Ice sheets, global warming and sea level

Ralf Greve
Institute of Low Temperature Science, Hokkaido University
Kita-19, Nishi-8, Kita-ku, Sapporo 060-0819, Japan
Fax: 81-11-706-7142, e-mail: greve@lowtem.hokudai.ac.jp

Global warming, also referred to as climate change, is the observed rise in the average temperature of the Earth's climate system and its related effects. It is established scientific consensus that the climate system is warming, and that human influence has been the dominant cause of the observed warming since the mid-20th century. A major consequence of global warming is sea level rise, currently occurring at a rate of 3.2 ± 0.4 mm per year. For the 21st century, the range predicted by the Fifth Assessment Report of the Intergovernmental Panel on Climate Change across different possible climate futures is between 0.26 metres and 0.82 metres. The largest source is thermal expansion of ocean water, followed by melting/discharge of ice sheets, ice caps and glaciers. In the long term, the two ice sheets of Antarctica and Greenland are the largest potential contributors to global sea level rise because of their enormous amounts of stored water, together amounting to ~ 65 metres of sea level equivalent. The ice sheets are therefore the focus of observational as well as modelling efforts.
Key words: Climate, Sea level, Ice sheet, Observation, Modelling

1. INTRODUCTION

Weather is the momentary state of the atmosphere. It is described by meteorological variables such as temperature, humidity, cloudiness, precipitation, pressure and wind speed. In contrast, *climate* is the statistics of weather over long periods of time. It is measured by long-term averages and variabilities of the meteorological variables.

In modern climate science, the concept of climate is extended even further. The *climate system* consists of the partly overlapping components atmosphere, hydrosphere (oceans, lakes, rivers), cryosphere (land ice, sea ice, snow etc.), biosphere, land surface and pedosphere (soil). On decadal and longer time scales, all components of the climate system interact with each other, so that it does not make sense to treat the atmosphere separately. Hence, in a wider sense, the term climate refers to the long-term statistics of the entire climate system [1].

2. GLOBAL WARMING AND SEA LEVEL RISE

Global warming, also referred to as climate change, is the observed decadal- to century-scale rise in the average temperature of the Earth's climate system and its related effects. Multiple lines of scientific evidence show that the climate system is warming. Many of the observed changes since the 1950s are unprecedented in the instrumental temperature record which extends back to the mid-19th century, and in paleoclimate proxy records covering thousands of years [2]. As an example, Fig. 1 shows an overall long-term, global warming trend for the period from 1880 CE until 2016 CE.

What is the cause of these changes? Climate has been varying on all time scales during the entire history of the Earth since its formation about 4.5 billion years ago. For instance, in the early Tertiary (~ 65–35 million years ago), the global climate was characterized by tropical-to-moderate worldwide temperatures and the complete absence of a cryosphere. In contrast, during the Last Glacial Maximum (~ 20,000 years ago), vast ice sheets covered much of Antarctica, North America, northern Europe and Asia, the climate was significantly cooler and the sea level about 120–130 metres lower than today. These natural variabilities are often misused for an argumentation along the lines that "climate has always varied, hence the recent changes are also natural". However, in 2013, the Intergovernmental Panel on Climate Change (IPCC) concluded in its Fifth Assessment Report (AR5) that "It is extremely likely (95–100% probability) that human influence has been the dominant cause of the observed warming since the mid-20th century" [3]. This is the established consensus of the worldwide climate science community.

A major consequence of global warming is sea level rise. Global mean sea level already rose by ~ 6 cm during the 19th century and ~ 19 cm in the 20th century [4], and recently (1993–2010) sea level has been

