Table 1. Various Greenhouse Gases as Proportion of Total Emissions

	Developed	*Developing*	*Least Developed*
CO_2	81%	41%	5%
N_2O	6	10	12
CH_4	11	16	21
Fluor gases	2	0	0
LUCF	0	33	62

Source: World Resources Institute, 2005 (data for year 2000)

to damage the ozone layer in the stratosphere and are banned in developed countries. They are used as refrigerants, propellants, and foaming agents for plastics.

Perfluorocarbons (PFCs), GWP 7,000–9,000

These chemicals are largely byproducts of aluminum production and semiconductor manufacturing.

Sulfur hexafluoride (SF_6), GWP: 23,900

This is produced for use as an insulator in various kinds of electrical equipment. This, together with the previous two man-made chemical categories, despite their very high GWP values, contribute roughly 2% of the world's greenhouse gas impact.

EMISSIONS AND ECONOMIC LEVEL

In agrarian economies with little heavy industry or electrical generation, methane is often the predominant greenhouse gas. In such countries, land-use change and forestry practice (LUCF) such as tropical deforestation account for a large share of emissions. In more industrial countries, electrical generation, transportation, industry, and heating of buildings contribute carbon dioxide, methane, and nitrous oxide, while CO_2 from land-use change is not significant (see Table 1).

Concentrations and GWPs for the six gases can be combined to yield one value expressed as million metric tons of CO_2 equivalent to make comparisons possible. On this basis—using data for the year 2000 (the most recent available in 2007)—the U.S. accounts for roughly 21% of world total, China 15%, and the European Union roughly 14%. The top ten countries account for 75% of emissions, while the top 25 account for 83%. [*See* Total Emissions and Emission Intensity, Year 2000, in Appendix.]

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—David J. Cuff

GREENLAND ICE SHEET

The Greenland ice sheet is the second largest ice mass on Earth and is about one-tenth the volume of the Antarctic ice sheet. It is the only significant ice mass in the Arctic today. [*See* Antarctica and Climate Change*; and* Ice Sheets.] It is an ice-age relict that overlies a bowl-shaped continent almost completely fringed by coastal mountains.

