Fighting the Waves: The Effect of North Polar Ice Cap Melt on Florida

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Abstract

A consequence of global warming that directly impacts U.S. citizens is the threat of rising sea levels due to melting of the North Polar ice cap. One of the many states in danger of losing coastal land is Florida. Its low elevations and numerous sandy beaches will lead to higher erosion rates as sea levels increase. The direct effect on sea level of only the North Polar ice cap melting would be minimal, yet the indirect effects of causing other bodies of ice to melt would be crucial. We model individually the contributions of various ice masses to rises in sea level, using ordinary differential equations to predict the rate at which changes would occur.

For small ice caps and glaciers, we propose a model based on global mean temperature. Relaxation time and melt sensitivity to temperature change are included in the model. Our model of the Greenland and Antarctica ice sheets incorporates ice mass area, volume, accumulation, and loss rates. Thermal expansion of water also influences sea level, so we include this too. Summing all the contributions, sea levels could rise 11–27 cm in the next half-century.

A rise in sea level of one unit is equivalent to a horizontal loss of coastline of 100 units. We investigate how much coastal land would be lost, by analyzing relief and topographic maps. By 2058, in the worst-case scenario, there is the potential to lose almost 27 m of land. Florida would lose most of its smaller islands and sandy beaches. Moreover, the ports of most major cities, with the exception of Miami, would sustain some damage.

Predictions from the Intergovernmental Panel on Climate Change (IPCC) and from the U.S. Environmental Protection Agency (EPA) and simulations

from the Global Land One-km Base Elevation (GLOBE) digital elevation model (DEM) match our results and validate our models.

While the EPA and the Florida state government have begun to implement plans of action, further measures need to be put into place, because there will be a visible sea-level rise of 3–13 cm in only 10 years (2018).

Introduction

Measurements and observations of Earth's ice features (e.g., glaciers, ice sheets, and ice packs) indicate changes in the climate [Kluger 2006; NASA Goddard Institute for Space Studies 2003; Natural Resources Defense Council 2005] and consequent raised ocean levels resulting from their melting.

Over the past 30 years, the amount of ice covering the North Pole has been reduced by 15%–20%. Additionally, the snow season in which ice is restored to the pack has grown shorter. By 2080, it is expected that there will be no sea ice during the summer [Dow and Downing 2007].

Besides the Arctic ice pack, glaciers of around the world are also shrinking. Warmer air and ocean waters cause the melting, and most glaciers have retreated at unparalleled rates over the past 60 years [Dow and Downing 2007].

Two other signs of a changing climate have direct impacts on people: increased weather-related disasters and a rising sea level. In 2005, the United States experienced 170 floods and 122 windstorms, compared with 8 floods and 20 windstorms in 1960. The statistics are similar for other countries, with 110,000 deaths due to weather-related catastrophes worldwide in 2005.

Sea-level rise results are visible. Small, low-lying islands in the Southern Pacific Ocean have either disappeared (e.g., two of the Kiribati islands in 1999) or had to be abandoned by residents (e.g., Carteret Islands in Papua New Guinea). Over the 20th century, the average sea-level rise was roughly 15 cm. If this trend continues, many more islands as well as the coastline of some countries would be lost [Dow and Downing 2007].

Assumptions

All the documentation that we encountered stated the same basic claim: *The North Polar ice cap melting will on its own affect the global ocean level by only a negligible amount.* This claim is simply a matter of the Archimedes Principle: The volume of water that would be introduced to the world's oceans and seas is already displaced by the North Polar ice pack, since it is comprised of frozen sea water floating in the Arctic Ocean.

However, the disappearing Arctic ice pack will speed up global warming, which encourages the melting of other land ice masses on Earth (e.g. Greenland, Antarctica, etc.). Thus, ocean levels *will* rise more as the North

Polar ice cap shrinks, due to indirect effects. In fact, North Polar ice cap melt is used as an "early warning system" for climate change around the world [Arctic Climate Impact Assessment 2004].

Worldwide Consequences of the Warming Arctic

As greenhouse gases increase in the atmosphere, snow and ice in the Arctic form later in the fall and melt earlier in the spring. As a result, there is less snow to reflect the sun's rays and more dark space (land and water) to absorb energy from the sun. The result, then, is the snow and ice forming later and melting earlier: A cycle emerges. Along the same lines, as snow and ice recede on the Arctic tundra, vegetation will grow on the exposed land, which will further increase energy absorption. Even though new trees would take in some of the CO_2 in the atmosphere, it would not be enough to compensate for the human-produced CO_2 causing the warming. Also, humans produce soot that is deposited in the Arctic by wind currents; the soot darkens the snow and further adds to soaking up energy from the sun. All of these changes will vary the world climate and lead to an increased global temperature [Arctic Climate Impact Assessment 2004].