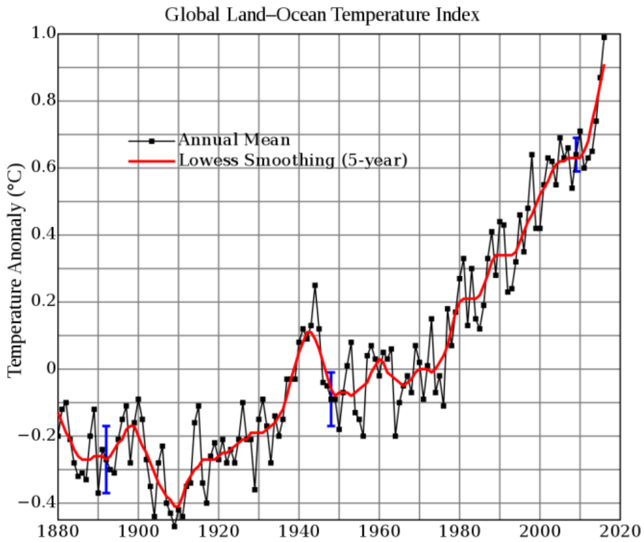

Fig. 1: Global land–ocean temperature relative to 1951–1980. Solid black line: global annual mean; solid red line: five-year LOWESS (locally weighted scatterplot smoothing); blue uncertainty bars: 95% confidence limit. (Credit: NASA Goddard Institute for Space Studies; public domain.)

rising at a rate of 3.2 ± 0.4 mm per year [3]. The observed contributions for the period 1993–2010 are listed in Table I. The largest source is thermal expansion of ocean water, followed by melting/discharge of land ice masses (see Section 3). Water storage on land comprises several different contributions, the most relevant one being human-induced groundwater depletion.

Table I. Observed contributions to global mean sea level (GMSL) rise for the period 1993–2010 [5]. Uncertainties (in square brackets) are 5–95%.

Source	**Value (mm per year)**	
Thermal expansion of ocean water	1.1	[0.8–1.4]
Glaciers and ice caps	0.76	[0.39–1.13]
Greenland ice sheet	0.33	[0.25–0.41]
Antarctic ice sheet	0.27	[0.16–0.38]
Water storage on land	0.38	[0.26–0.49]
Total of contributions	2.8	[2.3–3.4]
Observed GMSL rise	3.2	[2.8–3.6]

3. ICE ON EARTH

Ice on Earth, summarized as the cryosphere, occurs in several forms, 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 km^2) 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 km^2 are termed ice caps, and smaller ice masses constrained by topographical features (e.g., 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.

As we saw above, ice sheets, ice caps and glaciers are relevant for sea level rise. On the present-day Earth, there are the two ice sheets of Antarctica and Greenland, ~ 70 ice caps and ~ 200,000 glaciers. As a common feature, these ice bodies show gravity-driven creep flow (“glacial 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 (Fig. 2). Any imbalance of this dynamic equilibrium leads to either growing or shrinking ice masses [6].

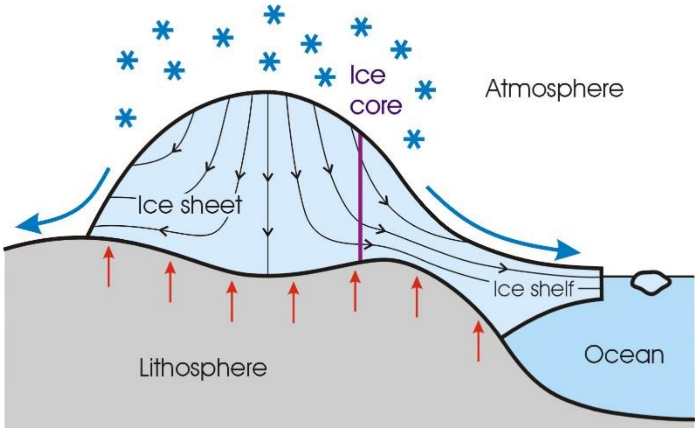

Fig. 2: Schematic cross-section of an ice sheet (with attached ice shelf). Glacial flow and interactions with the atmosphere (snowfall, melting), the ocean (melting, refreezing, calving) and the lithosphere (geothermal heat flux, glacial isostasy) are indicated. Vertical exaggeration factor ~ 200–500.

Table II lists the area, volume and turnover time of the Earth's ice masses. The enormous difference between the ice sheets vs. the glaciers and ice caps becomes evident. In terms of volume, Antarctica holds ~ 8 times more ice than Greenland, and Greenland holds more than 15 times more ice than all glaciers and ice caps combined. In case of complete disintegration, the Antarctic and Greenland ice sheets would cause a global mean sea level of as much as ~ 65 metres. However, their turnover time (which is a rough measure of the response time to changing external forcing such as global warming) is of the order of millennia, so that complete disintegration will certainly not happen in the near future. In contrast, the turnover time for smaller glaciers is only of the order of some decades, so that a larger fraction of the ice stored in glaciers and ice caps is prone to loss in the near future. Because of this, the current contribution of the glaciers and ice caps to sea level rise is about the same as that of Greenland and Antarctica together (Table I).

