



Snow and Ice on Planet Earth: Present State, Impacts and Projections

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Abstract

Snow and ice on our planet includes mountain glaciers, ice shelves, continental ice sheets, seasonal snow, frozen ground, sea ice and freshwater ice that occur in polar regions and in high mountain zones. There is abundant and significant evidence that most of these cryospheric components are undergoing a generalised reduction in response to global warming, with already detectable effects on the environment and on different human activities. The reduction includes a strong decrease of Arctic sea ice, a decreasing snow cover at a global level, widespread glacier wastage, and the collapse of floating ice shelves in the Arctic and the Antarctic, with associated flow acceleration and thinning of inland glaciers. The effects associated to cryosphere reduction include the modification of runoff patterns due to the increase of glacier melt; the earlier occurrence of spring snow melting; decrease of vehicle traffic on frozen Arctic roads; increased danger associated to glacier and slope instabilities due the mechanical weakening of soils under deglaciation; changes in freshwater and marine ecosystems affected by lake, river and sea ice reduction; changes in Arctic and mountain livelihoods; reduced skiing, ice climbing and outdoor activities in mountain areas affected by deglaciation; and higher ship traffic in the Arctic.

Key words: Snow, ice, cryosphere, glacier retreat, sea level rise

1. Introduction

The snow and ice on earth, known as the cryosphere, constitutes one of the most sensitive indicators of climate changes. The cryosphere includes mountain glaciers, ice shelves, continental ice sheets, seasonal snow, frozen ground, sea ice and freshwater ice that are found in polar regions and in high mountain areas (Fig. 1). Land cryosphere stores about 75% of the world's freshwater (Lemke et al., 2007), with more than 17% of the world's population living in basins fed by glaciers and snow melt (Stern, 2007). The cryosphere and associated changes are as well a critical component of the earth's climate system and the water cycle, with a strong influence on sea level change.

The earth's climate is affected by climatic changes at several time scales. One of the most notable natural cycles are the ice ages, which have affected our planet long before the

presence of humankind, during several stages in our geologic past. Glaciations have been followed by warmer periods known as interglacials. During the last 2 million years, period known as the Quaternary, glacial-interglacial cycles have lasted about 100,000 years, with cold glacial periods of about 75,000 years that have been up to 5°C colder than at present at tropical latitudes, and even colder at higher latitudes (Jansen et al., 2007). At the end of the last glaciation, also known as the Last Glacial Maximum - LGM, some 20,000 years ago, ice sheets covered major continental portions that included parts of North America, Scandinavia, Siberia and southern South America, with sea level about 120 m lower than today. Less prominent natural climatic cycles have occurred at shorter (millennial to centennial) time scales, the last of which is known as the “Little Ice Age”, which culminated in the mid-late 19th century, when temperatures were about 1°C colder than today and glaciers advanced in many mountain regions on earth. There are other multiple natural climate cycles that affect our planet at shorter time scales, with impacts that vary according to the geographical region, such as El Niño-La Niña cycles in the Pacific Ocean and the North Atlantic oscillation in the Atlantic.