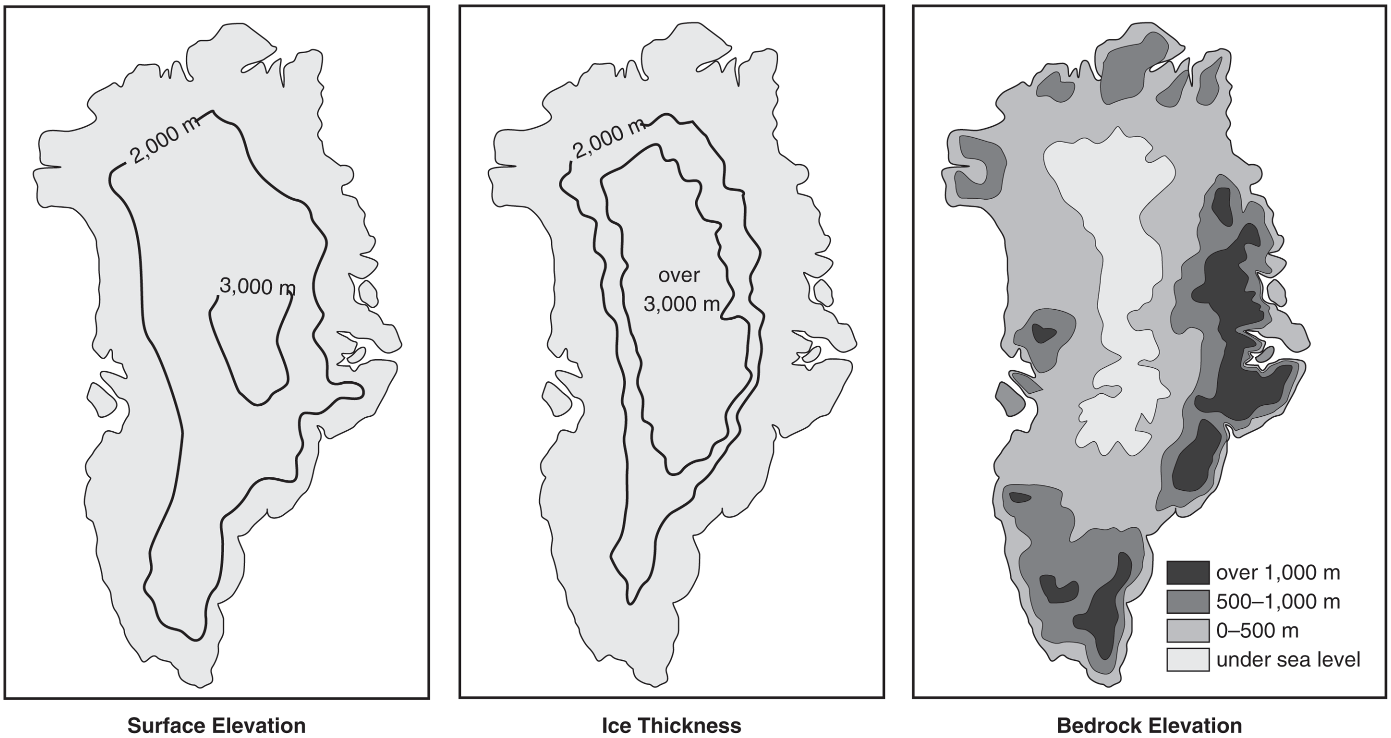
PHYSICAL-GEOGRAPHIC SETTING

The ice sheet extends from about 60° to 83°N over a distance of 2,400 km in the North Atlantic Ocean. The ice sheet covers 1.71 million km^2, or roughly 80% of the surface of Greenland. It consists of a northern dome and a southern dome, with maximum elevations of 3,230 m and 2,850 m, respectively, linked by a long saddle with elevations around 2,500 m. Its total volume is about 2.85 million km^3, which, if it were to melt entirely, would raise global sea level by about 7.2 m. The ice sheet has an average thickness of 1,670 m and reaches a maximum of 3,300 m in the center. The bedrock surface below the ice sheet is an extensive flat area near sea level, which would rebound by as much as 1,000 m if the ice sheet were removed (Figure 1).

Precipitation over Greenland generally decreases from south to north, ranging from about 2,500 mm per year in the southeast to less than 150 mm per year in interior northeastern Greenland. The southern high precipitation zone is largely determined by the Icelandic low and the resulting onshore flow which is forced to ascend the surface of the ice sheet. In contrast to Antarctica, summer temperatures on Greenland are high enough to cause widespread summer melting. This results in an ablation zone with negative mass balance all around its perimeter. Ablation rates are highest over the southwestern part of the ice sheet where they typically reach values on the order of 5 m per year. Most of the meltwater flows into the sea, either by surface runoff or by draining to the glacial bed via crevasses. The equilibrium line, which separates the ablation zone from the accumulation zone, ranges in elevation from 1,600–1,800 m in the southwest to less than 1,000 m along the northern coast. This setting makes the ice sheet sensitive to a warming climate. Surface melting is already an important component of its mass budget, and higher temperatures will raise both the amount of melting and the area over which the melting takes place.

Because of its comparatively high coastal temperatures, Greenland has no major ice shelves, only a few small ones along the northern and northeastern coasts. Ice not lost by ablation is discharged into the ocean by the calving of icebergs from outlet glaciers, in roughly the same amount as runoff. Iceberg calving takes place where the ice flow channelled into fast-moving outlet glaciers reaches the oceans. Some glaciers flow at speeds of up to several km per year. Jakobshavn Isbræ on the western side of the ice sheet is the fastest glacier on Earth, with velocities of up to 12 km per year or 32 m per day. Changes in oceanic temperature are suspected to control the calving dynamics and flow speeds at the margin.