Table II. Inventory of today's ice sheets, ice caps and glaciers. Volumes are expressed in metres of sea level equivalent (m SLE). The turnover time is the volume (in m^3) divided by the annual accumulation rate (in m^3 per year). Main source: [7].

	Glaciers and ice caps	**Greenland ice sheet**	**Antarctic ice sheet**
Area (10^6 km^2)	0.73*	1.80	12.3
Volume (m SLE)	0.41*	7.36	58.3
Turnover time (years)	~ 50–1000**	~ 5000	~ 12000

*Sum for all glaciers and ice caps. **Range of values for individual glaciers and ice caps.

Ice sheets, ice caps and glaciers can respond to global warming by two different mechanisms. The *static response* by mass balance follows the direct pattern

Global warming → higher air and ocean temperatures → melting of ice.

In contrast, the mechanism of the *dynamic response* by ice flow is schematically

Global warming → higher air and ocean temperatures → higher ice temperatures
→ softer ice → faster ice flow
→ ice is transported towards lower elevations / the coast → increased melting / calving.

Multiple positive and negative feedbacks exist that make quantitative predictions difficult. For instance, ice melt and retreat exposes rather dark areas of land. Due to their lower albedo compared to an ice surface, they absorb more solar radiation, which leads to locally enhanced warming and thus even more ice melt. A negative feedback results from generally increased precipitation rates due to global warming. As long as this precipitation still falls as snow over the ice body in question, it works against the mass loss.

4. FUTURE SEA LEVEL RISE

Prediction of future sea level rise requires comprehensive models of the climate system. Such models are operated by several working groups across the globe. The latest comprehensive summary and digest of results was provided in 2013 in the IPCC AR5. Figure 3 shows the projections of global mean sea level rise over the 21st century for four different Representative Concentration Pathways (RCPs). The RCPs describe four possible climate futures, all of which are considered possible depending on how much greenhouse gases will be emitted. RCP 2.6 is the most optimistic scenario and can only be realized by implementing consequent measures for climate change mitigation. RCP 8.5 is the most pessimistic one, in which essentially “business-as-usual” is assumed, and emissions continue to rise throughout the 21st century. RCP 4.5 and 6.0 are in between. For 2081-2100 relative to 1986–2005, the predicted likely range (66–100% probability) of global mean sea level rise across these four scenarios is between 0.26 metres and 0.82 metres. The relative contributions of the sources as listed in Table I are not predicted to change strongly. However, the uncertainties especially from the contributions of the Antarctic and Greenland ice sheet are quite large.

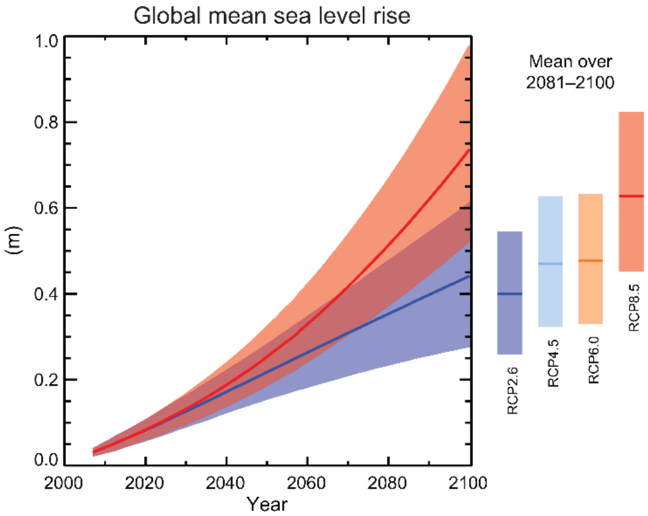

Fig. 3: Projections of global mean sea level rise over the 21st century relative to 1986–2005 from the combination of the CMIP5 ensemble with process-based models, for RCP2.6 and RCP8.5. The assessed likely range is shown as a shaded band. The assessed likely ranges for the mean over the period 2081–2100 for all RCP scenarios are given as coloured vertical bars, with the corresponding median value given as a horizontal line. Source: [3; their Fig. SPM.9 on p. 26]. © IPCC (https://www.ipcc.ch/home_copyright.shtml).

