Sea Level Changes in the Southeastern United States

Past, Present, and Future

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Contents

Preface

In the southeastern United States and particularly in Florida, folks concerned about climate change are usually focused on sea level rise rather than on warming. In Florida most long-term stations measuring sea level are currently registering a rise of about 2 millimeters per year or about 8 inches in 100 years. Most scientists expect this rate to increase. But how much and when?

This study estimates a rise of 32 inches by 2100 as the best guess for sea level rise in south Florida and a smaller probability of a rise of 40 inches. Most other studies tend to estimate a larger rise in sea level.

The Florida Climate Institute (FloridaClimateInstitute.org; jointly managed by the University of Florida and Florida State University) commissioned Professor Gary T. Mitchum of the University of South Florida to prepare this report. Dr. Mitchum is a world-class expert in sea level. The funds to support his efforts were obtained from the Southeast Climate Consortium (SEClimate.org).

This report should be used as a basic explanation of the existence and physics of sea level variations. Most readers will be fairly well informed about the physics of sea level rise if they read this report.

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Executive Summary

This paper is about past, present, and future sea level changes in the southeastern United States. It is aimed at non-scientists and scientists who are not specialists in sea level change. Although this report is about our specific part of the world, sea level change in any region is best viewed in the context of global sea level changes. This should be seen as encouraging, though, since measuring and predicting global sea level change is a much easier problem than predicting the changes at any particular location along a coastline.

Global sea level measures the volume of the oceans. This volume can change only if we add or remove water, or if we change the mean density of the water in the oceans. The most likely way to change the density is to warm or cool the oceans. For example, warmer water is less dense and therefore takes up more space, thus raising the sea level. So determining global sea level change is a relatively easy problem since we only have to determine how much water is added or subtracted from the oceans, or how much the oceans on average are warmed or cooled.

Regional and local relative sea level changes, on the other hand, are strongly influenced by land motion. Many people do not realize that the land we are standing upon is also slowly moving up and down. If the land is sinking, then the sea level appears to be rising, and vice versa. Also, even if the oceans are globally warming, that does not mean that the associated sea level increase will be felt everywhere uniformly. If our region is warming at an anomalously high rate, then we will see a higher rate of sea level change. Similarly, if the water added from ice melt does not immediately spread out over the entire ocean, then we may see higher or lower rates of sea level change. At present we do not know if our region is set to be a winner or a loser in this game.

Fortunately, though, the present sea level changes in the southeastern US region can be accounted for largely by the global changes once we take into account the local and regional land motions. The latter are small at most stations in our region, but nonetheless need to be accounted for. In some areas along our coastlines the land motions are in fact dominant.

I will suggest that the best projection of the future is about 80 centimeters of global sea level increase by 2100, an increase we need to plan for in our region. This is somewhat larger than the most recent global assessment from the Intergovernmental Panel on Climate Change, but I will argue that it is likely our present best guess. Unfortunately, the uncertainties in these analyses lead me to conclude that the probability of a larger increase is more likely than the chance that it will be substantially smaller.

It may seem a bit tangential, but I will also suggest that episodic changes due to changes in storm tracks, frequencies, and intensities should not be ignored. Climate change will almost certainly be felt most strongly as changes in what we call weather. Such changes are potentially the most important thing that we need to predict in the coming decades.

Finally, I will say that we can likely reduce the uncertainty in sea level rise rates over the next 10 years, but only if we maintain the superb observational system that we have in place now. We are now able to determine sea level change from the global scale, to the regional scale, and down to the local scale. If we simply continue to make the observations that we are making now for another decade, then we will most likely be able to intelligently inform the public about the real risks that might be associated with climate change.

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What Is Sea Level, What Causes It to Change, and What Can We Measure?

Sea level, often called sea surface height, is simply the height of the ocean surface above or below some reference, or zero, point. Sea level measurements have been made using tide gauges since the 19th century, and over the past two decades we have also begun to measure sea level from space using satellite altimeters. For a tide gauge the zero point is some point on the land near the gauge, and this measurement is generally called relative sea level because it measures the height of the ocean relative to the height of the adjacent land. This is important. If the land is rising or sinking, then the apparent rate of sea level change will be smaller or larger than the ocean rate of rise. For a satellite altimeter, the zero point is essentially the center of the Earth. This might seem to be more useful, but if you think about it, if you are concerned with the risk of inundation, it really doesn't matter if the ocean is rising or the land is falling; it is the relative sea level that is of local interest. We will return to this point shortly.

Anyone living near the coast knows that the most obvious changes in the sea level are due to the daily tides caused by the gravitational attraction of the sun and moon, but in fact there are smaller changes that can persist for a long time. These slower changes are what interest us. These changes are teased out of the sea level data by averaging the data over a day, a month, or a year. This allows the tides to cancel out, leaving behind the climate signals that mark changes over the course of the year, from year to year, and perhaps over many decades. This is often referred to as the mean sea level. In addition to this averaging in time, we can also average mean sea levels over a region such as the southeastern United States or the Gulf of Mexico, or over the entire globe, which results in the quantity we refer to as global mean sea level.

Now that we have defined some terms, let's consider what can cause such slow sea level changes. We will start at the global scale and work our way down to the regional scale and then to the local scale, meaning what one might see in a particular harbor or on a given segment of the coastline. We will also introduce some of the other observations that we use to understand these causes of sea level change. You might find the schematic shown in Figure 1 useful for this portion of the discussion.

Global mean sea level is what we obtain when we average the sea levels at some point in time over all the oceans in the world. For example, imagine that we have tide gauges measuring sea level everywhere in the oceans. If we were to average all the tide gauge data from January 1990, then we would have an estimate of the global mean sea level for that month. We would then repeat that calculation for all the different months. A bit of thought should convince you that if we can consider the shape of the ocean basins to be unchanging, then what we end up with is a measure of the total volume of the ocean. Think about a bathtub. If you measure the rate of change in the height of the water in the tub, then you are really measuring the rate of change of the volume of water. This is very useful because there are only two ways that you can change the volume of the ocean!

As with the bathtub, the most obvious way is to add or remove water from the ocean. One way this is done is through changing rainfall patterns. From year to year or even from decade to decade, we can see changes in the ocean volume due to changes in rainfall patterns, but over the long-term, meaning decades to a century, this effect should be small. By far the largest source of water that could be added to the ocean is the water stored as ice on Greenland and in Antarctica, and to a smaller degree in mountain glaciers elsewhere in the world. Thus, a major concern is that if the climate warms, then ice melt might cause substantial sea level rise. If all the ice were to melt, which we do not believe is possible in the next 100 years, then sea level would rise by something like 60 meters. Although this