The Greenland ice sheet affects the global environment through its high albedo and its elevated topography. These act as cooling surfaces for the atmospheric heat balance and are an effective barrier to atmospheric circulation patterns. The loss of meltwater and icebergs to the ocean plays an important role in the freshwater balance of the North Atlantic Ocean and potentially in



Greenland Ice Sheet. Figure 1. Configuration of the Present-day Greenland Ice Sheet.

Determined from a combination of satellite and airborne laser altimetry, barometric altimetry, and airborne radar (radio-echo) sounding.
Pictures reproduced from: Huybrechts P, and H. Miller (2005).

variations in the meridional (north-south) overturning circulation, and hence, in the strength and position of the Gulf Stream.

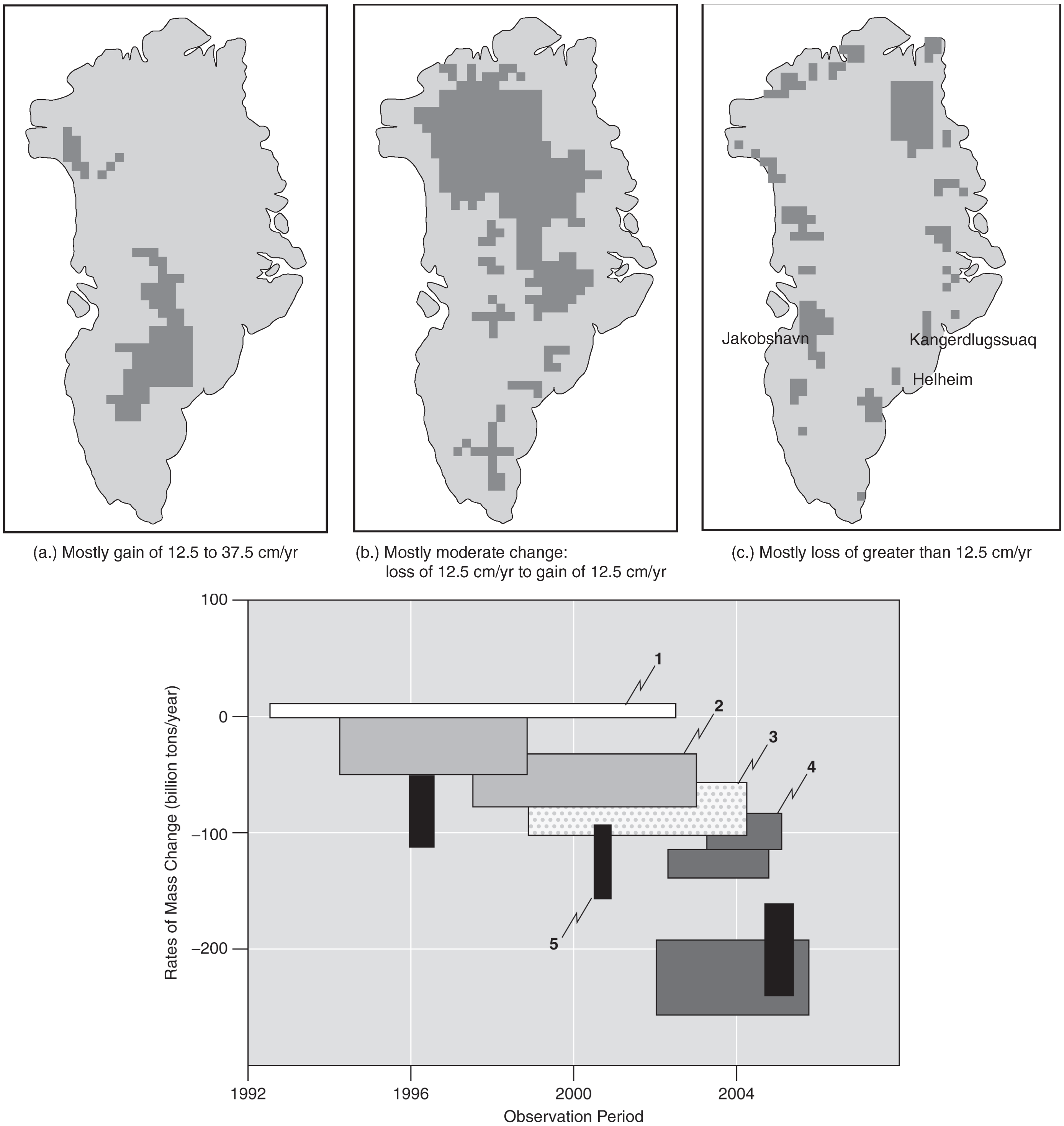
RECENT GLACIAL HISTORY

Glacier ice probably appeared first on Greenland in the late Miocene some 7 million years ago, but a continent-wide ice sheet did not form until the late Pliocene or early Pleistocene after about 3 million years ago. Greenland's glacial history is known best for the period since the ice sheet retreated from its Last Glacial Maximum position between 22,000 and 14,000 years ago. At that time, the ice sheet extended to the margin of the continental shelf over a distance of up to 200 km offshore. It joined the Laurentide ice sheet flowing out of Canada in the northwest over the Nares Strait and into the Kane Basin. The Greenland ice sheet was in full retreat between 13,000 and 8,000 years ago in response to rising sea levels, causing retreat of ice grounded on the sea floor, and to a warming climate, causing more surface melting. The ice sheet retreated to approximately the present coastline by 10,000 years ago and melted back further inland to near its present position by about 6,000 years before present. In central western Greenland, the ice sheet eventually retreated to a position at least 15 km behind its present position between 6,000 and 3,000 years ago following the mid-Holocene Climatic Optimum. The Neoglacial advance culminated with the Little Ice Age between 100 and 300 years ago.

CURRENT EVOLUTION