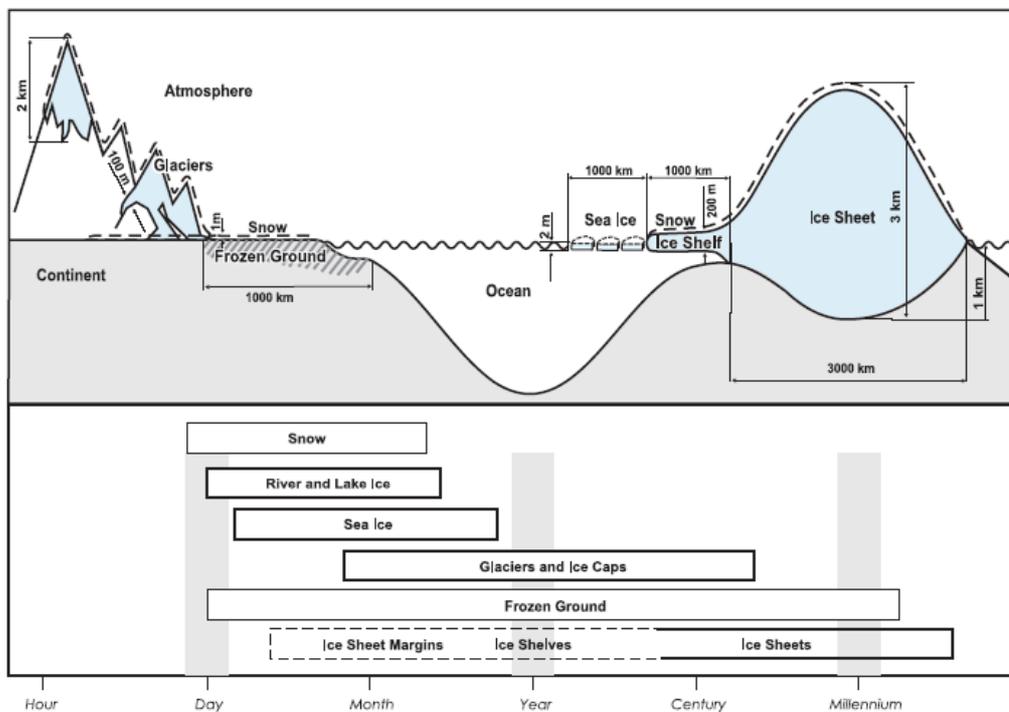


Figure 1. Different components of the cryosphere and associated time scales. Reproduced from Fig. 4.1 of IPCC (2007a).

It is now clear that the increase in anthropogenic greenhouse gases, which is unprecedented in at least the last 800,000 years (Lüthi et al., 2008), is largely responsible for the recent warming that has affected our planet. The warming amounts to 0.74°C in the last 100 years (IPCC, 2007a), which is most prominent within the last 50 years. This recent warming as produced a widespread cryospheric reduction, as is evident from ground studies, airborne sensors and satellite data (Lemke et al., 2007). This is particularly true for temperate snow and ice bodies, that is, ice at the pressure melting point, where atmospheric warming contributes directly to melting.

Here we describe the present state of the cryosphere, the observed impacts and projected changes under future warming scenarios.

2. State of the Cryosphere

Recent reviews of the state of the cryosphere are presented in IGOS (2007), Lemke et al. (2007), and UNEP (2007). Table 1 shows the area, ice volume, potential sea level rise and contribution to sea level for each cryospheric component (IPCC, 2007a). Current sea level rise is 3.1 mm/year (IPCC, 2007a), with a probable present contribution of 38% from glaciers, ice caps and ice sheets (Table 1).

a. Mountain glaciers and ice caps

Glaciers and ice caps have shown a widespread reduction in recent decades, most probably in response to post-1970 warming. The largest thinning rates and frontal losses have occurred in Alaska, northwest USA, southwest Canada and Patagonia. The main ice concentrations occur in Alaska, the Arctic and central Asia (Fig. 2), which consequently show the largest contributions to sea level. An example of a strongly retreating glacier in Patagonia is shown in Fig. 3. In Fig. 4 the global glacier mass balance data series shows a strongly negative trend, particularly in the last few decades. Glacier extent is now smaller than anytime in the last 5000 years, and present glacier retreat is outside the natural variability and can be attributed largely to anthropogenic warming (IPCC, 2007a). The estimated sea level rise contribution from glaciers and ice caps in 1993-2003 is 0.77 mm/year. An updated review of the present state of glaciers and ice caps is presented in Zemp et al., 2008.

Table 1. Area, volume and sea level equivalent (SLE) of cryospheric components. Indicated are the annual minimum and maximum for snow, sea ice and seasonally frozen ground, and the annual mean for the other components. The sea ice area is represented by the extent (area enclosed by the sea ice edge). The values for glaciers and ice caps denote the smallest and largest estimates excluding glaciers and ice caps surrounding Greenland and Antarctica. Source: Tables 4.1 and 4.6, Lemke et al. (2007).

