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— Author's final version (English translation) —

5-5 Global warming, the role of land ice, and sea-level rise

The frozen part of the terrestrial climate system is referred to as *cryosphere*. The cryosphere consists of several subsystems, namely ice sheets, ice shelves, ice caps, glaciers, sea ice, lake ice, river ice, ground ice and snow. Ice sheets are ice masses of continental size (area greater than 50,000 km²) which rest on solid land, whereas ice shelves consist of floating ice nourished by the inflow from an adjacent ice sheet, typically stabilized by large bays. Extended land-based masses of ice covering less than 50,000 km² are termed ice caps, and smaller ice masses constrained by topographical features (for instance a mountain valley) are called glaciers. Sea ice floats on the ocean; however, in contrast to an ice shelf it forms directly by freezing sea water. Similarly, lake ice and river ice form directly on lake and river water, respectively. Ground ice occurs as permafrost, that is, soil that stays in a frozen state year-round. Snow is precipitation in the form of crystalline water ice, consisting of a multitude of snowflakes, which accumulate on the ground at a bulk density significantly less than that of ice.

Ice sheets, ice caps and glaciers are subsumed as land ice, on which we will focus here. As a common feature, these ice bodies show gravity-driven creep flow, sustained by the underlying land. This leads to thinning and horizontal spreading, which is essentially compensated by snow accumulation in the higher (interior) areas and melting and calving in the lower (marginal) areas. Any imbalance of this dynamic equilibrium leads to either growing or shrinking ice masses.

5-5-1 Land ice on the present-day Earth

By far the largest single land-ice body on the present-day Earth is the Antarctic ice sheet, with a total ice volume of $25.7*10^6$ km^3 and in addition $0.58*10^6$ km^3 of the attached ice shelves (Ross ice shelf, Filchner-Rønne ice shelf, Amery ice shelf and others); this corresponds to a sea-level-rise equivalent of 61.1 m. The ice sheet and the ice shelves cover an area of $12.4*10^6$ km^2 and $1.1*10^6$ km^2, respectively, so that the mean ice thickness is approximately 2 km. Further extremes are a highest surface elevation of the ice sheet of 4.2 km a.s.l. (above sea level), an annual mean surface temperature which can be as low as –60°C in central East Antarctica, and the lowest temperature ever measured on the surface of the Earth, –89.2°C, at the Russian Vostok station. Due to these low temperatures, surface melting over the ice sheet is essentially non-existing, and the ice sheet loses its mass mainly by calving, that is, iceberg release into the Southern Ocean.

Compared to this, the second present-day ice sheet on Earth, the Greenland ice sheet, appears modest. Its ice volume amounts to $2.85*10^6$ km^3 or 7.2 m sea-level-rise equivalent, and the ice-covered area is $1.71*10^6$ km^2. Because of the absence of large bays, the ice sheet releases its outward mass flow directly into the ocean where it reaches the coast; noteworthy ice shelves do not exist. An important difference to the Antarctic ice sheet is that, due to the higher surface temperatures, the regions close to the ice margin experience a considerable amount of melting during the summer season, so that the mass loss of the Greenland ice sheet is approximately one half each due to melting and calving.

The more than 160,000 glaciers and approx. 70 ice caps have a combined volume of $0.18*10^6$ km^3 and cover an area of $0.68*10^6$ km^2. Their total sea-level-rise equivalent is therefore estimated as 0.5 m.

5-5-2 An excursion into the past

In the early Tertiary, the global climate was characterized by tropical-to-moderate worldwide temperatures and the complete absence of a cryosphere. However, in the course of the Tertiary climates slowly cooled. Antarctica drifted to its current position at the South Pole, and in the early Oligocene (about 30 million years ago) the Antarctic ice sheet started to form as a small ice cap which retreated and advanced many times until the Pliocene, when it came to occupy almost all of Antarctica. The Greenland ice sheet did not form at all until the late Pliocene, but developed very rapidly with the onset of the Pleistocene Glacial Epoch about 2 million years ago.

The Pleistocene lasted until about 10,000 years ago and showed a sequence of advances ("ice ages" or "glacials") and retreats ("interglacials") of ice sheets and glaciers, known as glacial cycles. According to the now widely-accepted Milankovitch theory, the main factor at work are periodic changes of the elements of the Earth's orbit around the sun (eccentricity, obliquity, precession), which affect the seasonal and latitudinal distribution of the solar insolation on Earth and, together with the effects of multiple positive and negative feedbacks (atmospheric CO_2 content, albedo, ice-sheet dynamics etc.), entail the glacial cycles. Until about 1 million years ago, their main period was 41,000 years (obliquity cycle), whereas thereafter the 100,000-year period (eccentricity cycle) prevailed.