The current evolution of the Greenland ice sheet is dominated by continuing retreat from its Little Ice Age maximum combined with a slower trend resulting from older climate changes and from continuing changes in basal-ice properties. On these are superimposed the direct effects of recent changes in surface mass-balance and ice dynamics. Until recently, it was not possible to determine with any confidence whether the Greenland ice sheet was growing or shrinking. Over the last decade, however, improved remote sensing techniques combined with accurate GPS positioning have made it possible to estimate more precisely the mass balance of the ice sheet for the period since the early 1990s. These data show a consistent picture of a small thickening of the accumulation zone offset by larger thinning rates at lower altitudes, with a total mass balance that became increasingly negative up to 2005 (Figure 2).

The slow thickening at high elevations since the early 1990s at rates that increased to about 4 cm per year after 2000 is consistent with expectations of increasing snowfall in a warming climate. Total loss from the ice sheet, however, exceeded mass gains, and the total volume deficit more than doubled between the early 1990s and 2005 from a few tens of billions of tons per year to more than 200 billion tons per year, equivalent to a global sea-level rise of 0.5 mm per year or 5 cm per century. These increasing losses are associated partly with recent warm



Greenland Ice Sheet. FIGURE 2. **Rates of surface-elevation change, late 1990s to 2003, derived by comparing satellite and aircraft laser-altimeter surveys.**

Maps are generalized: in areas of +12.5 cm/yr loss, large parts exceed 37.5 cm/yr loss. The graph shows rates of change according to five kinds of evidence through time: (1) satellite radar-altimeter, (2) airborne laser-altimeter, (3) airborne/satellite laser-altimeter, (4) temporal changes in gravity, (5) mass-budget calculations. Jakobshavn, Helheim, and Kangerdlugssuaq are fast glaciers that doubled in speed recently, though the latter two returned to near their previous flow speeds in 2006. (Picture reproduced from: *Global Outlook for Ice & Snow*, United Nations Environment Programme, 2007.)

summer temperatures causing more melting, and partly with increased discharge of ice from outlet glaciers into the ocean. The summers of 1998, 2003, and 2006 were record runoff years at levels not seen since an earlier warm period in the 1930s and 1940s. In addition, the speeds of three of Greenland's fastest glaciers have approximately doubled since 2000, although the two glaciers in the east (Helheim and Kangerdlugssuaq) again slowed to near their previous rates in 2006. The third glacier, Jakobshavn Isbræ, increased its speed to about 14 km per year after the rapid thinning and breakup of its floating ice tongue, and has shown no signs of slowing.