When ice forms on the Arctic ice pack, most of the salt is pushed to the water directly below the mass. Therefore, the salinity of the water where sea ice is being formed and melted increases, which is an important step in *thermohaline circulation*—a system driven by the differences in heat and salt concentration that is related to ocean currents and the jetstream. Heating and melting in the Arctic will greatly affect the ocean currents of the world by slowing thermohaline circulation: The rate of deep water formation will decrease and lead to less warm water being brought north to be cooled. As a result, there will be regional cooling in the northern seas and oceans and an overall thermal expansion in the rest of the world, leading to a rise in sea level [Arctic Climate Impact Assessment 2004; Bentley et al. 2007].

Another direct impact of warming in the Arctic is the melting of permafrost, permanently frozen soil in the polar region. The melting of permafrost could lead to the release of large amounts of carbon dioxide, methane, and other greenhouse gases into the atmosphere [NASA Goddard Institute for Space Studies 2003]. Although warming would have to be fairly significant for this to occur, the consequences could be great, since another cycle of warming will take hold [Arctic Climate Impact Assessment 2004].

As the Arctic warms and global temperatures continue to rise, land ice will melt at an increasing rate. The associated sea-level rise will cause major loss of coastal land around the globe [Dow and Downing 2007].

The Arctic ecosystem itself will be completely disrupted by the warming environment. Food and habitat destruction will have a devastating effect on the mammals, fish, and birds that thrive in this cold environment. What's more, ecosystems farther south will be impacted, because a large number of Arctic animals move there during the summer months in search of food and

for breeding purposes [Arctic Climate Impact Assessment 2004; Bentley et al. 2007].

Finally, the warming Arctic will change the lives of humans around the globe. The most directly impacted will be the native peoples living in the North Polar region who depend on the ice pack and northern glaciers as a home and hunting ground. These people will be forced to move farther south and find new means of survival. Many fishing industries that depend on the Arctic as a source of income will see a reduction in catches. There will also be easier access to oil and minerals that lie under the ocean floor— a happy thought for some and horrific for others [Arctic Climate Impact Assessment 2004; Bentley et al. 2007].

We focus on the effect of small ice caps, glaciers, and the Greenland and Antarctica ice sheets melting over the next 50 years, since these will have a direct effect on sea level. Furthermore, we predict the effects of a sea-level rise on Florida. Finally, we propose a response plan.

Modeling Small Ice Caps and Glaciers

Though ice caps and glaciers are small compared to the Greenland and Antarctica ice sheets, they are located in warmer climates and tend to have a quicker reaction rate in response to climate change, and they will cause more-immediate changes in sea level [Oerlemans 1989].
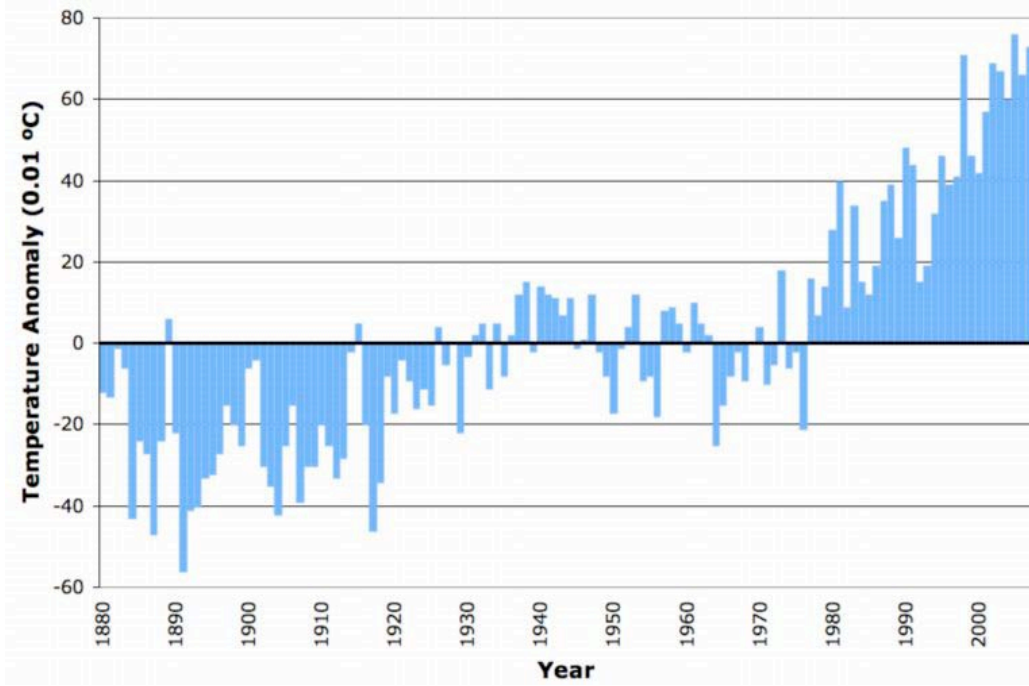
Global Mean Temperature

Global mean temperature is a measure of world-wide temperature change and is based on various sets of data. Overall trends in the temperature change can be detected, and periods of global warming and global cooling can be inferred.

Trends can clearly be seen in annual temperature anomaly data (relative changes in temperature) [NASA Goddard Institute for Space Studies 2008]. **Figure 1** shows global annual mean temperature for January through December of each year.