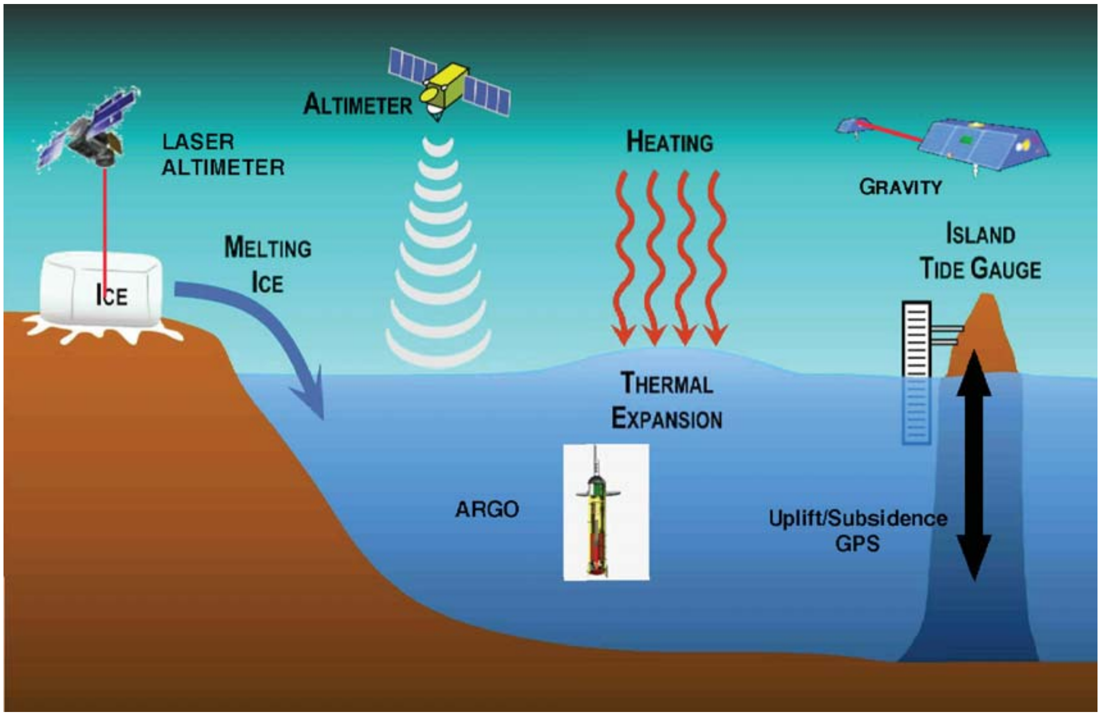

Figure 1. This is a schematic of the observational tools that we presently have for studying sea level change. It is essential that these observations continue if we are to understand why sea level is changing and how it might change in the future.

is not considered possible, it does give an idea of how much that reservoir of water might increase the ocean volume, and hence the sea level that we observe at our coastlines.

As an aside, we will be using metric units here, specifically millimeters, centimeters, meters, and degrees Celsius. If you are more comfortable with English units, you should note that there are 10 millimeters in a centimeter and 100 centimeters in a meter. An inch is about 2.5 centimeters or 25 millimeters, a meter is about a yard, and a foot is about 30 centimeters. A 1-degree change in Celsius corresponds to just less than a 2-degree change in Fahrenheit.

Returning to the ice sheets, how do we measure these changes? Until recently, most of the information we had concerning the ice sheets came from intermittent surveys carried out by teams on the ice. It is very difficult to make measurements in this fashion that are comprehensive enough to make accurate estimates of the volume of ice that is added or lost, and therefore to make accurate estimates of the water lost by or added to the ocean. More recently, however, the situation has improved dramatically thanks to satellite observations. First, we can now use altimeters on satellites to map out the topography of the ice sheet and therefore to directly estimate volume changes. Second, we now have the ability to measure the Earth's gravity field from space. These measurements actually allow us to "weigh" the continental glaciers from space and to determine how the amount of water contained in the ice sheets is changing. This is important because the ice changes are due to water being removed from or added to the oceans, which is the quantity we are interested in. These gravity measurements have fundamentally changed our ability to monitor the ice sheets, but unfortunately this has been possible only over the past nine years.

I said earlier that there are two ways to change global mean sea level, one of which is adding or removing water from the ocean, as just described. But if the amount of water in the ocean were to remain constant, would it still be possible to change the sea level? The answer is yes, but it requires changing the density of the water in the oceans. The density of seawater depends primarily on its temperature, but density also changes with the ocean's salinity, a measure of the amount of salt dissolved in the water. We will focus here on the much larger temperature effect. Warmer water is less dense than cooler water, so if the amount of mass stays the same then the volume must be larger. Remember that density is mass divided by volume. How large is this effect? If the upper 1000 meters of some portion of the ocean were to warm by 1 degree Celsius, then the sea level would increase by about 50 centimeters. This is not as easy to visualize as adding or removing water, but it is definitely important to consider when estimating what sea level might be if the climate warms.

To evaluate what effect ocean warming will have on global mean sea level we need to measure the temperature of the ocean globally. And we must measure not only at the surface, but also throughout the entire depth of the ocean, or at least the upper 1000 meters or so where we expect the largest temperature changes might occur. Historically our information about the temperature changes in the global oceans has come from ships and a rather small number of moored instruments. The dataset is extensive, but suffers from gaps in space and time that make estimating the global average challenging. As with the ice measurements, however, our capability to measure changes has improved dramatically over the past decade thanks to the development and deployment of autonomous floats. These instruments have the ability to profile the upper 1000 meters of the ocean every few days and to transmit the data to shore via satellite links that operate while the float is at the surface. Thousands of these floats are now operating, allowing us to compute the changing temperature and density of the global ocean. Again, though, this is a recent development.

So at the global scale we have a reasonably simple situation. Measure the changes in the ice sheets and the temperature of the oceans, which is now possible, and you can estimate the global sea level change. Of course, tide gauges and satellite altimeters measure the global sea level change directly, but these other measurements are very important for two reasons. First, these data serve as an independent check on the direct sea level measurements, and second, we can obtain information on why the sea level is changing; i.e., we can ask how much is due to ice melting and how much is due to ocean warming. This information will eventually lead to better projections of future changes.

Turning to the regional scale we find that the situation is not quite as simple. This is because more things can change the sea level in a region such as the coastline of the southeastern United States. Think about the bathtub again. If the addition of water from melting ice were to immediately spread uniformly around the globe, and if the warming of the oceans were to be the same everywhere, then the surface of our tub would remain flat and rise uniformly. This, however, may not be what happens. As the ice melts, distributing all of the additional water around the globe could take time, perhaps many decades. Don't get the idea, though, that a huge volume of water is just sitting next to the melt sites. The sea level changes are subtle, and the point we are trying to make is simply that it will not be the same everywhere. Some regions will see larger changes, some smaller. Warming may not be the same everywhere either. Ocean currents and winds move massive amounts of heat around the globe, particularly from the tropics to the poles, so the response to warming in any region depends on how these flows change with time.

In addition to these complications that arise from the spatial distribution of the volume changes associated with water additions and temperature changes, at the regional scale we also have to think about changes in sea level that are not associated with any net volume change. Imagine that your bathtub has a small child in it. The water is constantly sloshing back and forth and up and down, and the actual oceans do the same. These changes are what oceanographers refer to as "dynamic" changes. What does this have to do with climate change? Part of the sloshing is due to ocean currents, which in turn depend on the winds. If the climate changes and the winds change, then we expect that the ocean currents will also change, which in turn changes the sea level. All of this sloshing back and forth has no net effect on the global mean sea level, which is why estimating global mean sea level change is an easier problem, but it definitely complicates the problem of projecting sea level changes in any region of the world.

Land motion is another factor that must be taken into account. As I mentioned earlier, the sea level we care about and the sea level measured by our tide gauges is relative sea level, meaning the ocean's sea level change plus the effect of the land rising or falling. These land motions occur on a large range of spatial scales. At the largest scales we have something called *postglacial rebound*. During the last ice age, when there were massive ice sheets on the northern portions of North America and Europe, the weight of the ice depressed the land. It is easy to think of the Earth as solid, but in fact it is elastic. It moves very slowly, but it does move. So when the land under the ice was depressed, the crust in other parts of the world rose. When the ice melted, the situation reversed. The land that was previously ice covered is now rising relatively rapidly and the land in other parts of the world is falling on average at a slower rate. The relative sea level that we observe at tide gauges is actually falling at many high latitude locations despite an increase in the overall ocean volume.

In addition to these ice-related land motions, there are also regional land motions associated with plate tectonics. The classic picture of plate motion emphasizes the horizontal movements, but there are also smaller vertical motions as well. All of these events must be considered to assess the contribution of land motion to relative sea level change in any particular region of the world.