The mechanisms for these observed speed-ups are not well understood. The glaciers mentioned above have in common that their calving fronts are in deep bedrock troughs, indicating a strong linkage between bed topography and glacier vulnerability to change, possibly by oceanic erosion from higher water temperatures. In addition, marked increases in ice velocity occurring soon after periods of high surface melting suggest that meltwater making its way to the base of the ice lubricates glacier sliding. Such a mechanism provides near-instantaneous communication between surface forcing and basal-ice dynamics and may make the Greenland ice sheet more sensitive to a warmer climate with more surface melting.

The short records for which elevation changes and flow speeds are available are of concern. The recent slowdown of the Helheim and Kangerdlugssuaq glaciers suggests that there is a significant short-term variability in glacier flow-rates. Whereas the recent mass loss from Greenland parallels global-warming trends seen elsewhere, the interpretation of mass-balance estimates is complicated by high natural variability on a range of time scales. The separation of long-term trends in ice mass from the effects of short-term variability requires observations over longer time periods than are currently available.

OUTLOOK

Compared to its volume and potential to raise sea-level, the average contribution of the Greenland ice sheet to global sea-level rise has so far been very small. According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC AR4), Greenland ice contributed no more than 0.05 mm per year to the observed 1.8 mm per year for the period between 1961 and 2003, and 0.21 mm per year to the higher rate of 3.1 mm per year of total sea-level rise observed between 1993 and 2003.

Because of the poor understanding of the ice-dynamic changes currently taking place and the known variability of surface mass balance, the short-term evolution of the Greenland ice sheet is hard to predict. Observations over the last 5 years reveal that the current generation of ice-sheet models cannot simulate the rapid changes taking place at the margin today. These flow changes may simply represent natural variability hitherto undetected, in which case they would not matter much. On the other hand, they may also be a function of the climate warming itself, in which case the future mass loss from the ice sheet might be significantly larger than most predictions suggest. Climate and surface mass balance models generally predict that in a warmer climate the increase in runoff will generally outweigh the concomitant increases in snowfall, so that the ice sheet will shrink in a warmer climate. But such a relation is less evident on time scales shorter than 10 years.

For the next few decades, the evolution of the Greenland ice sheet will be largely locked in by past climatic changes and therefore will not be strongly dependent on twenty-first-century greenhouse-gas emissions. For the full range of emission scenarios, the IPCC AR4 predicts that the Greenland contribution to global sea-level rise will be between 1 and 13 cm by 2090–2099. This range takes into account changes in surface mass balance and assumes that the ice-dynamic imbalance from accelerating glaciers observed between 1993 and 2003 holds constant. If these accelerations were to scale with the warming, the Greenland ice sheet might contribute an additional 5 cm or more, but our understanding of these effects is too limited to assess their likelihood or provide a good estimate or an upper bound for sea-level rise. If the current accelerations are transient, the sea-level contribution from Greenland will be 1–2 cm less.

The evolution of the Greenland ice sheet over centuries and longer is, however, critically dependent on future greenhouse-gas emissions. If global average temperatures increase more than 1.9–4.6°C above pre-industrial values, loss by surface melting will exceed precipitation. Under these circumstances, the ice sheet must contract, even when iceberg production falls to zero as the ice sheet retreats from the coast. This threshold at which melting exceeds accumulation will already be crossed, according to most global-warming scenarios, in the second half of the twenty-first century. Depending on the strength and duration of the warming, the ice sheet may nearly disappear over a period of a few millennia, except for residual glaciers in the mountains (Figure 3). Without the ice sheet, the climate of Greenland would be much warmer because the land surface would be at lower altitude and, with less snow cover, would reflect less sunlight. Several model studies suggest that even if global climate were to return to pre-industrial conditions, the ice sheet might not regrow, in which case the demise of the Greenland ice sheet and the associated sea-level rise might be irreversible. For this reason, the Greenland ice sheet is often described as a relict ice mass. It survived the current Holocene interglacial solely because it creates its own cold surface-climate because of its elevation.

