The Impending Effects of North Polar Ice Cap Melt

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Abstract

Because of rising global temperatures, the study of North Polar ice melt has become increasingly important.

- How will the rise in global temperatures affect the melting polar ice caps and the level of the world's oceans?
- Given the resulting increase in sea level, what problems should metropolitan areas in a region such as Florida expect in the next 50 years?

We develop a model to answer these questions.

Sea level will not be affected by melting of the floating sea ice that makes up most of the North Polar ice cap, but it will be significantly affected by the melting of freshwater land ice found primarily on Greenland, Canada, and Alaska. Our model begins with the current depletion rate of this freshwater land ice and takes into account

- the exponential increase in melting rate due to rising global temperatures,
- the relative land / ocean ratios of the Northern and Southern Hemispheres,
- the percentage of freshwater land ice melt that stays in the Northern Hemisphere due to ocean currents, and
- thermal expansions of the ocean due to increased temperatures on the top layer.

The UMAP Journal 29 (3) (2008) 237–247.

We construct best- and worst-case scenarios. We find that in the next 50 years, the relative sea level will rise 12 cm to 36 cm.

To illustrate the consequences of such a rise, we consider four Florida coastal cities: Key West, Miami, Daytona Beach, and Tampa. The problems that will arise in many areas are

- the loss of shoreline property,
- a rise of the water table,
- instability of structures,
- overflowing sewers,
- increased flooding in times of tropical storms, and
- drainage problems.

Key West and Miami are the most susceptible to all of these effects. While Daytona Beach and Tampa are relatively safe from catastrophic events, they will still experience several of these problems to a lesser degree.

The effects of the impending rise in sea level are potentially devastating; however, there are steps and precautions to take to prevent and minimize destruction. We suggest several ways for Florida to combat the effects of rising sea levels: public awareness, new construction codes, and preparedness for natural disasters.

Introduction

We consider for the next 50 years the effects on the Florida coast of melting of the North Polar ice cap, with particular attention to the cities noted. This question can be broken down into two more-detailed questions:

- What is the melting rate, and its effects on sea level?
- How will the rising water affect the Florida cities, and what can they do to counteract and prepare?

Our models use the geophysical data in **Table 1** and the elevations of cities in **Table 2**.

Table 1.

Geophysical data.

Entity	Value	Unit
Total volume of ice caps	2.422×10^7	km^3
Surface area of world's oceans	3.611×10^8	km^2
Surface area of ice on Greenland	1.756×10^6	km^2
Volume of ice on Greenland	2.624×10^6	km^3

Table 2.
Elevations of Florida cities.

City	Average elevation (m)	Maximum elevation (m)
Key West	2.44	5.49
Miami	2.13	12.19
Daytona Beach	2.74	10.36

Preliminary Discussion of Polar Ice

There are two types of polar ice:

- frozen sea ice, as in the North Polar ice cap; and
- freshwater land ice, primarily in Greenland, Canada, and Alaska.

Frozen Seawater

Melting of frozen seawater has little effect because it is already floating. According to the Archimedean principle of buoyancy, an object immersed in a fluid is buoyed up by a force equal to the weight of the fluid that is displaced by the object. About 10% of sea ice is above water, since the densities of seawater and solid ice are 1026 kg/m^3 and 919 kg/m^3. So, if this ice were to melt, 10% of the original volume would be added as water to the ocean. There would be little effect on relative sea level if the entire North Polar ice cap were to melt.

The Ice Caps

Although the melting of the ice caps will not cause a significant rise in the sea level, several problems will indeed arise if they disappear.

- Initially there will be a small decrease in the average temperature of the oceans in the Northern Hemisphere.
- The ice caps reflect a great deal of sunlight, which in turn helps to reduce temperature in that region. When that ice is gone, additional energy will be absorbed and over time we will see a significant increase in global temperatures, both in the oceans and the air.

Freshwater Ice on Land

When freshwater ice on land melts and runs into the ocean, that water is added permanently to the ocean. The total volume of the ice on Greenland alone is 2.624×10^6 km^3. If all of this ice were to melt and add to the ocean (not taking into account possible shifting/depressing of the ocean floor or added surface area of the ocean), the average global sea level would rise 6.7 m—just from the ice on Greenland.

Our question now becomes:

How will the melting of freshwater land ice affect the relative level of the world's oceans over the next 50 years?