21,000 years ago, at the Last Glacial Maximum, ice sheets covered large parts of North America, Greenland, the European Alps, northern Europe including Scandinavia and Britain, north-western Eurasia, Patagonia and Antarctica. Also, there were glaciers in the equatorial Andes, on Mauna Kea (Hawaii), in New Zealand and Tasmania, on several mountains in east and central Africa and in the Atlas Mountains. Owing to the additional water stored in these ice masses, the sea level was about 120–135 m lower than today, so that Hokkaido was connected to Sakhalin, the present Bering Strait was a land bridge between East Siberia and Alaska and Great Britain was a part of continental Europe. After that, the ice has retreated gradually, and at around 10,000 years ago the last ice age ended, marking the transition to the Holocene Epoch with its current, interglacial ice cover.

5-5-3 Land ice and global warming

What will be the fate of the present-day ice sheets, ice caps and glaciers in a warming climate during the next decades and centuries? First of all, it is important to note that the smaller an ice body is, the faster it can respond to a change in the climatic conditions (surface temperature, precipitation). Therefore, the smaller glaciers and ice caps are much more vulnerable to global warming than the large ice sheets of Antarctica and Greenland. On the other hand, let us recall that the potential for sea-level rise of the glaciers and ice caps is limited to 0.5 m, whereas that of the ice sheets is almost 70 m.

During the 20th century, a global sea-level rise of 1–2 mm/yr has been observed. Modelling results suggest that of this amount 0.2–0.4 mm/yr can be attributed to the melting of glaciers and ice caps and 0–0.1 mm/yr to the recent melting of the Greenland ice sheet. By contrast, the contribution of recent adjustments of the Antarctic ice sheet is estimated to be a sea-level *lowering* of 0–0.2 mm/yr. This surprising finding is due to the fact that the extremely low temperatures over Antarctica do not allow for significant increases in surface melting, whereas increased precipitation rates as a consequence of global warming have deposited more snow on the Antarctic ice sheet. On the observational side, the current balance of the Antarctic and Greenland ice sheets is still unclear, whereas glaciers all over the world show a significant trend towards retreat (see Fig. 5-5-1).

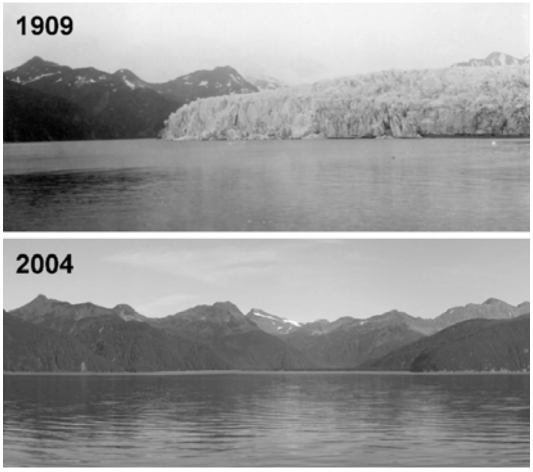

Fig. 5-5-1: Recession of McCarty Glacier in Alaska 1909 – 2004
(Sources: 1909 photo by Ulysses Sherman Grant, U.S. Geological Survey Photo Library, public domain. 2004 photo by Bruce F. Molnia, U.S. Geological Survey, public domain).

IPCC (Third Assessment Report 2001, Contribution of Working Group I, Chap. 11) projections for the climate change between 1990 and 2100 give an increase of the globally averaged surface temperature in the range of 1.4–5.8°C, and a global-average sea-level rise in the range of 0.09–0.88 m (0.8–8 mm/yr). These uncertainties are partly due to the assumption of a whole variety of greenhouse-gas-emission scenarios and partly due to model uncertainties themselves. For the standard emission scenario IS92a, the projected range of sea-level rise is 0.11–0.77 m, with a contribution from the glaciers and ice caps of 0.01 to 0.23 m, a Greenland contribution of –0.02 to 0.09 m and an Antarctica contribution of –0.17 to 0.02 m (further contributions are due to ocean thermal expansion, thawing of permafrost, etc.). Evidently, the likely largest contribution is from the small ice bodies. Note that the upper end of the range for glaciers and ice caps (0.23 m) is almost half of their entire sea-level-rise equivalent (0.5 m). This illustrates the large vulnerability especially of small glaciers, many of which will probably have vanished by the end of the 21st century. By contrast, the large ice sheets are much more inert, and the positive contribution of Greenland (due to increased melting and runoff) is expected to be more or less compensated by the negative contribution of Antarctica (due to increased precipitation).