The last time Greenland temperatures were several degrees higher than today was the last interglacial 125,000 years ago. Ice-core evidence for a smaller ice sheet is consistent with the observation that sea level then was several meters higher than today. At that time, the ice sheet did not disappear completely, probably because the warming was not strong enough and did not last long enough. The ice sheet was probably saved from extinction by the onset of the last glacial period several thousand years later.

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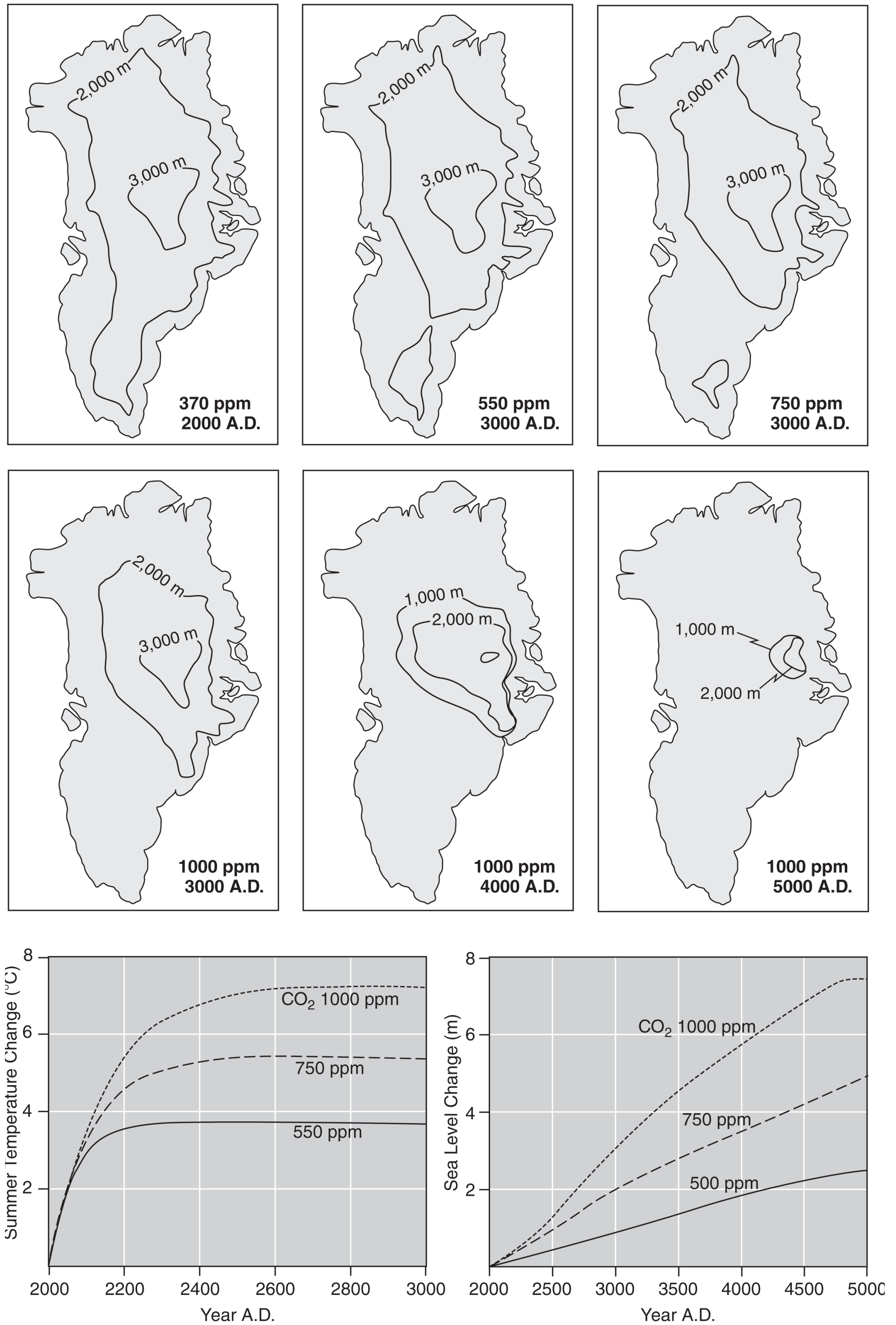