In the late 1800s, the temperature anomalies were negative yet increasing. For 1930–1970, the temperature anomalies hovered around 0; but then by the 1980s they remained positive and have been increasing.

Assumptions and Formation

We model the contribution of small ice caps and glaciers to sea-level rise by a model that uses a relation between the global mean temperature and the mass change of the small ice caps and glaciers [Oerlemans 1989; Wigley and Raper 1993]. We begin with the equation

Figure 1. Anomalies in global mean temperature, 1880–2007. The temperature is scaled in 0.01°C. Data from NASA Goddard Institute for Space Studies [2008].

$$\frac{dz}{dt} = \frac{-z + (Z_0 - z)\beta\overline{\Delta T}}{\tau}, \tag{1}$$

where

z is the sea-level change (initially zero) (m),

τ is the relaxation time (years),

β is a constant representing glacier melt sensitivity to temperature change ($°C^{-1}$),

Z_0 is the initial ice mass in sea-level equivalent, and

$\overline{\Delta T}$ is the global mean temperature change (°C).

We set $Z_0 = 0.45$ m, based on data from Oerlemans [1989]. We use data from Wigley and Raper [1993] for the values of τ and β, and we set these parameters for various estimates of sea-level rise as follows:

Low: $(\tau, \beta) = (30, 0.10)$
Medium: $(\tau, \beta) = (20, 0.25)$
High: $(\tau, \beta) = (10, 0.45)$.

The last parameter to estimate is $\overline{\Delta T}$. This could be done by finding a best-fit curve to the temperature anomaly data of **Figure 1**. For the years

after 1980, linear and logarithmic curves appear to fit the data. However, we use a temperature perturbation as an estimate for the change in annual global mean temperature, since this was implemented into models used in Oerlemans [1989]. The equation for the temperature perturbation is
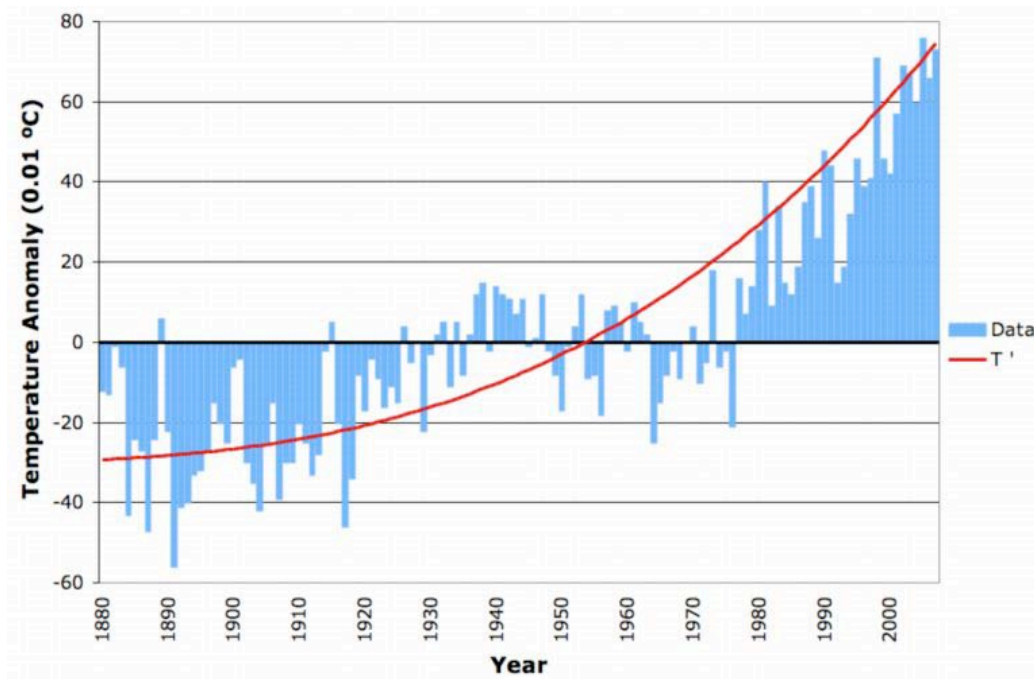
$$T' = \eta(t - 1850)^3 - 0.30, \tag{2}$$

where

η is the constant 27×10^{-8} °K·yr^{-3},

t is the year,

1850 is used as a reference year in which the Earth was in a state unperturbed by global warming, and

0.30 is a vertical shift (°C).

The comparison of **(2)** to the data in **Figure 1** is given in **Figure 2**.

Figure 2. Comparison of T' and actual data.

While the curve is not extremely accurate to each data point, the broad shape of the trend reflects the actual change in the global mean temperature. Fitting a polynomial of high degree could match the data better, but extrapolation past 2007 could be highly inaccurate. The moderate increase in global mean temperature represented by T' is realistic for our purposes of keeping the model simple.

