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Ice Sheets and Sea Level Rise

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Audience: Geography or Earth Sciences students in middle school and high school. No math is required beyond basic arithmetic.

Background: The ice sheets of Greenland and Antarctica contain massive amounts of frozen water (i.e., ice) that, if broken off or melted, for instance from extended global warming or from outward ice flow, would go largely into the oceans. In view of the vast size of the oceans, covering over 70% of the Earth's surface area, many people might at first think that the addition of ice or melted ice from the ice sheets would have little impact on global sea level. The numbers prove otherwise, however, and doing the calculations helps to instill this fact as well as recognition of the vast size of the Earth's two major ice sheets. The Antarctic ice sheet, for instance, has an area far exceeding the area of the United States, and over sizable regions its ice extends to a depth of greater than 2 miles (3.2 kilometers).

Exercise: Determine the amount that sea level would rise, averaged around the globe, in response to the complete melting of (a) the Greenland ice sheet, (b) the Antarctic ice sheet, and (c) both the Greenland and Antarctic ice sheets.

Needed information: The calculations require the area of the Earth's oceans and major seas (either as a total or as individual areas to be added), the volume of the ice sheets overlying land, the densities of ice and water, and knowledge that glacier ice is fresh-water ice rather than sea-water ice. This information can be obtained by the students from a world atlas or various other sources, or it can be handed to them in the form of tabulated information, as in Tables 1-3.

Table 1. Water Areas of the Earth.

Ocean or Sea	Area (in square kilometers)
Pacific Ocean	166,241,700
Atlantic Ocean	82,522,600
Indian Ocean	73,426,500
Arctic Ocean	14,056,000
Caribbean Sea	2,512,300
Mediterranean Sea	2,509,700
Bering Sea	2,266,250
Gulf of Mexico	1,554,000
Sea of Okhotsk	1,528,100
East China Sea	1,248,400
Sea of Japan	1,007,500
Hudson Bay	822,300
North Sea	575,000

Black Sea	479,150
Red Sea	437,700
Baltic Sea	422,170
Remaining surface water area	9,522,630

Source: *Hammond Citation World Atlas*, Hammond, Maplewood, New Jersey, 1992, p.352.

Table 2. Ice Sheet Areas and Thicknesses.

Ice Sheet	Area (in square kilometers)	Average Thickness (in kilometers)
Greenland	1,736,095	1.50
Antarctica	11,965,700	2.45

Source for the Greenland data: Williams, R. S., Jr., and J. G. Ferrigno, editors, Preface, *Satellite Image Atlas of Glaciers of the World: Greenland*, USGS Professional Paper 1386-C, United States Geological Survey, Washington, DC, 1995, p.v.

Source for the Antarctic data: Swithinbank, C., Antarctica, *Satellite Image Atlas of Glaciers of the World: Antarctica* (Richard S. Williams, Jr., and Jane Ferrigno, editors), USGS Professional Paper 1386-B, United States Geological Survey, Washington, DC, 1988, p.B12.

Table 3. Densities.

Substance	Density (in kilograms per cubic meter)
Fresh water	Approximately 1000
Glacier ice	Approximately 900 (generally between 830 and 917)

Solution: (1) Add the areas of the oceans, major seas, and other surface water areas (lesser seas, bays, etc.) from Table 1, obtaining 361,132,000 square kilometers. This is the area over which the added water must be averaged to obtain the resultant sea level rise.

(2) Calculate the volume of each ice sheet, by multiplying the ice-sheet areas by their average thicknesses, all provided in Table 2, obtaining ice sheet volumes of 2,604,142 cubic kilometers and 29,315,965 cubic kilometers for Greenland and Antarctica, respectively.

(3) Convert the Greenland and Antarctic ice sheet volumes to the approximate volumes of water that would result if the ice sheets were to melt. To do this, first calculate the ice mass, by multiplying the ice volume obtained in #2 by the ice density provided in Table 3. Then, recognizing from the principle of conservation of mass that the mass remains the same when the ice melts, divide by the density of water to obtain the corresponding water volume. The net calculation is simply a multiplication of the ice volumes by 0.9, obtaining water volumes of 2,343,728 cubic kilometers and 26,384,368 cubic kilometers for Greenland and Antarctica, respectively.

Note: Ice that calves into the ocean, becoming a floating iceberg, has the same effect on sea level as ice that melts and flows as liquid water into the ocean. This is because, by Archimedes' principle, the iceberg displaces the same volume of water as the volume of water that its melting would produce. Teachers and students can instructively demonstrate this using a see-through bowl (or beaker), water, and one or more ice cubes. First fill the bowl part way with water, leaving sufficient space at the top to allow the ice cubes to be added without overflowing, but being careful also to have the water deep enough so that the ice cubes will float. Mark the level of the water surface on the bowl. Then add the ice cubes and mark the new, higher level of the water, representing sea level rise. Finally, allow the ice cubes to melt and notice that the level of the water is the same after the melting as it was when the ice cubes were floating.

(4) Calculate the sea-level-rise answers by dividing the water volumes determined in #3 by the global surface-water area determined in #1, thereby spreading the effect of the ice sheet's water throughout the expanse of the Earth's surface-water area. The answers are: (a) (2,343,728

cubic kilometers)/(361,132,000 square kilometers) = 0.0065 kilometers = 6.5 meters for the Greenland ice sheet; (b) (26,384,368 cubic kilometers)/(361,132,000 square kilometers) = 0.0731 kilometers = 73.1 meters for the Antarctic ice sheet; (c) 6.5 meters + 73.1 meters = 79.6 meters for Greenland and Antarctica together.

Further suggestions: Have students look on a map with contour lines of heights above sea level to see the geographic effects that the calculated sea level rises would have. For instance, in the event of a complete melting of both Greenland and Antarctica, Florida would be almost completely underwater, although the peaks of some Florida hills would remain above sea level, as islands off the reduced North American continent. Students should consider whether or not the current location of their community would be underwater.

Qualifiers: (a) There are approximations and uncertainties in several of the numbers used in the calculations, and hence the answers should be considered as only roughly correct. (b) Strictly speaking, the calculations assume that the oceans and seas have vertical sides, with the area covered by water remaining constant throughout the process of sea level rise. Instead, as sea levels rise, the area covered by water would increase, which would reduce the magnitude of the rise. Still, in spite of the cautions of (a) and (b), the calculations outlined above provide a reasonable first-order estimate of the sea-level-rise response. (c) No knowledgeable person expects the Greenland and Antarctic ice sheets to disappear completely within the lifetime of anyone alive today, or within the lifetime of any of their children or grandchildren. Hence, the threat of a 79.6-meter sea level rise should not be seen as an immediate concern.

Much smaller rises in sea level, however, might well occur and in fact sea level appears to have risen approximately 0.2 meters over the past century. The twentieth-century sea level rise has resulted partly from thermal expansion of the water due to warming and partly from melting of mountain glaciers. It is not certain how much if any of the twentieth-century rise has resulted from changes in the Greenland and Antarctic ice sheets, due to a lack of adequate data. These two ice sheets, however, are the largest potential contributors to sea level rise, and concern has been raised in particular over the possibility that the portion of the Antarctic ice sheet termed the West Antarctic ice sheet, lying largely in the western hemisphere, might be unstable and might decay relatively rapidly, perhaps even causing sea level rises of several meters within 100 years. Although such a decay is not highly probable, it is possible, and if it were to occur, the resulting several-meter sea level rise would cause serious economic and personal consequences to all highly populated low-lying coastal regions.