Can we measure these land motions? Actually, we can do that very well now thanks to the development of the Global Positioning System (GPS). Although most people use GPS to find horizontal locations, the system also returns vertical positions. To take advantage of this we place a high-quality GPS receiver near the coast and operate it continuously for several years. What we gain is the ability to detect land motions as small as 1 centimeter per decade or smaller. At present, these measurements are not made everywhere, but the system is rapidly expanding, the technology is well developed, and only a few years of measurements are needed to obtain land motion rates that are useful for sea level change studies.

What about the local scale, meaning individual harbors or small stretches of coastline? At this scale land motion is likely the most important consideration. In addition to glacial rebound and tectonics there can be substantial local changes in the land motion rate. One of the most significant is due to the removal of ground water or oil. Removing these fluids from the subsurface causes the land to sink, sometimes at a fairly rapid rate. Also, in some areas, particularly river deltas, the sediments can compact over time, which also causes the land to fall. In both cases the relative sea level rise will be higher than expected from the global and regional effects alone. It is, in fact, not difficult to find local rates of land motion that exceed 10 centimeters per decade!

To conclude this introduction I would like to point out an additional concern that is easily overlooked: the effect of storms, particularly winter storms. The sea level rise that we've been talking about thus far is a slow, creeping process, in contrast to the sometimes spectacular flooding along our coasts that can occur because of what your local weather person calls storm surge. Most people are well aware of the flooding dangers associated with hurricane storm surges and I will not discuss these. Hurricanes are infrequent, but winter storms are not and these storms can often cause surges in sea level of 50 centimeters or more. Although these storms pass in a day or so, the flooding risk is still there. And what if such storms become more frequent or more intense? Why might that happen? As I mentioned earlier, one of the possible consequences of climate change is changes in the wind patterns. These changes affect what are called the storm tracks, with the result that some regions may see more winter storms and some may see fewer. Assessing the risk of regional sea level rise should take this into account. Also, although it is not a sea level change issue, the inland effects and the economic consequences of these storms can be profound and may be the most significant impacts of climate change felt by most people.

The Global Context

We will continue our discussion with a review of what is known about global mean sea level change and how the rate of change has varied in time. Although the focus of this report is on the southeastern US region, the global picture provides a context for the regional analysis and therefore seems the right place to start. Also, as explained earlier, the global rate is somewhat easier to analyze and I prefer to begin where our knowledge is the most reliable.

Our best source of information for the global rate of sea level change over the longest time period is from the global tide gauge network. In fact it is arguably the only quantitative information that we have about global sea level change over the past 50–100 years. Figure 2 shows an example of what is known as a global sea level reconstruction. This curve is created by taking the entire available tide gauge dataset and forming a global average at each point in time. Various corrections are applied that vary from one researcher to another, but all of them result in a curve that differs from this only in the details. On this figure I also show the global mean sea level curve from satellite altimetry. Over the time period when we have both types of data, both give very consistent estimates of the rate of sea level change.

In looking at this curve it is critical to note that the number of available tide gauges drops dramatically as we go back in time. Furthermore, as we go back the gauges cover less and less of the Earth's surface. Prior to about 1950 most of the tide gauge records that we have are located in northern Europe and along the coasts of North America. Very few gauges are located

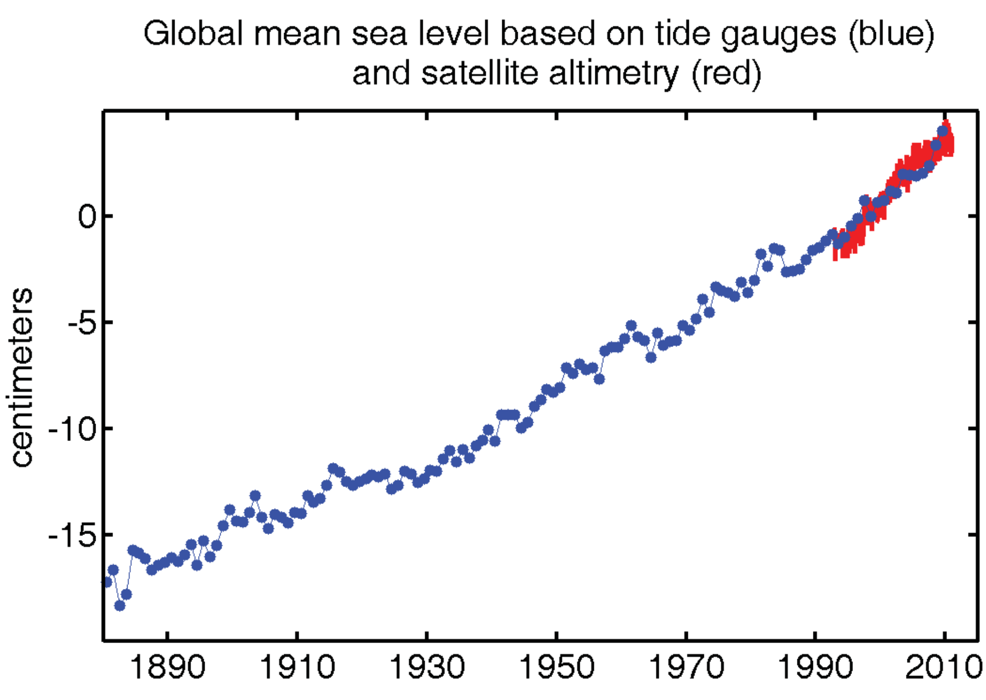

Figure 2. **The blue dots are from averaging the observations that we have from the global tide gauge network. The red ones are from the more recently available satellite measurements. The sea level rise rate over most of the 20th century is about 2 mm/yr, but this has increased to more than 3 mm/yr over the past 2-3 decades.**

in the Southern Hemisphere in the earlier time period. Why is this important? Again, think about the bathtub and the fact that the real oceans are constantly sloshing back and forth for reasons unrelated to true volume change. As a consequence, in order to obtain a reliable global average we need to have sufficient coverage to allow the sloshing signals to cancel out, leaving behind the true signature of ocean volume change. Given the distribution of gauges over time we are fairly confident that there were sufficient gauges to do this after 1950, but the uncertainties prior to that time are definitely larger.

So what do we see in the global sea level reconstruction from the tide gauges? During the second half of the 20th century, when we have the most confidence in the tide gauge network, the global mean sea level is rising at 1.5 to 2 centimeters per decade. Many researchers using a variety of methods have reproduced this rate and I consider this result firm. Over the late 19th century to the early part of the 20th century the global sea level is increasing but at a slower rate of about 1 centimeter per decade. Some researchers consider this evidence for an early acceleration of the sea level rise rate whereas others doubt that the tide gauge network can support this result because of the spatial distribution issues outlined previously.

If one looks carefully at the global sea level reconstruction curve it is easy to pick out time periods when the rate of change is somewhat higher and somewhat lower than the average rate of 1.5 to 2 centimeters per decade. Given the limitations of the data it is difficult to assess the veracity of these changes, but I will discuss this shortly after presenting the results from the satellite altimetry data.