Now we set $\overline{\Delta T}$ equal to T' by plugging **(2)** into **(1)**, giving

$$\frac{dz}{dt} = \frac{-z + (Z_0 - z)\beta(\eta(t - 1850)^3 - 0.30)}{\tau}.$$

Results of the Model

Low Sea-Level Rise

With $\tau = 30$ (the relaxation time in years) and $\beta = 0.10$ (the glacier melt sensitivity to temperature change in $°C^{-1}$), a low sea-level rise is estimated. Using these parameters, there is a decrease in sea level between 1850 and 1910, then a steady increase to a change of about 0.10 m by 2100 (**Figure 3a**). This curve is concave up. Focusing on the years 2008–2058, the change in sea level ranges between 0.015 m and 0.055 m (**Figure 3b**). This curve is also concave up.

Medium Sea-Level Rise

With $\tau = 20$ and $\beta = 0.25$, a medium sea-level rise is estimated. There is a decrease in sea level between 1850 and about 1900, and then a steady increase to a change of about 0.20 m by 2100 (**Figure 3c**). The curve is concave up, with a slight possible change to concave down around 2075. For 2008–2058, the change in sea level ranges between 0.045 m and 0.13 m (**Figure 3d**). This curve is almost linear.

High Sea-Level Rise

With $\tau = 10$ and $\beta = 0.45$, a high sea-level rise is estimated. There is a decrease in sea level between 1850 and 1890, and then a steady increase to a change of about 0.275 m by 2100 (**Figure 3e**). This curve is concave up with a shift to concave down around 2025. Focusing on the years 2008–2058, the change in sea level ranges between 0.10 m and 0.21 m (**Figure 3f**). This curve is concave down.

Modeling Ice Sheets

We focus on modeling the contribution of the ice sheets in Greenland and Antarctica. There are only simple models to simulate changes in volume over time, since "existing ice-sheet models cannot simulate the widespread rapid glacier thinning that is occurring, and ocean models cannot simulate the changes in the ocean that are probably causing some of the dynamic ice thinning" [Bentley et al. 2007].
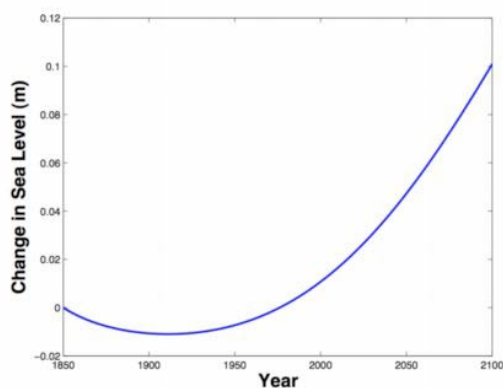
1880–2100   2008–2058
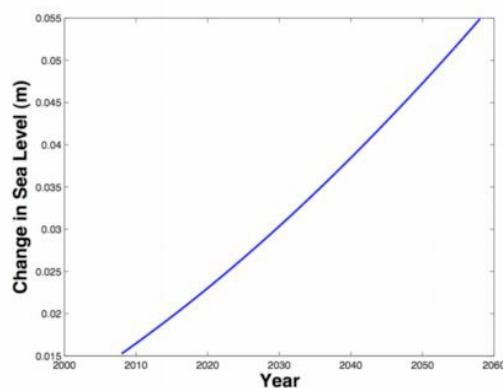
Figure 3a. $\tau = 30$, $\beta = 0.10$.   **Figure 3b.** $\tau = 30$, $\beta = 0.10$.
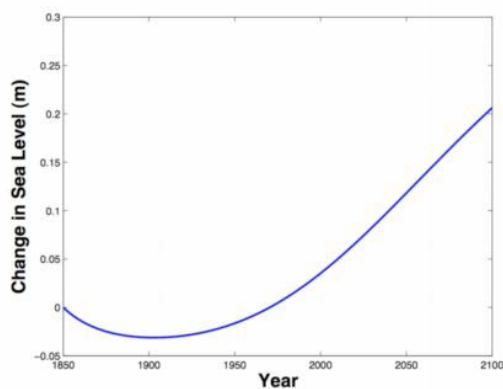
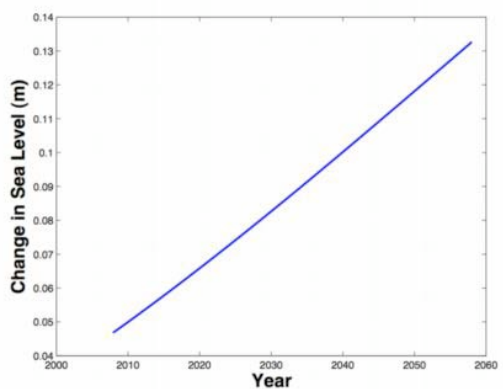**Figure 3c.** $\tau = 20$, $\beta = 0.25$.   **Figure 3d.** $\tau = 20$, $\beta = 0.25$.
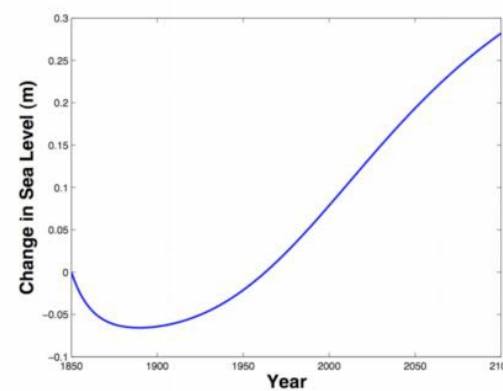
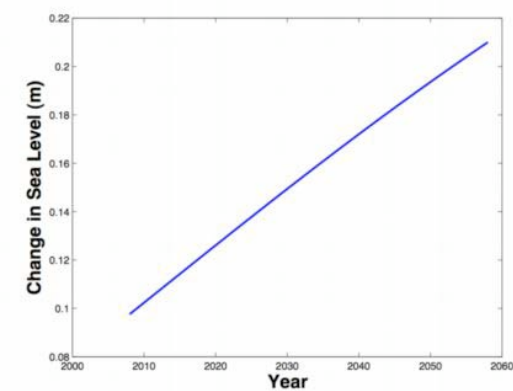**Figure 3e.** $\tau = 10$, $\beta = 0.45$.   **Figure 3f.** $\tau = 10$, $\beta = 0.45$.