Cryospheric Component	Area (10 ⁶ km ²)	Ice Volume (10 ⁶ km ³)	Potential	Sea Level Contribution	
			Sea Level Rise (m)	mm/year	
				1961-2003	1993-2003
Northern Hemisphere (NH) snow on land	1.9-45.2	0.0005-0.005	0.001-0.01	~0	~0
Sea ice	19-27	0.019-0.025	~0	~0	~0
Glaciers and ice caps ^{a,b}	0.51-0.54	0.05-0.13	0.15-0.37	+0.32 to +0.68	+0.55 to +0.99
Ice shelves ^c	1.5	0.7	~0	~0	~0
Greenland ice sheet ^d	1.7	2.9	7.3	-0.07 to +0.17	+0.14 to +0.28
Antarctic ice sheet ^c	12.3	24.7	56.6	-0.28 to +0.55	-0.14 to +0.55
Seasonally frozen ground (NH) ^e	5.9-48.1	0.006-0.065	~0	~0	~0
Permafrost (NH) ^f	22.8	0.011-0.037	0.03-0.10	~0	~0
TOTAL	66-159	28.4-28.6	64.1-64.4	0.69 ± 0.47	1.19 ± 0.42

Notes: a) Ohmura (2004); glaciers and ice caps surrounding Greenland and Antarctica are excluded. b) Dyurgerov and Meier (2005); glaciers and ice caps surrounding Greenland and Antarctica are excluded. c) Lythe et al. (2001). d) Bamber et al. (2001). e)

Zhang et al. (2003). f) Zhang et al. (1999), excluding permafrost under ocean, ice sheets and glaciers. g) Assuming an oceanic area of $3.62 \times 10^8 \text{ km}^2$, an ice density of 917 kg m^{-3} , a seawater density of $1,028 \text{ kg m}^{-3}$, and seawater replacing grounded ice below sea level.

b. Ice shelves

Floating ice shelves occur mostly in Antarctica, as a continuation of inland ice. Many floating ice shelves several thousand years old such as Wordie and Larsen B have collapsed in the northern Antarctic Peninsula due to enhanced warming, which is also happening in the Arctic as well (e.g. Ward Hunt ice shelf) (Lemke et al. (2007). Since ice shelves are already floating they do not contribute to sea level.

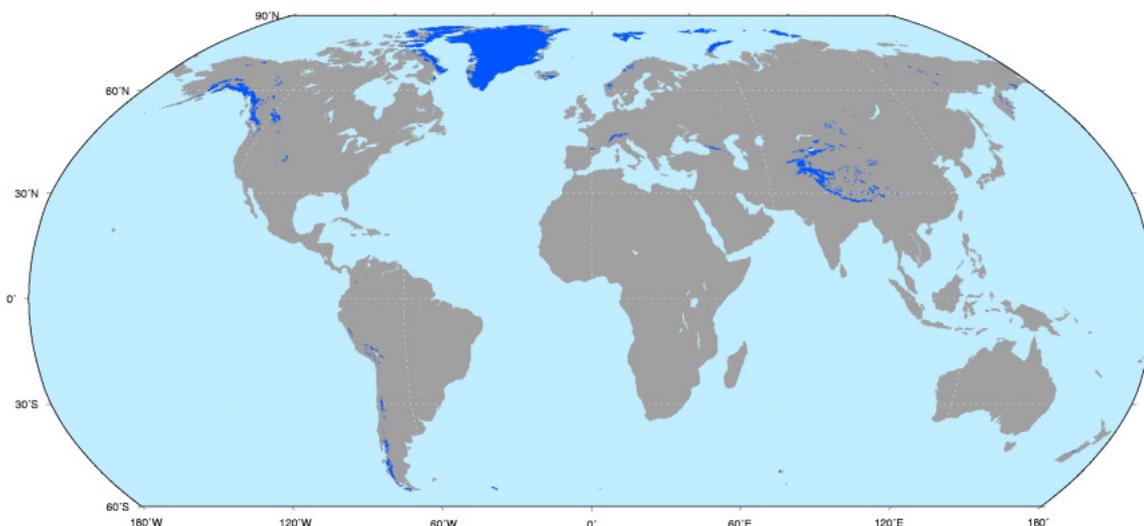


Figure 2. Source: figure and glacier database provided by Michael Zemp from WGMS, Zurich and Bruce Raup from University of Colorado, USA.