Figure 3 shows the global mean sea level curve obtained from the satellite altimeter measurements over the much shorter time period from 1992 to the present. These curves show a fairly steady rate of sea level increase at something over 3 centimeters per

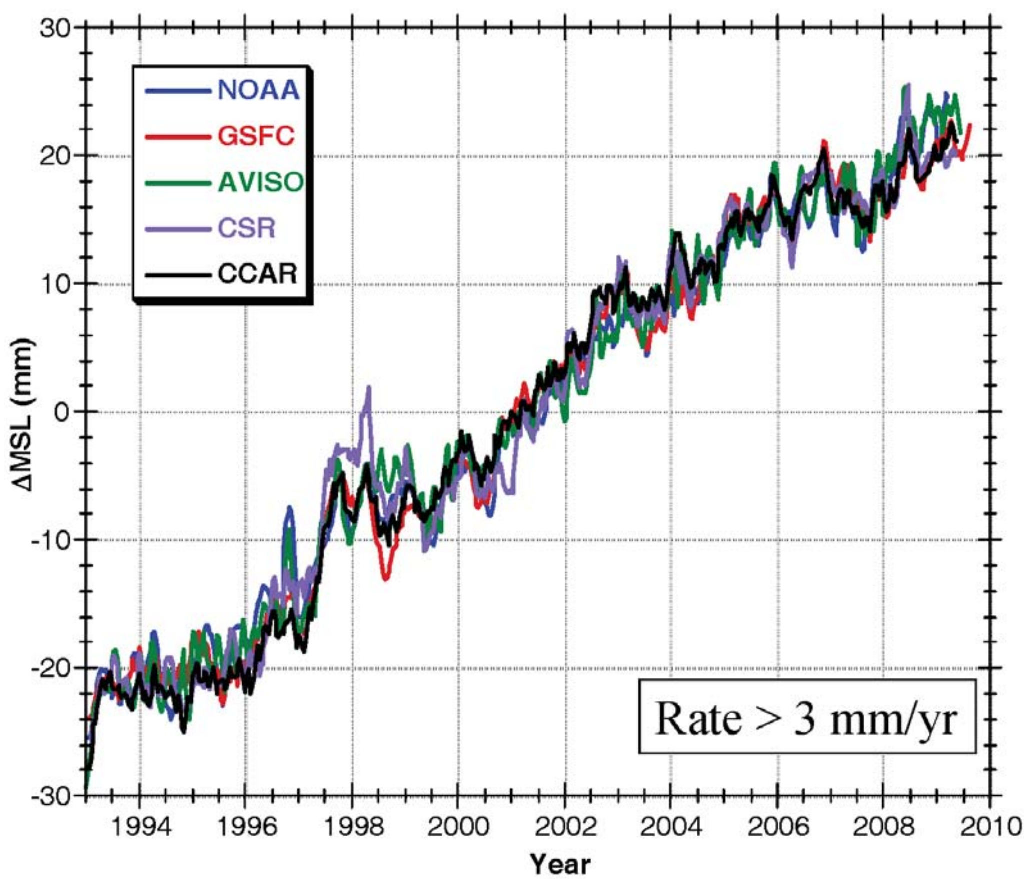

Figure 3. **Here are five different versions of the red line shown on the previous figure. The main point is that the apparent increase of the sea level rise rate does not depend on who does the analysis.**

decade, nearly twice the rate observed in the second half of the 20th century. How much confidence do we have that this increase is real? Actually, the evidence is quite strong for several reasons. First, recall that satellite altimetry observes very nearly the entire global ocean. When we average these data we are quite sure that the sloshing signals that were of such concern with the tide gauge analysis are not going to be a problem; i.e., we are truly and directly measuring the volume of the ocean. Second, if you look carefully at the tide gauge sea level reconstruction you will also see the higher rate of increase in that analysis over the past two decades. These two analyses are completely independent, meaning that this agreement is not forced to happen. You may recall that earlier I said that the value of the ice volume from gravity and the ocean temperature from ocean profilers is that these data allow another independent check on the total sea level rate of change obtained from the tide gauges and the altimeters. In fact, several groups have done the calculation and their results do indeed agree.

Closer examination of the sea level curve from satellite altimetry shows that the overall steady increase in global mean sea level over the past two decades is occasionally disturbed for relatively short time periods when the rate is larger or smaller than usual. See, for example the upward bump around 1998 and the smaller downward bump just before 2008. One naturally wonders what causes these departures from the overall trend. The answer is that the upward bump occurs during a large El Niño event and the downward one occurs during a La Niña event, which can be thought of as a negative El Niño. During El Niño rainfall patterns change globally with the net result being that less rain falls over land during these times. Although it may not be obvious, the water that rains out over the land comes from water evaporated from the oceans. Therefore during an El Niño less water leaves the ocean on average and global mean sea level and ocean volume are temporarily increased. The opposite occurs during La Niña events. These events are very interesting in their own right, but for the purposes of determining long-term sea level change, this effect is not of central importance. One should note, however, the danger in interpreting sea level trends from short subsets of this time series, a mistake that has been made more than once over the past decade.

The net result is that we have high confidence that global mean sea level increased over the second half of the 20th century at about 1.5 to 2 centimeters and that the rate of increase rose over roughly the past two decades to over 3 centimeters per decade. There has been much discussion as to whether this increase is a signature of climate change. The most serious objection to this conclusion revolves around the decade–to–decade variations in the global sea level change rate inferred from the tide gauge reconstructions that I pointed out previously. Basically the question is whether there are natural variations in the sea level change rate as large as what we are seeing now. This is still an open question, but the most recent research indicates that the present rate is indeed higher than anything we have seen in the historical record. This conclusion is not yet firm by any means, but I would say that the natural variability argument is becoming more and more difficult to justify.

I will conclude this section about the global context with some observations about ice melt contribution to the present sea level change rate. We now have an excellent tool for measuring this contribution, namely gravity from space, but unfortunately these measurements cover only about the past nine years. During that time, however, the ice melt rate is much higher than anything suggested by the historic observations of the ice sheets. What is more worrisome is that the rate has also been increasing rapidly during this time. This is too short a time for us to decide if this is an anomaly, meaning that the rate will decrease in the future, as some researchers believe, but it is definitely something that will bear close watching in the future. We will return to the issue in the final section of this report when we discuss projections of future sea level change.

Southeastern US Region

Let's turn now to the primary focus of this report, the observations in the southeastern United States. The regional tide gauge network is our preferred source of information for regional changes in relative sea level change, which again is the total rate of change obtained by combining ocean changes and land motions. We are fortunate in this region to have an excellent set of gauges, with many spanning most of the 20th century. I have selected a set of 12 gauges located from Texas to North Carolina primarily on the basis of the length and quality of record. Some shorter records are included in order to fill spatial gaps. Some of these gauges are outside the immediate area of interest but are included to provide the larger context.

Figure 4 shows the time series. As discussed in the introduction, I have chosen to use monthly averages of the sea level data in order to suppress the tidal and storm-driven variations. I have also chosen to suppress the winter–summer differences in sea level in order to focus our attention on the long-term trends and the year–to–year changes. The plot is designed so that if you follow down the first set of plots and then up the second set, you are moving from Texas to Florida and then up to North Carolina. For each tide gauge I have estimated and plotted the long-term trend using standard statistical methods and have listed the sea level change rates in centimeters/decade on each panel.

Consider the relative sea level change rates first. These rates vary from just over 1 to about 3 centimeters per decade, with higher rates in Texas and Louisiana. The rates tend to be on the lower side of