Figure 3. Change in sea level for small ice caps and glaciers, in m/yr.

Assumptions and Formation

To create a simple model of sea-level rise, we make assumptions about average volumes and ice-loss rates. These averages were taken from a number of sources that used laser measurements as well as past trends to make conclusions as accurately as possible [NASA 2008; Steffen 2008; Thomas et al. 2006]. **Table 1** lists the parameters and their values for our equation to compute the contribution to sea-level rise.

Table 1.

Parameters and their values.

Symbol	Meaning	Value	Units
A_o	Total water area of the Earth	361,132,000	km^2
A_g	Area of Greenland	1,736,095	km^2
A_a	Area of Antarctica	11,965,700	km^2
V_g	Greenland ice sheet volume	2,343,728	km^3
V_a	Antarctica ice sheet volume	26,384,368	km^3
δ_g	Greenland accumulation	26	cm/yr
δ_a	Antarctica Accumulation	16	cm/yr
λ_g	Greenland loss rate (absolute value)	238	km^3/yr
λ_a	Antarctica loss rate (absolute value)	149	km^3/yr
ρ	Fresh water density	1000	kg/m^3
μ	Glacier ice density	900	kg/m^3

The equations for volume changes and corresponding sea-level rise are based on a simple model [Parkinson 1997]. We make a few modifications to this model to show a gradual change over a time period of 50 years (starting in 2008). The basic principle is to convert the loss rates of Greenland (λ_g) and Antarctica (λ_a) into water volumes using:

$$\frac{dV_g}{dt} = \frac{V_g \mu}{\rho}\,\lambda_g, \qquad \frac{dV_a}{dt} = \frac{V_a \mu}{\rho}\,\lambda_a.$$

The total volume change from the contributions of Greenland and Antarctica is a simple matter of addition:

$$\frac{dV}{dt} = \frac{dV_g}{dt} + \frac{dV_a}{dt}.$$

To calculate the total rise in sea level, there is one more aspect to consider—thermal expansion. As water warms, it expands in volume. We calculate the total sea-level rise by adding to the rise γ due to thermal expansion (γ) (approximately 1.775 mm per year [Panel on Policy Implications of Greenhouse Warming 1992]) the rise due to losses in Greenland and Antarctica:

$$\delta = \gamma + \frac{\frac{dV}{dt}}{A_o} \times 1000.$$

Sea-level rises produced by complete melting would be 7 m (Green-land) [Arctic Climate Impact Assessment 2004] and more than 70 m (Antarctica) [Kluger 2006].

Results of the Model

The contributions of the largest ice sheets plus thermal expansion do not raise the sea level as much as might be thought: 5.7 cm after 50 years.

Limitations of the Models

We chose efficiency and simplicity over complex models that apply only to small sections of the world, since they rely heavily on factors of specific ocean temperature, salinity and depth.

Model for Small Ice Caps and Glaciers

Parameter values have uncertainty, because it is difficult to measure the exact area, volume, and sea level equivalent of the small ice caps and glaciers. The same relaxation time and sensitivity values are used for all glaciers; incorporating many individual values would be difficult, because there is no specific information regarding how response time is related to ice volume [Oerlemans 1989].

We set the only cause of the melting of small ice caps and glaciers to be changes in global mean temperature. However, the causes of previous melting have not yet been specifically determined [Oerlemans 1989], so predicting the causes of future melting is limited in scope. Many other factors, such as accumulation and ablation rates, could play a role.

Model for Ice Sheets

The most prevalent uncertainties for the ice sheets are in the loss rates, plus thermal expansion of water. Loss rates were calculated by averaging over a number of decades.

Liquid densities depend on temperature, which does not factor into this model. The density of fresh water is approximately 1,000 kg/m^3 at 4°C [SiMetric 2008], which is the value we use, since the water generated by ice sheets will be near freezing. Similarly, glacier ice density is generally between 830 kg/m^3 and 917 kg/m^3 Parkinson [1997], with an average of about 900 kg/m^3 [Menzies 2002]—the value we use.