c. Continental ice sheets

Ice sheets are by far the largest ice masses on earth in terms of volume, with Antarctica (Fig. 5) representing 88% of the cryospheric fraction or a potential sea level rise of 56.6 m, and Greenland (Fig. 6) 11% or 7.3 m of potential sea level rise (Table 1). In Greenland peripheral thinning due to ice flow acceleration and melt (Fig. 6) has offset enhanced snow accumulation in the interior, with a positive contribution to sea level estimated as 0.21 mm/year. The Amundsen sea sector of West Antarctica has shown retreat, thinning, ice flow acceleration and ice shelf collapse, as well as the Antarctic Peninsula and some other areas around the margin of Antarctica. Most mass balance estimates for Antarctica now indicate negative values, although there is still no consensus on the sign of its contribution to sea level.

d. Seasonal snow

Snow cover shows a decreasing trend in most regions, particularly in spring and summer, with an associated snow line rise (Lemke et al., 2007). Decrease of snow cover and

snowpack are normally associated to warming, while snow growth is usually related to precipitation increase.

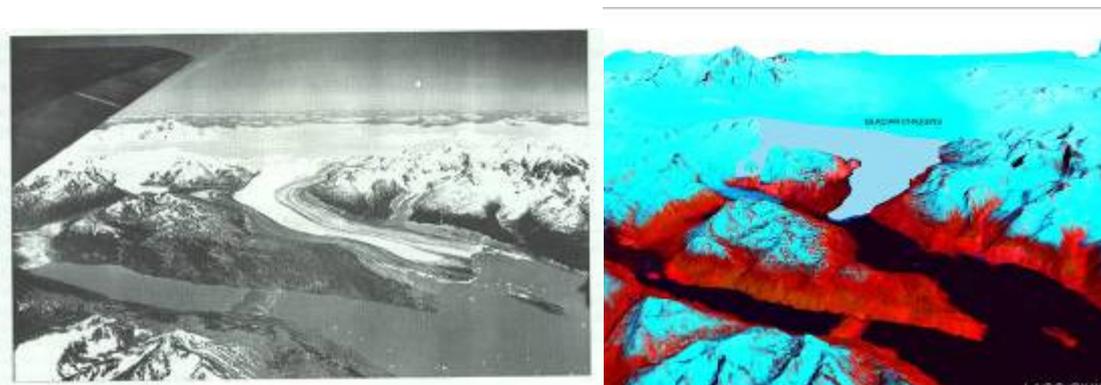


Figure 3. Retreat of O'Higgins Glacier, Southern Patagonia Icefield, view toward the west. This is a calving glacier which exhibits the maximum retreat in South America: 15 km in 100 years (Casassa et al., 1997). The left image is an oblique aerial photograph acquired in 1945 by the U.S. Air Force, while the right image is a computer-generated representation of the glacier in 2005. In 1896 the glacier front reached the small island which appears on the lower right in the images, and sometime before 1937 the glacier started to retreat very rapidly into the fjord of O'Higgins Lake, which has a maximum water depth of 800 m in this area, making it the deepest lake in the Americas. The glacier is still wasting away, but with a slower retreat rate since 1995 when it reached shallower water depths.

e. *Frozen ground*

Permafrost temperature in the top layers has increased up to 3°C in the Arctic, with evidence for thawing in Alaska and Tibet (Lemke et al., 2007). Seasonally frozen ground has decreased by ~7% in the northern hemisphere in 1901-2002, with a spring decrease of up to 15%, evidence for thickness decrease and seasonal snow depth increase (Lemke et al., 2007).

f. *Sea ice*

Arctic sea ice has declined at a rate of $7.4 \pm 2.4\%$ per decade since 1979, with an annual mean decline of $2.7 \pm 0.6\%$ per decade (Lemke et al., 2007; Figs. 4. and 7). Antarctic sea ice (Fig. 5) shows large interannual variability but no consistent trends (Fig. 4).

g. *Freshwater ice*

In spite of its large spatial variability, river and lake ice in the northern hemisphere shows later freeze-up dates at a rate of 5.8 ± 1.6 days/century and earlier breakup dates at a rate of 6.5 ± 1.2 days/century, which is interpreted to be an effect of climate warming (Lemke et al., 2007).