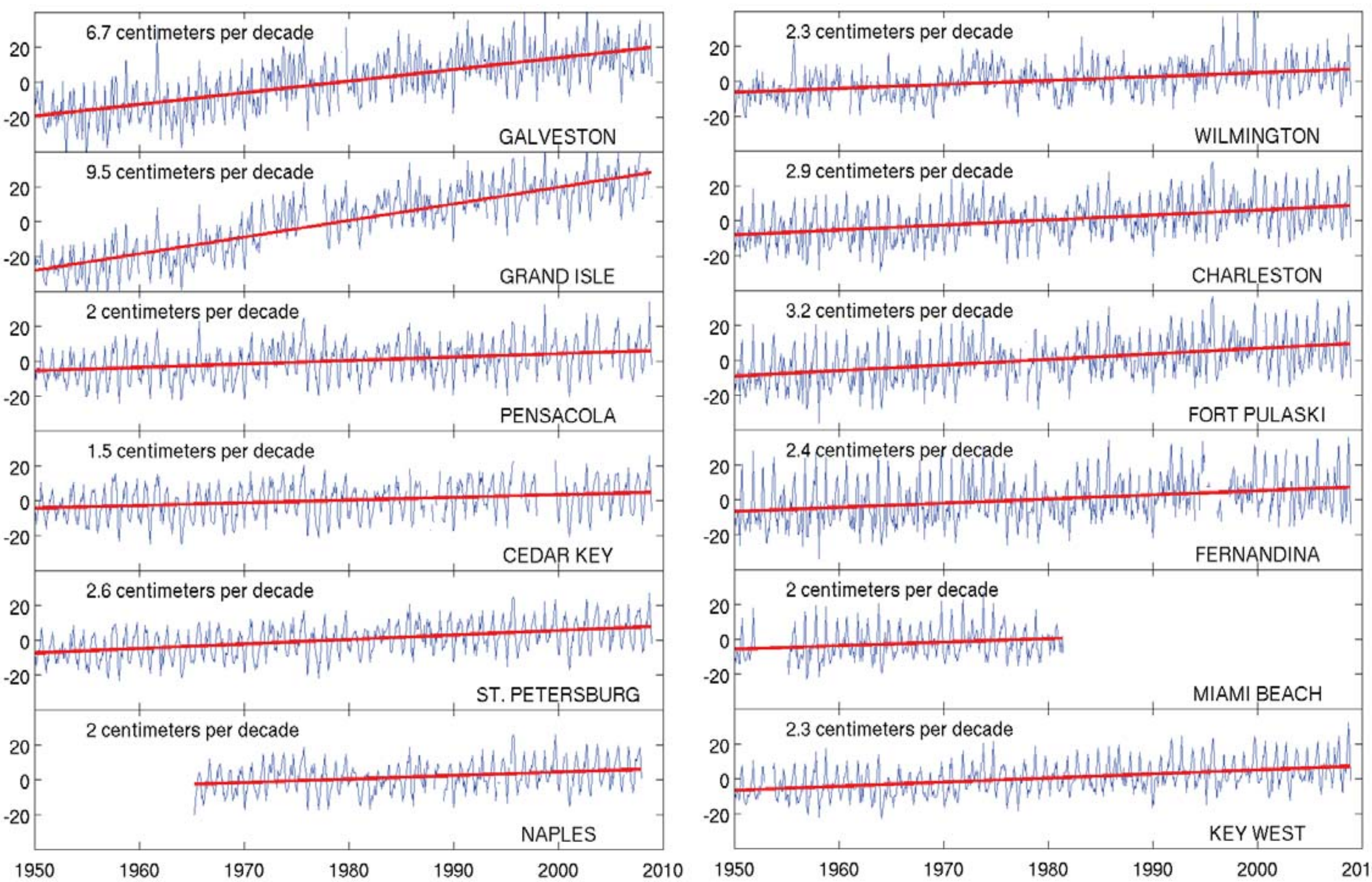

Figure 4. **These are actual observations of sea level from our tide gauges. These data stretch from Galveston, Texas, to Wilmington, North Carolina. The blue lines are the month–by–month observations and the red lines are the best-fit linear trends over the past 60 years.**

the range on the west coast of Florida as compared to the east coast of the United States. Although there is some scatter, which we will address shortly, overall the rates are slightly higher, but generally consistent with, the global mean sea level change rate of 1.5 to 2 centimeters per decade observed over the same time period. But is there a simple explanation for the scatter in the rates?

Land motion rates need to be considered as well. At Galveston, Texas, the rate is substantially higher than at most of the other tide gauges. This is a documented response to the extraction of fluids from the ground, as we discussed in the introduction. At Grand Isle, Louisiana, the rate is even higher. This is most likely due to sediment compaction in the Mississippi River Delta, although I do not know this for a fact. The rates are also somewhat higher along the east coast from Fort Pulaski, Georgia, northward. If you look back to the discussion of postglacial rebound, you can recognize this as most likely due to the land falling slightly along the east coast as the land in the northern portion of North America (the areas covered by ice during the last ice age) rebounds and rises. At the remainder of the stations in this region the rates range from 1.5 to 2.6 centimeters per decade with 6 of the 7 stations lying between 2 and 2.6 centimeters per decade. The average of these 7 stations is 2.2 centimeters per decade, which is roughly 20% higher than the globally averaged mean sea level rate of the second half of the 20th century.

Overall, however, aside from the local effects in Texas and Louisiana, the southeastern US region appears to be rather stable as far as land motion is concerned, although it would seem necessary to allow for an additional 20% of sea level change above the global mean value. This basic consistency with the globally averaged rate of sea level change is important because it means that the rate of sea level change that we observe can be understood as the global sea level change rate of the oceans with some relatively small adjustments for land motion. We are fortunate in this respect. If we have global sea level change projections that we trust, then to a reasonable approximation these should apply to our region as well.

Of course, these slow increases in sea level are only part of the story. In fact, many researchers argue that the main impact of a mean sea level increase will be to exacerbate episodic events that occur along our coastlines more frequently. For example, suppose that you have a 1-meter surge due to a weak hurricane or a winter storm. Consider how much more damaging such a storm might be if it were superimposed on a background sea level height that was already a meter above what we have now, effectively resulting in a 2-meter surge. Consider as well how much more damage might occur if the winter storms that produce a meter or so of ephemeral sea level rise were to occur significantly more often than they do now.

Let us look at the possible decade–to–decade changes first, which are detailed in Figure 5. To produce this figure I have done the following. First, I removed the trend from the time series at each tide gauge. If you look back to Figure 4, what we are looking at is simply how far the blue line is above or below the red straight line at each point in time. These are called the anomalies from the trend. Second, I plotted all of the anomaly series on top of one another. This very simple method is sometimes called "stacking" the series; I think that you can see that we are just searching for sea level events that are different from the overall trend but consistent from one tide gauge to another throughout the region.

What we see in Figure 5 is a rather remarkable degree of covariation between the tide gauge time series in this region. This particular decade–to–decade variation has actually been recognized by oceanographers for many years. The prevailing theory is that it is due to changes in the wind blowing over the open Atlantic very far from the coast. If the winds over the Atlantic are modified by climate change, it is possible that these decade–to–decade changes in the sea level might be either enhanced or suppressed. I contend,

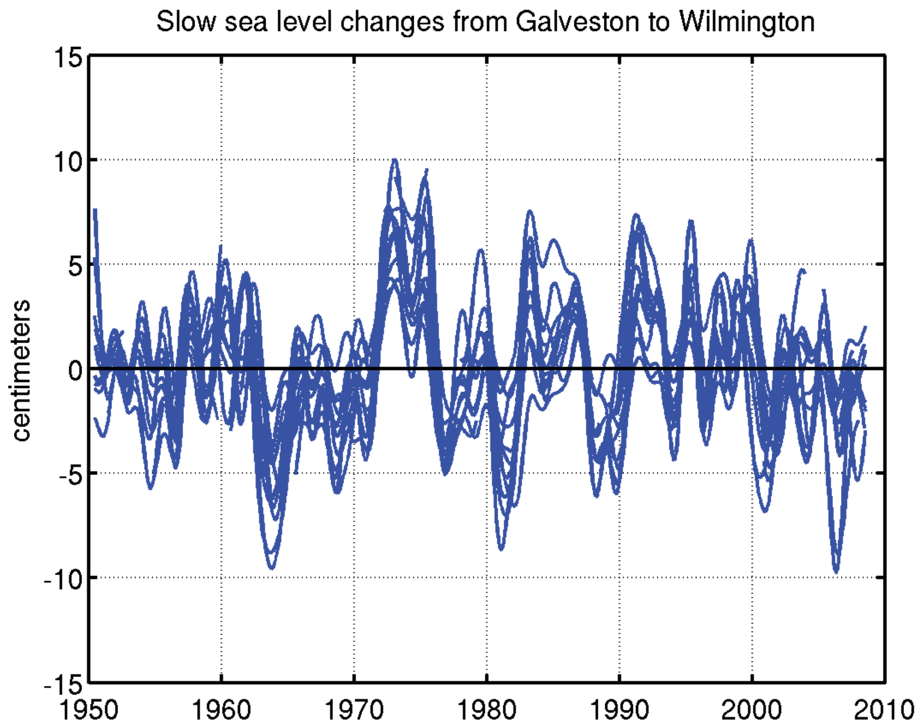

Figure 5. **If we take the tide gauge data from the previous figure and simply plot the differences from the trend, we get these time series. What's remarkable is how similar these sea level changes are over such a large region. This is due to changes in the ocean currents. The currents change if the winds that drive them change, meaning if the wind direction or speed at any location changes.**

however, that this does not really matter all that much if you are worried about sea level inundation. If you look carefully at the scale on the *y*-axis of the figure, you will see that these signals are typically only about 5 centimeters above or below the background sea level change curve. Even if we change this by a factor of two or even three, it is probably not large enough to worry about.