The thermal expansion factor contributes the greatest amount of uncertainty to this particular model.

Validation of the Models

Adding the total sea-level rise for the small ice caps, glaciers, and ice sheets results in the overall total rise by 2058 of between 11 cm and 27 cm. Using 2008 as the reference year, beginning in 2018 there is a linear relationship between time and total sea-level rise, as shown in **Figure 4**.
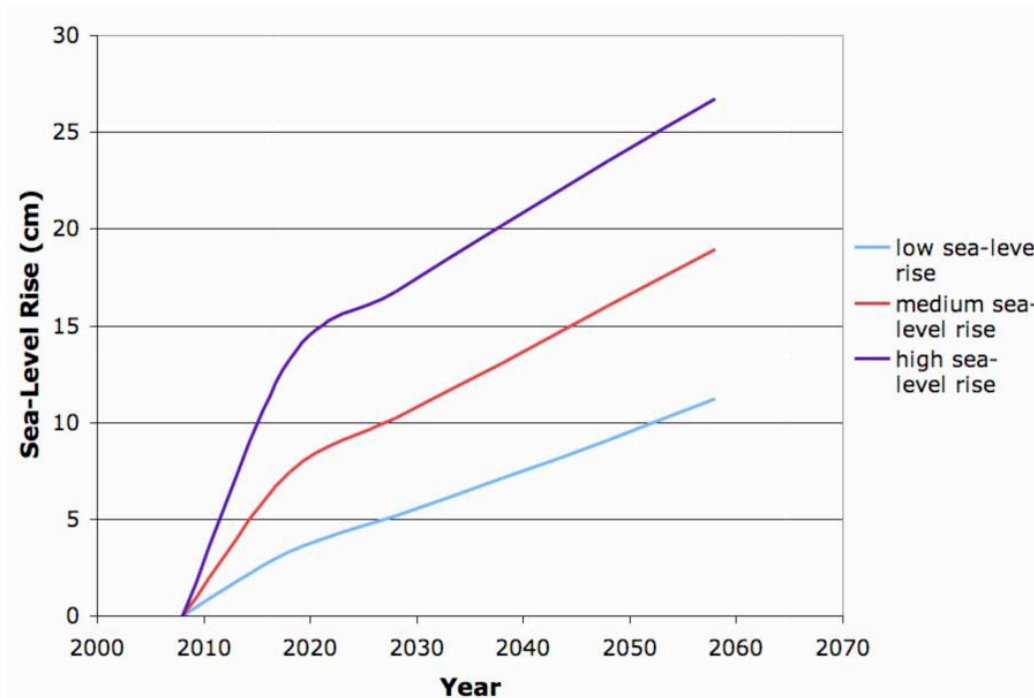
Figure 4. Change in sea level, 2008–2058, for low, medium, and high scenarios.

These results are in the range of sea-level-rise predictions from many sources:

- 50 cm in the next century [Arctic Climate Impact Assessment 2004].

- 10–30 cm by 2050 [Dow and Downing 2007].

- 1 m by 2100 [Natural Resources Defense Council 2005].

- Probabilities of increases by 2050 relative to 1985 are: 10 cm, 83%; 20 cm, 70%; and 30 cm, 55% [Oerlemans 1989]. (Note: The change from 1992 and 2007 was approximately 0.50 cm [Nerem et al. 2008].)

- 8–29 cm by 2030 and 21–71 cm by 2070 [Panel on Policy Implications of Greenhouse Warming 1992].

- 18–59 cm in the next century [U.S. Environmental Protection Agency 2008].

- 20–30 cm increase by 2050 [Wigley and Raper 1993].

Modeling the Coast of Florida

There is a direct relationship between vertical rise in the ocean and a horizontal loss of coastline. Specifically, one unit rise in the sea level corresponds to a horizontal loss of 100 units of land [Panel on Policy Implications of Greenhouse Warming 1992].

Hence, for a worst-case rise of 27 cm by 2058, we estimate the loss of 27 m of coastline. This does not appear to be as disastrous as one might think. We examine the extent of flooding.

Effects on Florida

In 2000 Florida had approximately 16 million people [Office of Economic and Demographic Research 2008]. Maps of population density, geographic relief, and topography show that about 30% of the counties in Florida are at a high risk of losing coastline; these counties also have large populations.

Many of Florida's major cities are located in these counties. We examine how much damage a retreat of 27 m of coastline would affect the cities of Cape Coral, Jacksonville, Pensacola, Miami, St. Petersburg, and Tampa.

Effects on Major Cities

In the next 50 years, most of the major cities are safe from destruction, but the outlying islands and outskirts of the cities are in danger. We measured the distance from the coastline near major cities inland to predict the extent of land that would be covered by water [Google Maps 2008].

- **Cape Coral:** Sanibel and Pine Islands would be mostly flooded, though the city center of Cape Coral would be spared.

- **Jacksonville:** Jacksonville would lose all of its coastal beaches. The city would also be in danger, depending on how much the St. Johns River rises as well. The outskirts of the city will be affected by flooding from the river.