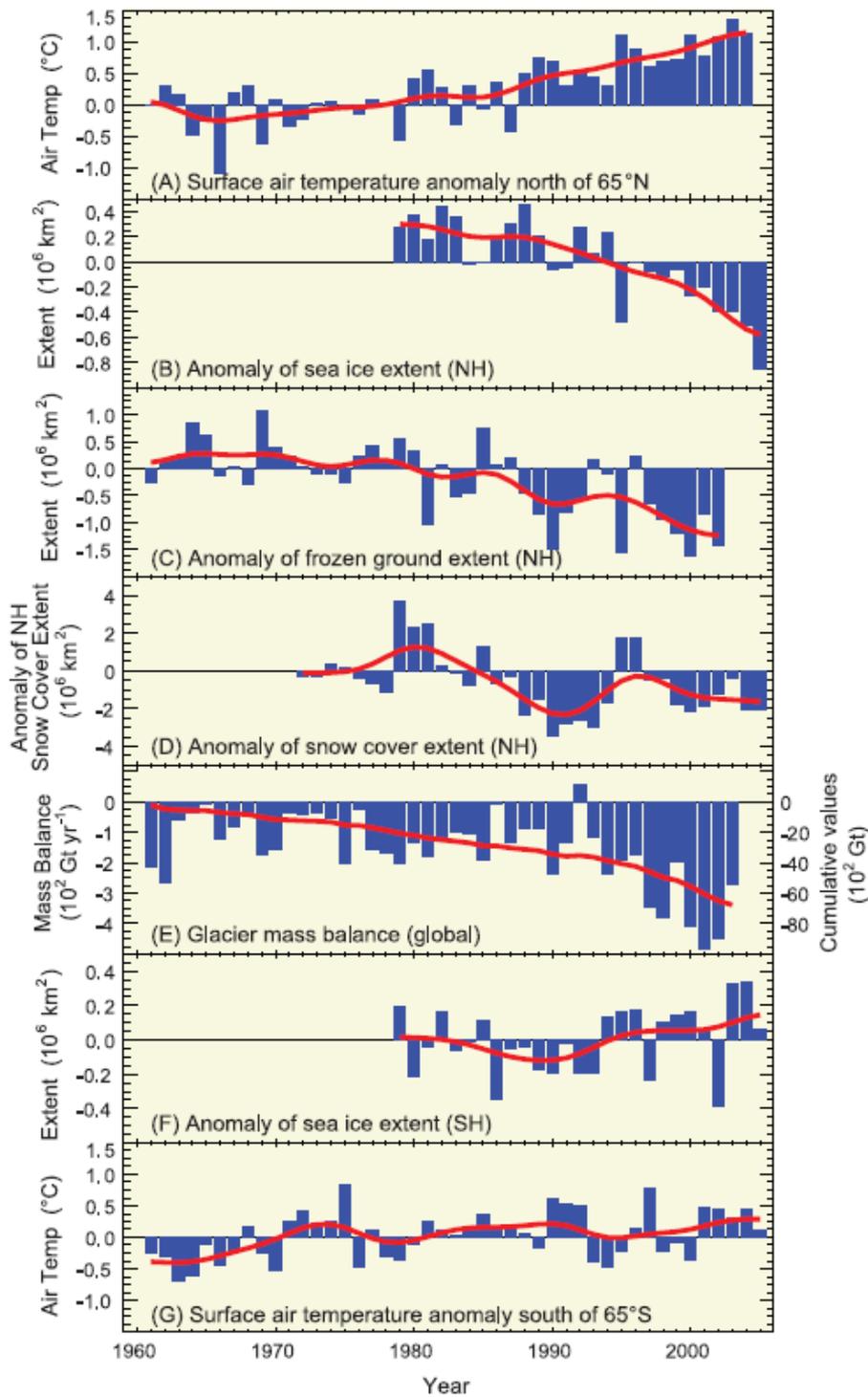


Figure 4. Anomaly time series (departure from the long-term mean) of polar surface air temperature (A, G), Arctic and Antarctic sea ice extent (B, F), Northern Hemisphere (NH) frozen ground extent (C), NH snow cover extent (D) and global glacier mass balance (E). The solid red line in E denotes the cumulative global glacier mass balance; in the other panels it shows decadal variations (see Appendix 3.A). Source: FAQ 4.1, Figure 1 (Lemke et al., 2007).