Storms are another story. Anyone living in the southeastern US region undoubtedly watches the news carefully during hurricane season. We have all heard about the dangers of storm surge, and I will not belabor that point here, except to repeat that a storm surge on top of a higher sea level due to climate change is more damaging than the storm surge alone. I will instead talk a bit about the dangers of winter storms, which I think have received too little attention.

Winter storms can easily raise the sea level by 50 centimeters or more. While this may not seem to be all that much, it is comparable to the background sea level change that we might expect from climate change over the next 100 years, and the two together have the potential to be very damaging. In addition, as I said earlier, these storms impact people far inland and there is the possibility that the frequency and intensity of these storms might also change if our climate warms. In addition to the direct damage, more severe winter storms in the southeastern US region could have substantial economic impact due to the increased demands on our utility industries for heating during these events, for example.

On average the southeastern United States is affected by about 10 winter storms per year. These storms can be detected in the same tide gauge records that I showed above, although in this case we use the hourly sea level heights after removing the tides with a more sophisticated method than simply averaging over a day or more. All of the details are not important here, only that we can count the number of winter storms that occur from year to year. Earlier work has shown that the number of storms varies according to whether or not we are in an El Niño year. But recent research suggests that there is more to the story.

If we average the number of severe winter storms over decades using the sea level data over the past 80 years or so, then the El Niño effect is not important. But we still observe substantial changes in what we call storminess, and these changes are persistent over many decades. Figure 6 shows the average number of storms per decade over the southeastern US region. After a rather quiescent period in the first half of the century we see a large increase (about 25%) beginning in about 1950. At the end of the record the storm count appears to be returning to the pre-1950 level, but there may be more to tell.

The rest of this story is somewhat speculative, but it is possible that this change in storminess is related to larger scale climate patterns. Specifically, the increase in the number of storms per year is due to changes in the position of the jet stream, which changes the path that storms take over the United States. This change in position is in turn possibly related to the strength of something called the Arctic Oscillation. It is not important here to understand what the Arctic Oscillation is, only that some climate models predict that a warmer Earth will produce a climate state in which the pattern that we have observed, one where we have more winter storms in the southeastern United States, might become more common.

The main point of this side trip into winter storms is that the effects of climate change may not be direct, but rather subtle and unanticipated. Slow sea level changes could easily be felt more strongly through the intermittent, but just as large, increases that come with our winter storms.

Returning to the main point of this part of the discussion, the analysis at the beginning of this section suggests that projecting sea level change in the southeastern United States comes down to taking the global sea level change projections and making corrections for land motions. Therefore, we will conclude this report with a discussion of projections of global mean sea level change.

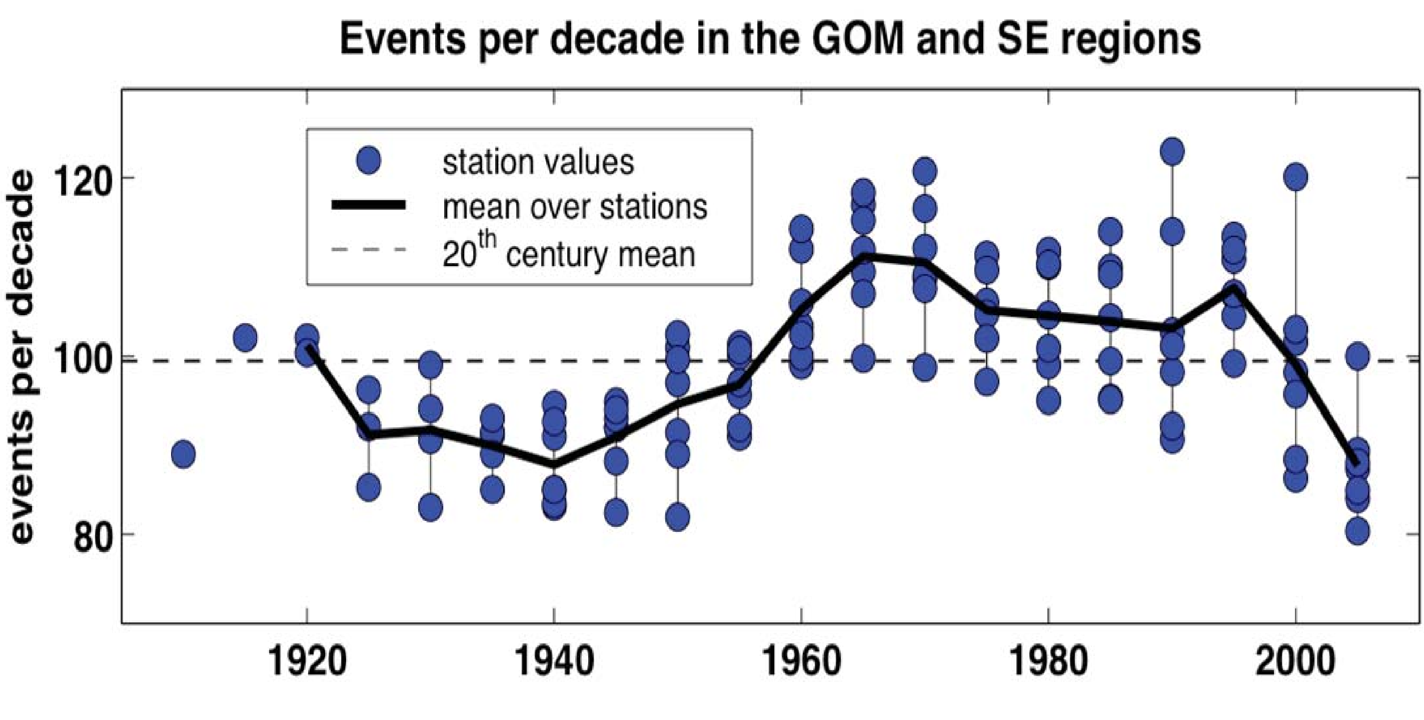

Figure 6. **For this figure we have used the tide gauges to count winter storms over the southeastern portion of the United States. On average there are about 10 storms per year, or about 100 per decade, but we see in the figure that this number has changed markedly over the 20th century.**

Projecting Future Changes

The observed relative change in the southeastern United States is at present consistent with the observed global mean sea level change in the oceans plus an additional 20% or so that is most likely a regional land motion signal. This additional sea level change that we see in the southeast might, however, also reflect regional changes in the ocean's temperature changes, or changes in the oceanic circulation, or a non-uniform distribution of the water that is removed from the ice sheets on land. I do not think that we can currently determine the reason for this relatively small discrepancy from the globally averaged sea level change, but I doubt that it matters much at this point. In order to predict what might happen in our region in the future, I would say that the most important action we can take is improving our estimates of what the global sea level change might be. This is, of course, subject to change as we learn more in the coming years.

The standard reference for climate change projections, including sea level change forecasts, is the Intergovernmental Panel on Climate Change (IPCC) report that comes out every few years. These reports certainly have detractors, but I do not know of a more thorough review of climate science. Hundreds of scientists offer large amounts of their time to review and balance all of the published science in order to come up with a forecast. This process is sometimes criticized as being simply a "vote," implying a political process, but this is not true. All opinions are not given equal weight, which might be part of the reason for its unpopularity in some quarters. Rather, the scientists working on these assessments are required to use only results that have appeared in the peer-reviewed scientific literature. This creates an unfortunate lag time that I will mention shortly, but it also means that the work that is used to form the final projections has been thoroughly reviewed by many scientists at many stages in the process.