5-5-4 Changes on a time-scale of 1000 years

On a longer term, if global warming continues, glacier and ice-cap retreat will go on, and the loss of a substantial fraction of their mass is likely within a few centuries. Also, the Greenland ice sheet will finally suffer a significant decay. For instance, a local warming of 8°C sustained for a millennium will give an estimated 6-m contribution to sea-level rise and leave the ice sheet largely eliminated. As a further example, a simulation result obtained by R. Greve with the ice-sheet model SICOPOLIS is shown in Fig. 5-5-2. The impact on the Antarctic ice sheet as a whole will likely be limited; however, melting and runoff will finally outweigh increased precipitation, and due to its huge volume a contribution to sea-level-rise of a few meters within 1000 years is possible.

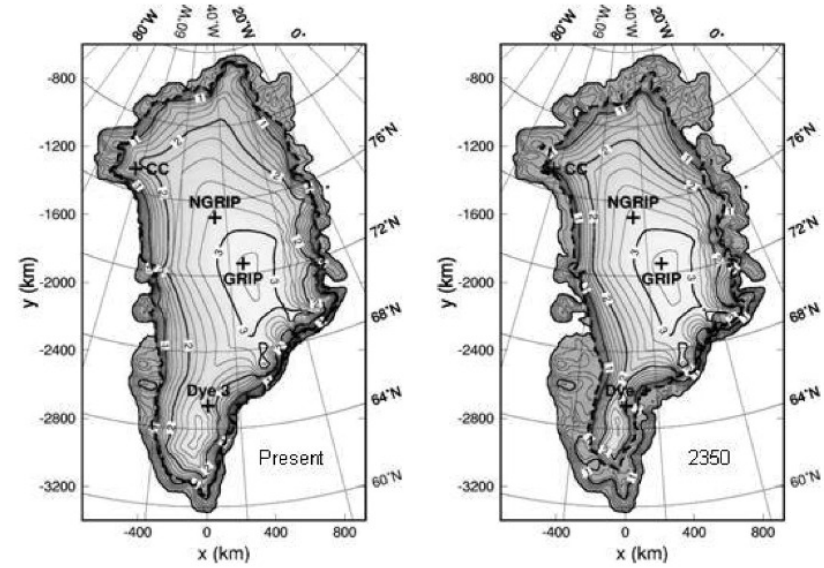

Fig. 5-5-2: Present-day (1990) topography of the Greenland ice sheet vs. simulated topography in the year 2350 for a greenhouse-gas-emission scenario with assumed CO_2 stabilization at 1000 ppm (“WRE1000”). Elevation contours in km a.s.l., spacing 200 m. The decreased ice volume is equivalent to a sea-level rise of approx. 1.8 meters.

Poorly understood internal ice-flow dynamics make these predictions to some extent uncertain, especially for Antarctica. Disintegration of attached ice shelves and accelerating ice streams and outlet glaciers may lead to an acceleration of the coastward mass flux of the ice sheet and therefore destabilize it. This possibility has been discussed in particular for the smaller part of the ice sheet in the western hemisphere (West-Antarctic ice sheet, sea-level-rise equivalent 6 m). While there is some consensus that such an ice-dynamic instability is not likely for the next centuries, firm predictions are not possible at present due to inadequate understanding of the related processes.

5-5-5 Global-scale feedbacks

Since the cryosphere is an integral part of the climate system, changes of its state will inevitably feed back on other subsystems. While for the smaller glaciers and ice caps such feedbacks are limited to local effects due to changes in albedo and hydrology, ice-sheet decay can affect the climate on a global scale. For the 21st century, the greatest foreseeable problem is the increased freshwater discharge into the North Atlantic from the melting Greenland ice sheet. Together with increased precipitation rates, this meltwater reduces the salinity and density of the surficial water in the North Atlantic and therefore hampers the formation of North Atlantic Deep Water (NADW). Since NADW plays a vital role in driving the North-Atlantic drift (also known as Gulf Stream), this warm surface current may experience a weakening or even a complete shutdown, with severe consequences for the climate in Europe and the whole pattern of heat distribution by the Global Conveyor Belt.

On longer time-scales, albedo changes due to exposed ice-free land in Greenland feed back positively on surface temperatures, which can lead to an accelerated, irreversible disintegration of the ice sheet. Also, major orographic changes of the Greenland ice sheet disturb the atmospheric circulation by altering the stationary Rossby wave pattern. This process may entail a complex pattern of regional climate change in the Arctic and sub-Arctic areas, which is difficult to assess in detail.

Acknowledgement

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