- **Pensacola:** The harbor and the edges of the city would be covered by water, and a large portion of Gulf Breeze, Santa Rosa Island, and the Pensacola Naval Air Station would be submerged.

- **Miami:** Miami would be spared, at least for the next 50 years. Key Biscayne and Miami Beach would not be as lucky, though, and most of the Florida Keys would disappear under the ocean. However, predictions further into the future indicate that Miami will most likely be the first major city of Florida to become completely submerged.

- **St. Petersburg and Tampa:** Edges of St. Petersburg would be under water. The boundaries of Tampa would also be lost due to the surrounding

Old Tampa Bay and Hillsborough Bay. All coastal beaches, such as Treasure Island, would be mostly submerged. This area will have the largest displacement of urban population by the year 2058.

Validation of Loss of Coastal Land

The prediction of Florida coastline loss is validated by simulations from the Global Land One-km Base Elevation (GLOBE) digital elevation model (DEM) and is illustrated in **Figure 5**. The majority of Florida's population would be safe for the next 50 years, but mere loss of land is only one of the problems that would occur due to global warming.
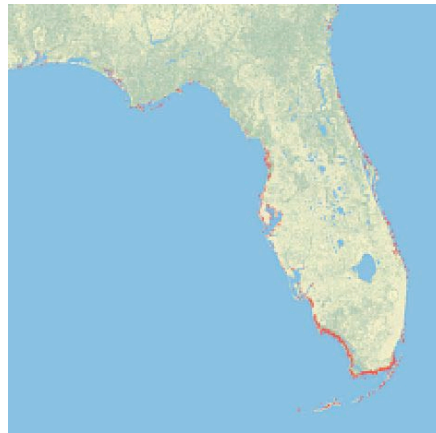
Figure 5. The effect of 27-cm sea-level rise in Florida: The coastline of Florida that would be covered with water shown in red [Center for Remote Sensing of Ice Sheets 2008].

Other Impacts on Florida

The impacts of global warming (enhanced by the melting of the polar ice cap) on Florida could be tremendous [Natural Resources Defense Council 2001]. They include:

- overall changing climate,
- "dying coral reefs,"
- "saltwater intrusion into inland freshwater aquifers" (thus impacting groundwater),
- "an upswing in forest fires,"
- "warmer air and sea-surface temperatures,"
- "retreating and eroding shorelines,"
- health threats,
- and increased hurricane intensity.

A few of the effects are described in further detail below.

Endangered Species and Biodiversity

The World Wildlife Fund has identified the Florida Keys and Everglades, located in southern Florida where there is the greatest risk of lost coastline, as one of the Earth's "200 Most Valuable Ecoregions" [World Wildlife Fund 2008]. Wildlife, including the Florida panther, roseate spoonbill, and green sea turtle, is greatly threatened by habitat loss. Plants and animals will most likely have a difficult time adapting to new climatic conditions and stresses, and the change in biodiversity in Florida will ultimately result in problems for biodiversity in surrounding areas [Dow and Downing 2007].

Tourism

Tourism, one of Florida's biggest industries, is in extreme danger if Florida loses most of its coastline.

Health threats

As of 2000, the annual number of Disability Adjusted Life Years per million people from malnutrition, diarrhea, flooding, and malaria caused by climate-related conditions was under 10 in the United States [Dow and Downing 2007]. However, with higher global temperatures, Florida is at risk for various diseases and pests. Lyme disease is spreading in the United States and flooding of the Florida coastlines could increase the risk of cholera, typhoid, dysentery, malaria, and yellow fever [Dow and Downing 2007].

Food Production

Most of the orange and grapefruit production occurs in southern Florida, and many orchards are located along the coast, so orchards will slowly lose land. Increased salt concentration in groundwater will also threaten citrus crops [Natural Resources Defense Council 2001].

Possible Responses

Responses have been prepared to the various threats that global warming poses to the state of Florida [Florida Environment 2000; Natural Resources Defense Council 2001; U.S. Environmental Protection Agency 2008]. The U.S. Environmental Protection Agency (EPA) and the Florida state government have begun implementing some of these suggestions (marked with an asterisk in the lists below) [U.S. Environmental Protection Agency 2002].

Responses to Changing Landscape

- Limit or stop land development along coastlines.

- * Work to protect coastlines and sand dunes that could weaken and erode.

- Enact a program to prevent people living on the coast from removing vegetation and trees as well as to encourage their planting.

- Set up a fund (either state or national) to aid people in the case of an emergency evacuation due to land loss and to aid those whose businesses will be obliterated.

Responses to Changing Climate

- Improve drainage systems, to decrease flooding and to avert stagnant water (a breeding ground for mosquitoes).

- Make flotation devices a mandatory feature of all homes and businesses in flooding areas.

- Encourage the public to keep emergency preparation kits and provide suggestion lists in supply stores.*

- Build more hurricane shelters and increase standards for new buildings to withstand hurricanes.

- Put permanent fire breaks around large areas at risk of burning.

Responses to Health Threats

- Store malaria pills in preparation to combat an increased mosquito population.