The last IPCC report was in 2007. The next one is underway now and will be available in another year or two. I will review the 2007 projections, but will also attempt to update using results that have come out since that time. As I said, the requirement that the IPCC report be based on papers that have already been through the peer-review process, which can take months to a year or more, means that the most recent papers will inevitably not be taken into account in the IPCC assessment. At the same time, I will also suggest that we not make any firm decisions about sea level change until the next assessment is available. In fact, I believe that any projections, whether mine or those of the IPCC, should always be considered a moving target. Everyone wants certainty, but in the climate change arena this is not possible. We make our best estimates but remain prepared to adjust as more data and better models become available.

On the topic of the IPCC projections, we also need to note that the projections depend on predictions of what human society will do over the next 100 years. How much will population increase? Will the per capita use of fossil fuels increase or decrease? How much energy will come from alternative sources? All of these issues must be addressed in order to decide how to force our atmosphere and ocean models. The approach taken is to run the models over a range of possible future scenarios and to then present the results as a range of possible outcomes.

So what did the last IPCC assessment conclude? Over a range of possible future scenarios, the predicted sea level rise is 20 to 60 centimeters by the year 2100. There is a problem, though. Do you remember the gravity measurements that I talked about in the first section of this report? The data that allow us to weigh the ice sheets? At the time of the last IPCC assessments the results based on these measurements were just becoming available and were suggesting that the ice sheets were responding much more quickly than we previously considered likely. The authors of the report knew about this, and clearly stated that their projections were probably too low because the changes in the ice melt rates might be underestimated. In fact, they provided a first estimate of these so called "dynamic" effects, but given the rules could not include them in the projections. If we include these effects, and also take into account that more recent research suggests that these were underestimated, then the most likely prediction for sea level change becomes something like 40 to 80 centimeters by 2100.

At the time of the last assessment it was also still thought that Antarctica was actually gaining ice and hence removing water from the ocean, but again, the observations coming out at that time showed clearly that we were actually losing ice from Antarctica and adding this water to the ocean. At that time we were seeing that the melt rates were higher than the models were reproducing. As if this were not enough of a concern, the data since indicate that the melt rates are continuing to increase. At this point it seems most sensible to take the upper end of the 2007 IPCC projection, 80 centimeters by 2100, to actually be the most likely estimate. Many people argue that this is still an underestimate if we assume that the ice melt rates will continue to increase. On the other hand, other experts argue that such high melt rates are not sustainable. On balance I have decided that 80 centimeters by 2100 is our current best estimate for the globally averaged sea level change. As noted above, however, I also know that this estimate will likely have to be adjusted as more and better data come into play.

So what does this mean for the southeastern United States? The sea level change in this region over the 20th century is about 20% higher than the globally averaged change over the same time period. If we take the global change to be 80 centimeters and assume that this ratio will remain constant, then we obtain an estimate of about 1 meter of sea level increase by the year 2100. If land motion is the reason for this excess sea level change in the southeastern United States, then this estimate will be too high. If, on the other hand, this excess is due to more rapid warming or reflects a non-uniform response to the ice melt, then it might be too low. At present I think that the excess is primarily due to land motion, meaning that 80 to 85 centimeters is the best guess. One should note, however, that the chances of significantly higher increases are greater than the chances of much lower increases. My best guess at this point is 80 centimeters by 2100, but planning for 1 meter of sea level increase between now and then might be the sensible hedge bet.

Is there an alternative to the model-based IPCC assessments? Models of the atmosphere and ocean are wonderful tools, but these models also seem to have a tendency to underestimate the observed sea level change, so it would be helpful to have a more data-based method. The models tend to do a better job at estimating global air temperature change, and recently such a method has been developed that attempts to exploit this strength. The idea is that we can use the model estimates of future air temperature change to infer sea level change via a statistical relationship. In this method, data are used to show that in the past for each atmospheric temperature increase of 1 degree Celsius, the sea level change rate has increased by 3 to 4 centimeters per decade. This relationship is then used to convert the model predictions of air temperature change to an equivalent change in global mean sea level. Over the range of scenarios used in the last IPCC assessment, this relationship predicts a change in sea level of 50 to 140 centimeters by 2100. Although the range is large it is reassuring to note that our estimate of 80 centimeters for the global sea level change is quite reasonable, albeit possibly on the low side. The mid-range of this projection, 95 centimeters, is not significantly different from our 1 meter by 2100 hedge bet.

I have said several times that we should consider the future sea level change prediction as a moving target. We will need to adjust after the next IPCC assessment is completed, and adjust again as more data and better models become available. How long might it take before we can be comfortable that our predictions can be trusted? I do not know the answer to that question, but I would like to make a suggestion. Note carefully that what you will read next has not been published, meaning that it has not been vetted with other sea level researchers, so please take it with a grain of salt.

As you read earlier, satellite altimetry directly measures the total sea level, or ocean volume, change, meaning that it captures the effects of ocean warming or cooling and ice melt or accretion. These data, unfortunately, span only the past two decades, but we expect that this time series will be extended into the foreseeable future. So how can we exploit this?

Let us assume that climate change will result in a sea level change rate that increases with time in a linear fashion. By linear I mean, for example, that the rate of change might go from 3 centimeters over this decade, to 4 centimeters over the next decade, to 5 centimeters over the decade after that, etc. That would be an increase in the rate of sea level change of 1 centimeter per decade per decade. These contributions can be added up over time to obtain a predicted sea level curve. That prediction can in turn be compared to the data that we have and the future data that we will soon have. The example that I gave above, 1 centimeter per decade per decade, is of course only one possibility. We could also assume an increase in the rate of 2 centimeters per decade over each subsequent decade, or 3 centimeters or whatever. The result is that we can draw a family of curves and see where the actual data fall.

Figures 7 and 8 show this family of curves for differing assumptions about the speed at which the sea level rise rate might increase. The more the rate increases the higher the sea level will be by 2100. I also show the actual satellite altimetry measurement of the global mean sea level versus time. The only difference between the two figures is that one projects out to 2100 and the other is a blow-up showing the same curves out to 2020, or about ten years from now. So what do we see?

At present the data lie between the curves that predict a total sea level change by 2100 of between 80 and 140 centimeters, with the latest data closest to the 80 centimeter prediction. Note that this is the same prediction that we used earlier for the global mean sea level change based on the IPCC assessment after adjusting for the more recent ice melt research. The data curve (in blue) appears to be trending to lower values, and it will be very interesting to see whether this trend continues over the next decade. More importantly though, looking at Figure 8, I think it is fair to say that by 2020 the prediction curves will have separated enough that the global mean sea level data from altimetry will be able to tell us fairly well which curve we are following.

I know that 10 years is a long time, but it might be that long before we can provide sea level change predictions that are trustworthy, at least if we are talking about one meter versus half a meter or two meters of sea level change over the coming century.