3. Impacts of cryospheric changes

Abundant impacts in the physical, chemical and biological environment have been reported due to cryospheric changes, as shown below (IPCC, 2007b, Rosenzweig et al., 2007). These changes are also producing changes in indigenous livelihoods in the Arctic and other human activities (Rosenzweig et al., 2007).

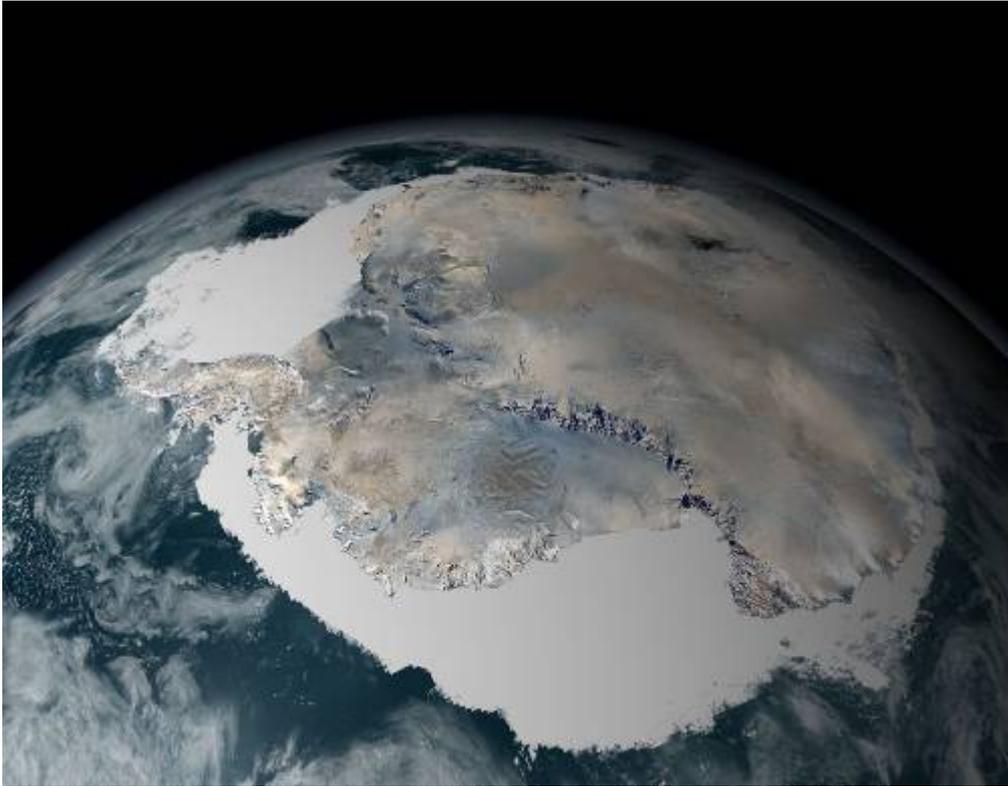


Figure 5. *The Antarctic ice sheet and its winter sea ice cover. Source: NASA/SVS.*

a. Mountain glaciers and ice caps, ice sheets and ice shelves

Impacts include runoff changes, changes in hazard conditions in mountain areas, tourism and sports (Rosenzweig et al., 2007). In the short term glacier runoff should increase due to enhanced melt, but continued glacier shrinkage should lead to a reduction in water availability (Fig. 8). There is evidence for enhanced runoff in high elevation basins in the Alps, Peru, northern British Columbia and Yukon, and central Asia, while lower basins in the Alps and in southern British Columbia already show reduced runoff (Casassa et al., submitted). Glacier melt in Alaska is resulting in crustal uplift (Rosenzweig et al., 2007). As glaciers melt the valuable paleoclimatic records preserved in the firn and ice layers are destroyed (Rosenzweig et al., 2007). As glaciers retreat lakes located at their margins start growing, representing a high potential for generation of jökulhlaups or glacial lake outburst floods (GLOFs), as is already reported in the Himalayas (Rosenzweig et al., 2007). Reduction of glaciers is resulting in the loss of ice climbs, and may also impact tourism in alpine areas. Skiing activities are also affected by glacier reduction, as has already