Greenland Ice Sheet. Figure 3. Future of the Greenland Ice Sheet

Calculated from a 3D ice-sheet model forced by three greenhouse gas stabilization scenarios. The warming scenarios correspond to the average of seven IPCC models in which the atmospheric carbon dioxide concentration stabilizes at levels between 550 and 1000 ppm after a few centuries. For a sustained average summer warming of 7.3°C (1000 ppm), the Greenland ice sheet is shown to disappear within 3000 years, raising sea level by about 7.5 m. (Picture reproduced from: Alley, R.B., et al., 2005.)

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—PHILIPPE HUYBRECHTS

GROUND WATER

In some parts of the world, ground water is the main source of water for industrial, municipal, and agricultural use. Some rocks, including sandstones and limestones, have characteristics that enable them to hold and transmit large quantities of water, which can be reached by installing pumps and boreholes.

Considerable reductions in ground-water levels have been caused by abstraction. The rapid increase in the number of wells tapping ground water in the London area from 1850 until after World War II caused substantial changes in groundwater conditions. The water level in the confined chalk aquifer (water-bearing stratum) fell by more than 60 meters over hundreds of square kilometers.

In some industrial areas, recent reductions in industrial activity have led to less ground water being withdrawn and groundwater levels have begun to rise, a trend worsened by considerable leakage from ancient, deteriorating pipe and sewer systems. This is happening in British cities such as London, Liverpool, and Birmingham. In London, a 46% reduction in ground-water withdrawal has caused the water table in the Cretaceous chalk and younger Tertiary beds to rise by as much as 20 meters. Such a rise has numerous effects:

- increased spring and river flows
- reemergence of flow from dry springs
- surface flooding
- pollution of surface and underground waters
- flooding of basements
- increased leakage into tunnels
- reduction in stability of slopes and retaining walls
- reduction in the weight-bearing capacity of foundations and pilings
- increased hydrostatic uplift and swelling pressures on foundations and other underground structures
- swelling of clays as they absorb water
- chemical attack on building foundations.

—ANDREW S. GOUDIE

GROUNDWATER DEPLETION IN SAUDI ARABIA

Most of Saudi Arabia is desert, so climatic conditions are unfavorable for the rapid large-scale recharge of aquifers, and much of the groundwater that lies beneath the desert is a fossil resource, created during more humid conditions—pluvials—that existed in the Late Pleistocene, between 15,000 and 30,000 BP. In spite of these unfavorable circumstances, Saudi Arabia's demand for water is growing inexorably as its economy develops. In 1980, the annual demand was 2.4 billion cubic meters. By 1990 it had reached 12 billion cubic meters (a fivefold increase in just a decade), and it is expected to reach 20 billion cubic meters by 2010. Only a very small part of the demand can be met from desalinization plants or surface runoff; over three-quarters of the supply is obtained from predominantly non-renewable groundwater resources. The drawdown on aquifers is thus enormous. It has been calculated that, by 2010, the deep aquifers will contain 42% less water than in 1985. Much of the water is used ineffectively and inefficiently in the agricultural sector (Al-Ibrahim, 1991) to irrigate crops that could easily be grown in more humid regions and imported.

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—ANDREW S. GOUDIE

GULF STREAM

See Thermohaline Circulation.