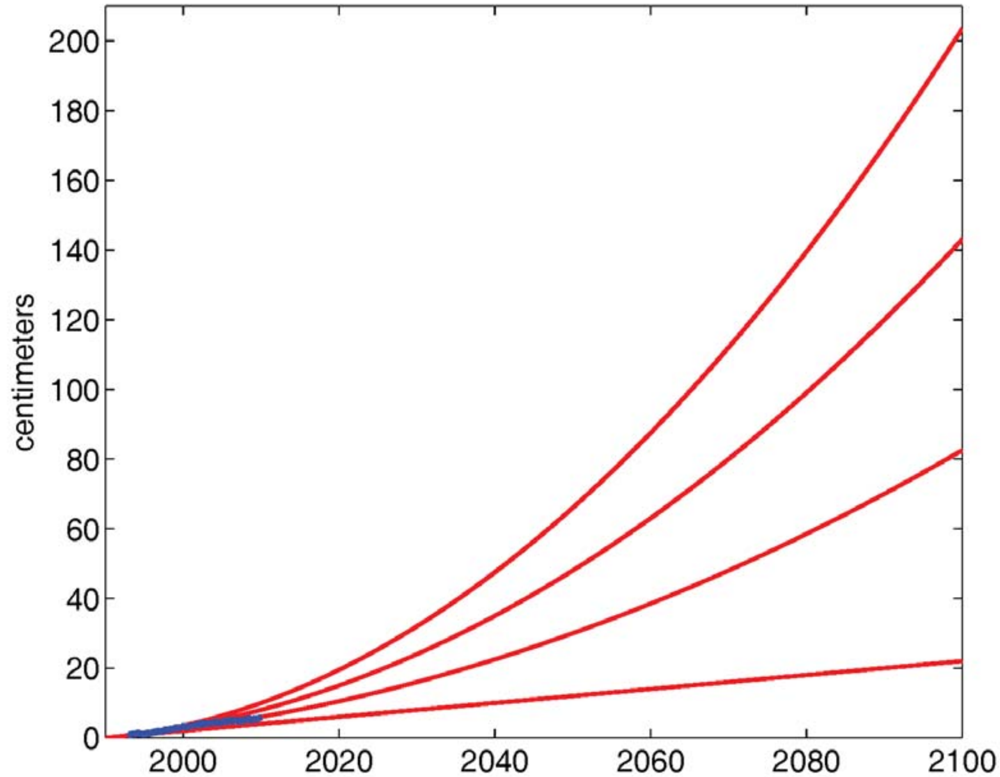

Figure 7. The red lines are possible future sea level change scenarios. The possibilities depicted range from a constant sea level change rate of 2 centimeters per decade (the lowest red line) to a sea level change rate that increases by 3 centimeters per decade each decade (the highest red curve). The model we're using is very simple and is only intended to give an idea of the scale of changes that are possible. The blue line is from the satellite measurements. Ultimately, the data must determine which red line is most likely.

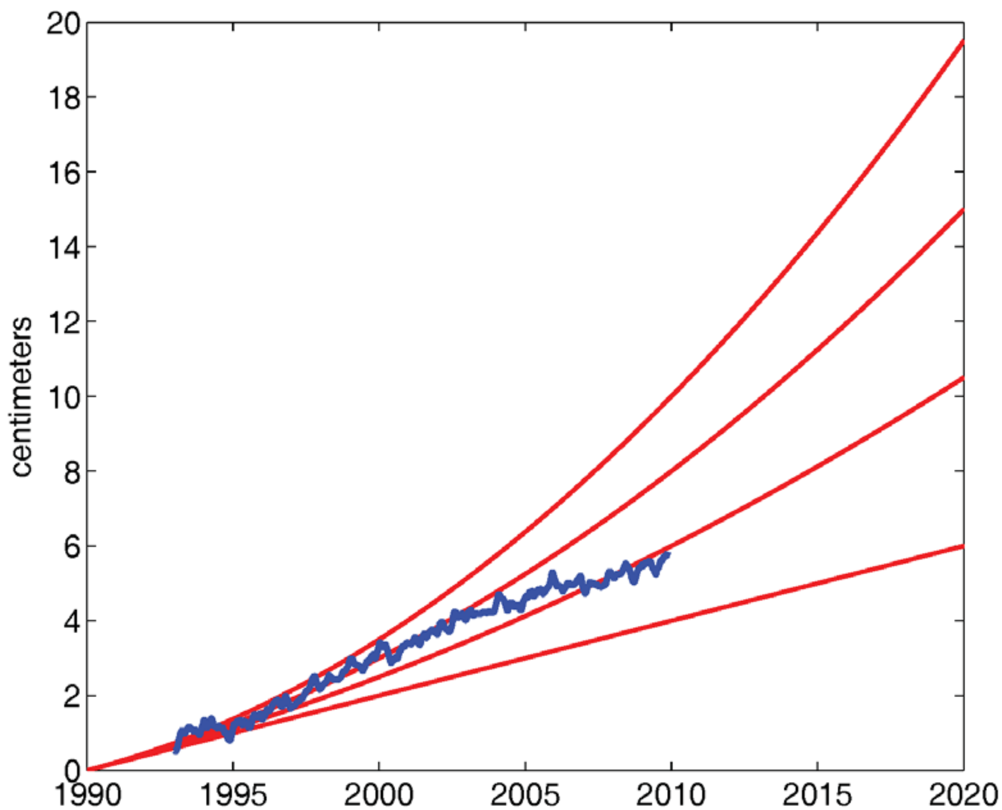

Figure 8. This is simply a blow-up of the previous figure. We are not arguing for any particular red curve yet. Our model is much too simple for that. Instead, the point is that if we continue our observations for another decade, then by 2020 the red lines separate by an amount that is larger than our observation errors. This means that we will have a fighting chance of deciding from actual observations which future estimate of sea level change is most likely.

Take-Home Messages

• Although the emphasis here is regional, global sea level change is much easier to interpret and predict. This is because the global ocean volume can change only if water is added or subtracted by melting or freezing ice on land, or if the density of the ocean changes, mainly because of changes in the average temperature of the ocean.

• Regional sea level changes can occur if the heating changes are spatially non-uniform, or if the added water does not distribute evenly. In addition, local relative sea level changes are strongly influenced by land motion. If the land is rising, sea level will appear to be dropping, and vice versa. This is why we call it relative sea level. At the local scale, these are often the largest apparent changes that we see.

• The 20th-century relative sea level changes observed at the tide gauges in the southeastern US region can largely be accounted for by adding the observed global changes to the local land motions. There is no strong evidence yet for enhanced rates in our region due to anomalous ocean temperature changes or non-uniform water additions.

• In this report I adjust the previous global projections to take into account more recent research concerning how the ice sheets in Greenland and Antarctica are changing. The net result is that the present best guess for our region is 80 centimeters of sea level increase by 2100. This estimate, however, is more likely to be too low than too high.

• We can likely reduce this uncertainty in the next 10 years, but this depends on the superb observational system that we currently have in place. These observations simply must be continued.

• Episodic changes due to changes in storm tracks, frequencies, and intensities should not be ignored. These changes will most likely have the largest impacts. Humans will feel climate change incrementally, meaning via changes in what we usually term weather.

About The Author

Gary T. Mitchum is a Professor of Physical Oceanography at the University of South Florida College of Marine Science, where he has been since 1996. After receiving his PhD from the Florida State University Department of Oceanography in 1985, he spent 11 years at the University of Hawaii Department of Oceanography, first as a postdoctoral researcher and then as a member of the research faculty and as the Director of the University of Hawaii Sea Level Center. His research interests emphasize short-term climate changes, ranging from interannual variations such as El Niño–Southern Oscillation, to decadal processes, to the long-term sea level rise problem. He has also done work on continental shelf dynamics, mesoscale eddy interactions with mean flows, internal tide generation and propagation, and physical controls on fisheries variables. Although he has used many types of data in his research, he is especially interested in analyses of tide gauge and satellite altimetric data, and notably proposed and developed the presently accepted method of calibrating altimeters via comparisons with the global tide gauge network.

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Affiliate Organizations

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Front cover photos (clockwise from top left): Biscayne Island in Miami, FL (credit: Marc Averette); relocating the Cape Hatteras, NC, lighthouse in 1999 due to receding shoreline (credit: NCDOT); Greenland glacier (credit: Christine Zenino); 2010 hurricanes Karl, Igor and Julia (credit: NOAA). Bottom cover photo: Jacksonville Beach, FL (credit: Cecil Goodwin).