Model 1: Constant Temperature

Predicted Increase in Sea Level

To model the effects of ice-cap melt on Florida, we develop a model that provides a quick estimate of expected flooding. We assume:

- No increase in the rate of current ice-melt.
- Uniform distribution of the water from the ice melt throughout the world's oceans.
- No significant change in global temperatures and weather conditions.

We use the notation:

% Melt = percentage of land ice melting per decade

V_I = current volume of land ice in Northern Hemisphere

$C_{\mathrm{I}\to\mathrm{W}}$ = conversion factor volume of ice to volume of water = 0.919

$\mathrm{SA}_{\mathrm{WO}}$ = surface area of the world's oceans = $3.611 \times 10^8 \mathrm{km}^2$

For a given decade, our equation becomes

$$\text{Increase in ocean sea level} = \frac{\%\ \text{Melt} \times V_I \times C_{\mathrm{I}\to\mathrm{W}}}{\mathrm{SA}_{\mathrm{WO}}}.$$

Data from satellite images show a decrease in the Greenland ice sheet of 239 km^3 per year [Cockrell School of Engineering 2006]. Extrapolating linearly, after 50 years we get an increase in sea level of 3.3 cm.

We must also take into account the contributions of smaller land ice masses in Alaska and Canada, whose melting is contributing to the ocean sea level rises of 0.025 cm and 0.007 cm per year [Abdalati 2005]. Extrapolating linearly over 50 years, the total from the two is 1.6 cm, giving a total increase in sea level of 4.9 cm $\approx$ 5 cm $\approx$ 2 in. by 2058.

Effects on Major Metropolitan Areas of Florida

Even after 50 years there will not be any significant effect on the coastal regions of Florida, since all of these coastal cites are at least 2 m above sea level on average. There will, however, be correspondingly higher flooding during storms and hurricanes.

Unfortunately, these results are based on simple assumptions that do not account for several factors that play a role in the rising sea level. We move on to a second model, which gets us closer to a realistic value.

Model 2: Variable-Temperature Model

Our next model takes into account the effect of a variable temperature on the melting of the polar ice caps. Our basic model assumes constant overall temperature in the polar regions, which will not be the case.

Predicted Increase in Temperature

The average global temperature rose about 1° C in the 20th century, but over the last 25 years the rate has inreased to approximately °C per century [National Oceanic and Atmospheric Administration (NOAA) 2008]. In addition, much of the added heat and carbon dioxide gas will be absorbed by the ocean, which will increase its temperature.

Consequently, scientists project an increase in the world's temperature by 0.7 to 2.9°C over the next 50 years [Ekwurzel 2007]. An increase in overall temperature will cause freshwater land ice to melt faster, which in turn will cause the ocean to rise higher than predicted by the basic model.

We examine how an increase of 0.7 to 2.9°C over the next 50 years will affect sea level.

Model Results

We consider best- and worst-case scenarios. Again, we linearize; for example, for the best-case scenario of 0.7°C over 50 years, we assume an increase of 0.14°C per decade.

Best-Case Scenario: Increase of 0.7°C Over 50 Years

The ice caps will absorb more heat and melt more rapidly. We calculate sea-level rise at 10-year intervals.

The extra heat Q_x absorbed can be quantified as

$$Q_x = msT,$$

where

x is the duration (yrs),

m is mass of the ice cap (g),

s is the specific heat of ice (2.092 J/g-°C), and

T is the change in overall global temperature (°C).

We find

$$Q_{50} = 4.85 \times 10^{18} \text{ kJ}.$$

To determine how much extra ice will melt in the freshwater land-ice regions due to an overall increase in 0.7°C, we divide the amount of heat absorbed by the ice by the specific latent heat of fusion for water, 334 kJ/kg at 0°C, getting a mass of ice melted of 1.45×10^{16} kg.

Since water has a mass of 1,000 kg per cubic meter, the total volume of water added to the ocean is 1.45×10^{13} m^3. Dividing by the surface area of the ocean gives a corresponding sea-level rise of 4.0 cm.

This volume is in addition to the height of 4.9 cm calculated in the steady-temperature Model 1. Thus, in our best-case scenario, in 50 years the ocean will rise about 9 cm.

Worst-Case Scenario: Increase of 2.9°C Over 50 Years

Using the same equations, we find in our worst-case scenario that in 50 years the ocean will rise about 21 cm.