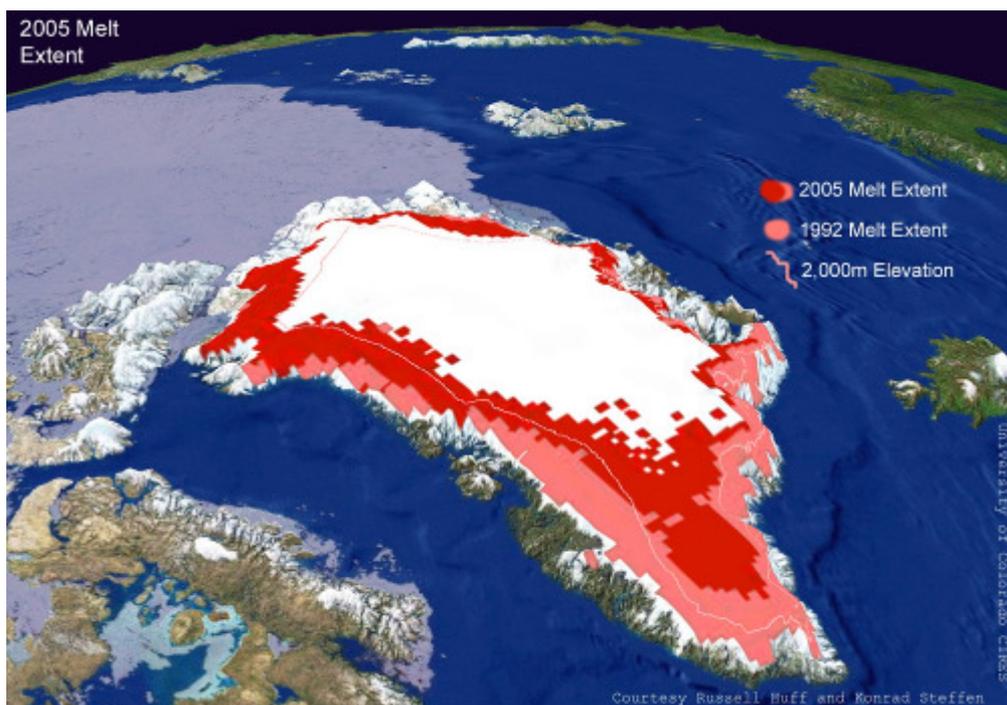


Figure 6. Extent of snow and ice melt on the Greenland ice sheet in 2005 compared to 1992. Source: <http://cires.colorado.edu/science/groups/steffen/greenland/melt2005/>, courtesy Russel Huff and Konrad Steffen.



Figure 7. Arctic ice cover at the end of the 2003 summer. The Northwest Passage that connects Labrador Sea on the right (southwest of Greenland) with Bering Strait on the left can be seen almost completely free of sea ice. NASA image obtained from <http://geology.com/articles/northwest-passage/sea-ice-2003-high-res.jpg>.

occurred in Chacaltaya Glacier in Bolivia (Rosenzweig et al., 2007). Finally, glacier shrinkage results in plant and faunal colonisation in deglaciated terrain.

b. *Snow cover*

Spring peaks in river flows occur now 1-2 weeks earlier in North America and Eurasia, as well as an increase in winter base flow (Rosenzweig et al., 2007).

c. *Frozen ground*

Degradation of seasonally frozen ground and permafrost is producing land changes such as increased wetland extent and associated “greening” in the Arctic and Eurasia, i.e. plant colonisation. A potential increase of carbon from buried methane sources is also predicted, but there is no evidence for this yet. Drainage systems are also affected in the Arctic and Eurasia, with initial lake expansion and subsequent drainage in permafrost. The travel period for wheeled vehicles over frozen roads in Alaska is becoming shorter due to enhanced frozen ground melt. Degradation of frozen ground should traduce in mechanical weakening of the ground and subsequent effect on infrastructure, but there is no evidence for this yet. Frozen ground degradation in alpine areas should produce slope instability and rock falls, such as the exceptional rock-fall activity in the Alps during the summer of 2003 (Rosenzweig et al., 2007).