- Make emergency management drills a monthly or bi-monthly event, rotating among major cities.

- Improve interoperability between fire, EMS, and police services.

Responses to Global Warming

- Provide incentives for people to lead a "green" lifestyle, e.g., free street/garage parking for hybrids, tax cuts for purchasing Energy Star products, etc.

- Use heat-reflective paint on the tops of buildings to reduce air conditioning use.

- Encourage renewable energy sources.

- * Work with corporations and companies to reduce their output of greenhouse gases.

- • * Work to protect indigenous wildlife and plants as well as the unique landscape, such as the Everglades.

Action should be taken now with the worst-case scenario in mind. The most important aspect, however, is to *keep people informed*; make it clear that *land will be lost* no matter what, but people can slow down the process by becoming part of the solution.

Conclusion

Over the next 50 years, Florida will experience changes to its geography. Melting of ice sheets and glaciers and thermal expansion in the oceans will lead to a gradual rise in sea level.

The loss of land over time illustrates the seriousness of the problems of global warming. Living generations may be faced with the consequences of lost coastal land. If steps are not taken to reduce the increase in sea level, southern Florida will slowly disappear.

References

Arctic Climate Impact Assessment. 2004. *Impacts of a Warming Arctic: Arctic Climate Impact Assessment.* New York: Cambridge University Press. `http://amap.no/acia/`.

Bentley, Charles R., Robert H. Thomas, and Isabella Velicogna. 2007. Global outlook for ice and snow: Ice sheets. *United Nations Environment Programme* (2007): 99–114.

Center for Remote Sensing of Ice Sheets. 2008. Sea level rise maps and GIS data. `https://www.cresis.ku.edu/research/data/sea_level_rise/`.

Dow, Kirstin, and Thomas E. Downing, 2007. *The Atlas of Climate Change: Mapping the World's Greatest Challenge.* London: Earthscan.

Florida Environment. 2000. Public plans for sea level rise. `http://www.floridaenvironment.com/programs/fe00501.htm`.

Google Maps. 2008. `http://maps.google.com/`.

Kluger, Jeffrey. 2006. Global warming heats up. `http://www.time.com/time/magazine/article/0,9171,1176980-1,00.html`.

Menzies, John. 2002. *Modern and Past Glacial Environments.* Boston, MA: Butterworth-Heinemann.

National Aeronatics and Space Administration (NASA). 2008. Educational brief: Ice sheets. `http://edmall.gsfc.nasa.gov/99invest.Site/science-briefs/ice/ed-ice.html`.

NASA Goddard Institute for Space Studies. 2003. Recent warming of Arctic may affect worldwide climate. `http://www.nasa.gov/centers/goddard/news/topstory/2003/1023esuice.html`.

———. 2008. GISS surface temperature analysis. `http://data.giss.nasa.gov/gistemp/`.

Natural Resources Defense Council 2001. Global warming threatens Florida. `http://www.nrdc.org/globalwarming/nflorida.asp`.

———. 2005. Global warming puts the Arctic on thin ice. `http://www.nrdc.org/globalWarming/qthinice.asp`.

Nerem, R. Steven, Gary T. Mitchum, and Don P. Chambers. 2008. Sea level change. `http://sealevel.colorado.edu/`.

Oerlemans, Johannes. 1989. A projection of future sea level. *Climatic Change* 15: 151–174.

Office of Economic and Demographic Research: The Florida Legislature. 2008. Florida population. `http://edr.state.fl.us/population.htm`.

Panel on Policy Implications of Greenhouse Warming. 1992. *Policy Implications of Greenhouse Warming: Mitigation, Adaptation, and the Science Base.* Washington, DC: National Academy Press.

Parkinson, Claire L. 1997. Ice sheets and sea level rise. The PUMAS Collection `http://pumas.jpl.nasa.gov/`.

SiMetric. 2008. Density of water (g/cm^3) at temperatures from 0 °C (liquid state) to 30.9 °C by 0.1 °C inc. `http://www.simetric.co.uk/si_water.htm`.

Steffen, Konrad. 2008. Cyrospheric contributions to sea-level rise and variability. `http://globalwarming.house.gov/tools/assets/files/0069.pdf`.

Thomas, R., E. Frederick, W. Krabill, S. Manizade, and C. Martin 2006. Progressive increase in ice loss from Greenland. *Geophysical Research Letters* 33: L1053.

U.S. Environmental Protection Agency. 2002. Saving Florida's vanishing shores. `http://www.epa.gov/climatechange/effects/coastal/saving_FL.pdf`.

———. 2008. Coastal zones and sea level rise. `http://www.epa.gov/climatechange/effects/coastal/`.

Wigley, T.M.L., and S.C.B. Raper. 1993. Future changes in global mean temperature and sea level. In *Climate and Sea Level Change: Observations, Projections and Implications*, edited by R.A. Warrick, E.M. Barrow, and T.M.L. Wigley, 111–133. New York: Cambridge University Press.

World Wildlife Fund. 2008. South Florida. `http://www.worldwildlife. org/wildplaces/sfla/`.

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