Model 3: Ocean Volume under Warming

The previous two models determined the total volume of water to be added to the world's oceans as a result of the melting of freshwater land ice. However, they do not take into account the relative surface areas of the oceans of the Northern Hemisphere and the Southern Hemisphere. The difference in the ratios of land area to ocean area in the two hemispheres is quite striking and gives a way of improving our model of water distribution.

Northern Hemisphere Ocean Surface Area

Approximately 44% of the world's ocean surface area is located in the Northern Hemisphere and 56% in the Southern Hemisphere [Pidwirny 2008]. The surface area of the ocean in the Northern Hemisphere is 1.58×10^8 km^2.

Percentage of Ice Melt Staying in the Northern Hemisphere

Similar melting freshwater land-ice is occurring in southern regions. So, we have water pouring down from the North Pole and water rushing up from the South Pole. There is very little information regarding flow rates and distributions of water throughout the world's oceans. Since most of the ice melt is added to the top layer of the ocean, that water will be subject to the major ocean currents, under which water in the Northern Hemisphere mainly stays in the north. For the sake of argument, we assume conservatively that just half of the melted freshwater land ice from the north stays in the Northern Hemisphere.

Expanding Volume Due to Increasing Ocean Temperatures

Several factors contribute to warming the ocean:

- The rising air temperature too will warm the ocean.
- As the polar ice caps melt, they will reflect less and less sunlight, meaning that the ocean will absorb a great deal of that heat.
- Progressively higher levels of carbon dioxide will be forced into the ocean.

In the ocean below 215 m, the pressure and lack of sunlight counteract increases in temperature. The water in the top 215 m of the ocean, however, will warm and expand in volume. Water at that temperature (15°C) has a coefficient of thermal expansion of 2.00×10^{-4} K^{-1}. We estimate the water level rise for the best and worst-case scenarios via:

$$V_{\text{change}} = V_{\text{start}} B T_{\text{change}},$$

where

- V_{start} = initial volume,
- V_{change} = change in volume,
- B = the thermal expansion factor (2.00×10^{-4} K^{-1}), and
- T_{change} = the change in temperature.

By dividing out the surface area of both volumes (roughly equal), we find a change in depth: 2 cm in the best-case scenario, and 12.5 cm in the worst case, after 50 years.

Putting It All Together

Figure 1 shows the results from Model 3. After 50 years, the sea level surrounding Florida will rise between 12 and 36 cm.

Effect on Florida

While the ocean-level rise surrounding each of the four cities will be comparable, there will be differential effects due to topography.

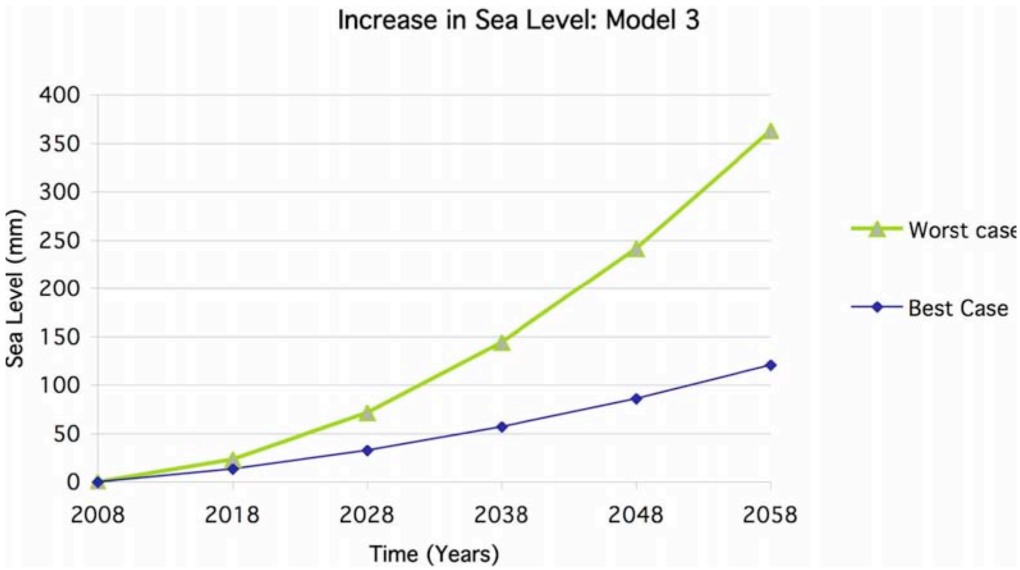

Figure 1. Results from Model 3.