As an example of a longer-term scenario, let us assume a spatially and temporally uniform warming of +10°C over the Greenland ice sheet sustained for 1000 years. In order to simulate such scenarios, a dynamic/thermodynamic ice sheet model is required. Here, we use the model SICOPOLIS (“SImulation COde for POLythermal Ice Sheets”, www.sicopolis.net) for that purpose. Figure 4 depicts a comparison of the present-day ice thickness and the simulated thickness after 1000 years. The impact on the ice sheet is drastic: it loses approximately two thirds of its entire volume, amounting to ~ 5 metres of sea level equivalent. The assumed scenario is of course quite extreme. However, in a “business-as-usual” world without efficient measures for climate change mitigation, it is not completely unrealistic in the longer term because of the well-known process of Arctic amplification: Warming in Arctic regions (like Greenland) is expected to be much more pronounced than global average warming. Therefore, the Greenland ice sheet is potentially the greatest contributor to global sea level rise on longer (multi-centennial) time scales.

5. CHALLENGES OF ICE-SHEET RESEARCH

Owing to the great amount of water stored in the Antarctic and Greenland ice sheets (Table II), it is important to monitor changes of their mass balance and dynamics closely. This is challenging and expensive because of their size and limited accessibility. Satellites allow a global coverage; however, it comes at a limited resolution. Ground-based observations allow a much higher resolution, but the coverage is only local. In between are observations from airplanes.

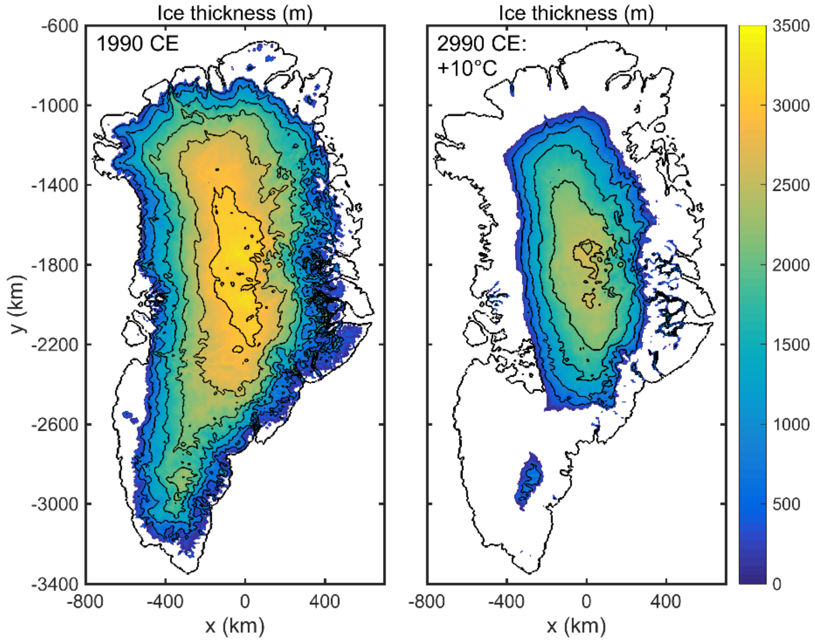

Fig. 4: Thickness of the Greenland ice sheet. Left panel: Observed thickness [8] (assigned to the reference year 1990). Right panel: Thickness simulated with the SICOPOLIS model [9] 1000 years in the future for an assumed spatially and temporally uniform +10°C warming over the ice sheet.

Modelling efforts aim at understanding the relevant processes, reproducing the observed changes in the past and predicting the future evolution of ice sheets, including impacts on other components of the climate system. Difficulties lie in the still limited understanding of important dynamical processes, so that ice sheet dynamics remains to be a major source of uncertainty for the prediction of future sea level rise. These issues are consequently a hot topic in current climate research.

Both observations and modelling produce enormous amounts of data that need to be managed properly. Societal challenges lie in the need to communicate scientific findings, including uncertainties, to stakeholders and the general public in order to create awareness and initiate appropriate action.

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