d. *Sea ice*

The strong reduction of Arctic sea ice is already affecting the population of the iconic polar bears. There are initial signs of increased navigation in northern routes, which might raise issues of water sovereignty. More offshore oil operations are to be expected as well. An increase in sea traffic and oil operations can produce positive economic impacts but increased pollution as well (Rosenzweig et al., 2007).

e. *Ocean freshening, circulation and ecosystems*

In the North Atlantic and in the Ross Sea an ocean freshening has been reported, which is probably related to glacier melt. Impacts in ocean ecosystems have ben reported, such as krill biomass reduction and salp increase in Antarctica, and reduction of marine algae in the Arctic due to replacement of freshwater species (Rosenzweig et al., 2007).

f. *Lake and river ice*

The shortening of the freezing period of 12 days measured in the last 150 years in lake and river ice in the northern hemisphere should impact ice skating, and potentially affect freshwater hydrology and winter transportation as well. There is a reported reduction in ice jam floods due to a decrease in freshwater freezing. Increased melt can also result in more intense ice jamming due to more frequent break-up events, but there is no evidence for this yet. Changes in thermal structure and quality/quantity of habitation under the ice has been reported in lakes, together with changes in suspended particles and chemical composition. These changes may in turn have effects on lake ecology.

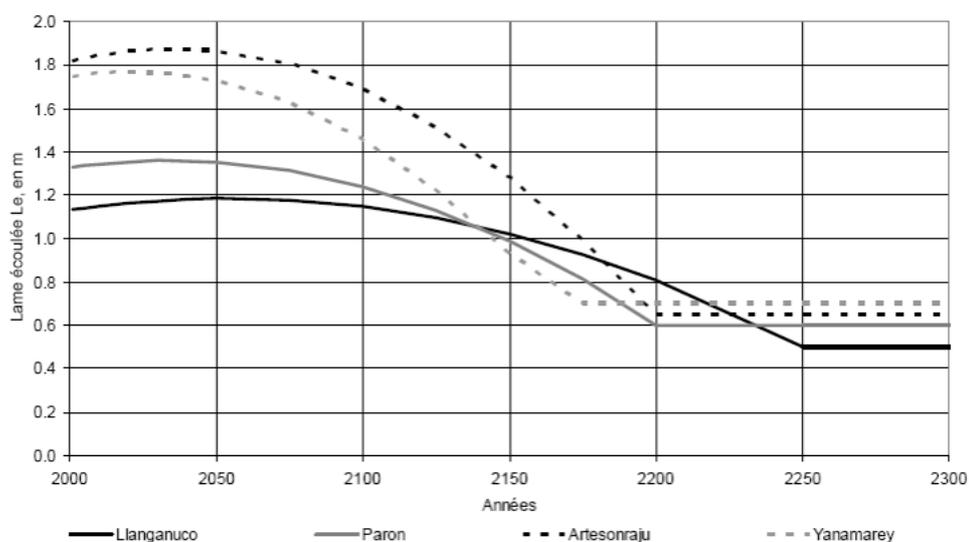


Figure 8. Runoff simulation for the period 2000-2300 for 4 glacierized basins in Cordillera Blanca, Peru under a warming scenario. Runoff increases in the short-middle term as glacier melting is enhanced. After a few decades the glaciers are reduced below a certain critical level, and runoff starts to decrease until a base level is reached after the glaciers completely disappear. The smallest glacier is Yanamarey (1 km²), which is predicted to disappear in the year 2175, while the largest glacier, Llanganuco (33.7 km²), is predicted to disappear in 2250. Source: Fig. 11 of Pouyaud et al., 2005.

4. Conclusions

A significant melting and reduction of all cryospheric components has been observed globally, including snow, ice and frozen ground. In turn this has produced relevant impacts in physical, biological, and chemical systems, in indigenous livelihoods in the Arctic, and in human activities such as sport and tourism in alpine areas. Future warming scenarios will result in an amplification of all these effects, leading possibly to major impacts such as the extinction of polar/high altitude species, destruction of infrastructure in permafrost terrain, destructive rock avalanches, and increased glacial lake outburst floods. Positive effects such as increased sea traffic and offshore oil operations will probably be offset by enhanced contamination.

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