Key West

Key West is the lowest in elevation of our four chosen coastal cities, with an average elevation of 2.44 m. After 50 years, the sea level will rise between 12 cm (4.7 in.) and 36 cm (14.3 in.).

This city is by far the most susceptible to flooding. When the sea level rises, there will be a proportional rise in the water table of the city. So, not only will the city begin to flood at higher elevations than it does currently, but it will also be harder to drain water after storms. In addition, there will be problems with overflowing sewers.

Based on our projections in Model 3, 75% of Key West will be at serious risk for flooding in about 50 years, including the airport. Key West needs to consider how to prevent water from entering the airport area or even start thinking about building a new airport at a higher elevation. [This is of particular importance considering the flooding of Key West in the summer of 2008.]

Miami

Miami will experience problems similar to those of Key West. Under the range of the scenarios, there will be a small loss of beachfront land and some minor flooding along the Miami River. Again, there will be possible problems with overflowing sewers and drainage due to the raised water table. However, one of the biggest problems might arise during a significant storm such as a hurricane. With the added height of the ocean and the low elevation of the Miami downtown area, the city could experience long-lasting floods of up to 36 cm where flooding is now currently minimal.

In 50 years, many buildings could be far too close to the ocean for comfort, and their structural integrity might be compromised.

Daytona Beach

Daytona Beach will experience some loss of shoreline property and be slightly more susceptible to flooding in low-lying areas. In addition, flood risks will be more severe in times of tropical storms and hurricanes. However, since there is a sharp increase in the elevation as one goes inland, flooding will be minimal and city drainage will remain relatively normal.

Tampa

Tampa will experience very little change from its current situation, since its lowest-lying regions are above 8 m. However, Tampa needs to be prepared for additional flooding and possible drainage problems.

General Recommendations for Coastal Florida

- **Limit coastal erosion.** The more erosion, the more beachfront property will be lost.
- **Monitor the water table.** As the sea level rises, so will the water table, which affects foundations of buildings and sewers. It would be advisable to restrict building construction within a set distance of the coast.
- **Prepare for flooding.** Higher sea level will produce greater flooding in storms. Cities should prepare evacuation and emergency plans.
- **Use government information resources.** When it comes to predicting whether or not one's particular town is in danger, there is an excellent online source for viewing potential flood levels. We highly recommend use of such resources of the Federal Emergency Management Agency at `www.fema.gov`.
- **Inform the public now.** Information is the key to preparation, and preparation in turn is the best way to combat the effects of the rising sea level over the years to come.

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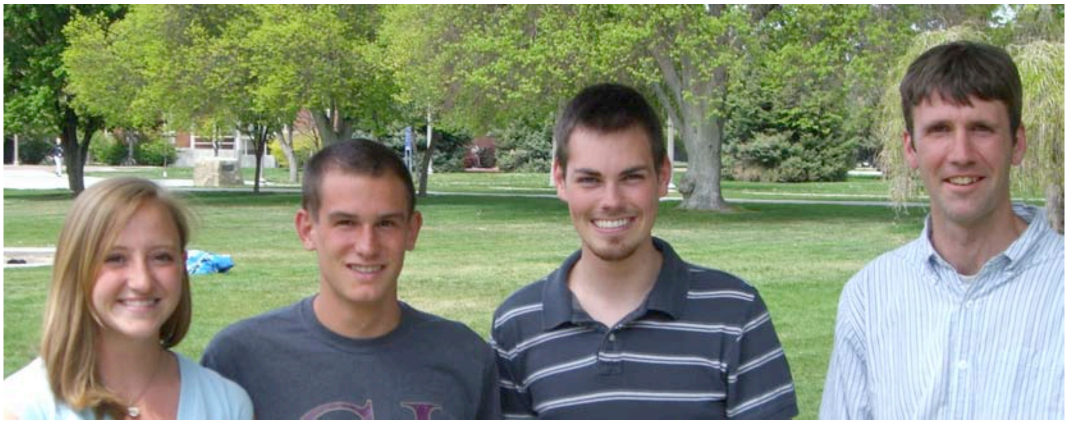

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