it applies to the open ocean, mostly independent of near-shore variations, and is averaged across the whole ocean. The current average sea rise rate is ~3.2 mm/yr (~2.9 mm/yr without GIA correction), but that value differs from those measured by many tidal gauges because of regional, near-shore ocean effects and vertical land movement. The 0.3 mm/yr GIA correction applied to satellite data is generally not relevant to local tidal sea rise rates.

Both satellite and tidal gauge sea rise data are quite sensitive to changes in global temperature over durations of a decade or more (e.g., Fig. 8). Over the last century, there have been periods when average sea rise was as low as 0.5 mm/yr and as high as >3 mm/yr. Because the globe has been strongly warming over the past few decades, the rise rate is now above 3 mm/yr and possibly growing. Effects of global temperature changes is observed in both satellite data and many tidal data.

As for future sea rise, that largely depends on future global temperature and the stability of polar ice caps. Both subjects are clearly uncertain. The overall rise in sea level since the mid-1800s was likely caused by increasing temperature since the end of the little ice age around 1800. About 40% of sea rise depends directly on ocean temperature and possibly on deep ocean mixing. Melting polar ice caps currently contribute about 40% to sea rise. At current melting rates of Greenland ice, it would require a few thousand years to melt the entire polar cap. The last interglacial (the Eemian, 130-116 Myr ago) experienced temperatures a few degrees higher than current global temperature (reported values range ~2-6 C^{o} higher) and these higher temperatures persisted for ~11 kyr. It is estimated that melting Greenland ice contributed a few meters to sea rise during that interglacial. (The Greenland ice cap did not entirely melt.)

Whatever future satellite data may give for the average sea rise rate, tidal gauge readings for sea rise at individual seashores will give higher rise rates in some locations and lower rise rates in others. And it is the local sea rise rate that is of most interest to those who dwell near seashores.

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