The Earth’s Cryosphere and Sea Level Change

Introduction

Following the establishment of an Earth Science Initiative at ISSI, ISSI is planning to arrange a workshop on the Earth’s Cryosphere and Sea Level Change. The purpose of the workshop is to provide an in-depth insight into the future of mountain glaciers, ice caps and the Greenland and Antarctic ice sheet and permafrost as exposed to natural climate variations and human effects such as increasing greenhouse gases and aerosols and the effect this will have on sea level change.

There are several important scientific issues to address including to better identify the natural variability of the mass balance of glaciers and land ices and to determine the risk for a larger increase of sea level rise in the 21st century. Under present long-term scenarios in atmospheric forcing what long-term equilibriums or quasi-equilibriums might be expected?

Background

Cryosphere

The mass exchange between the Earth’s cryosphere and the ocean is one of the most important processes regulating the sea level. In the current warming climate, the cryosphere is also expected to play a major role in the future sea level rise. The Antarctic ice sheet with its mass and the surface area is considered to play the most significant role. Although the total mass balance of this ice sheet is not known, sufficient information about the total mass balance of the Antarctic ice sheet exists for a reliable present and near-future mass balance of the Antarctic ice sheet.

The mass balance of the Greenland ice sheet is better known than for the Antarctica. The former’s surface mass balance is well investigated. However, the understanding of the total mass balance is still hampered, mainly because of the current difficulty of assessing the sub-glacier mass balance. Some new investigations in this direction are at a sufficiently mature stage to be integrated into the total mass balance.

Mountain glaciers and ice caps constitute only 3% and 0.3% of the global glacier surface area and volume, respectively. The importance held by these glaciers is more than these statistics might indicate. These glaciers react quickly to the current warming because they lie in relatively warm climatic zones. The mass balances of these glaciers are most intensely investigated and assumed to be best understood. There is a grave sampling problem for the mass balance studies of the glaciers of this type. Only about 400 of estimated 200,000 glaciers are being investigated. Of these only about 100 glaciers have been observed for a period longer than three decades. All glaciers whose annual mass balances have been investigated for more than three decades lie in regions with small accumulations. New methods are being developed to investigate mountain glaciers and ice caps on a global scale.

An amount of ice comparable to the amount held by mountain glaciers and ice caps is locked in the permafrost. The melting permafrost may make a significant contribution to the sea level
change as a large temperature rise is expected in the present permafrost regions. Discharge from the melting permafrost may flow directly into the ocean. The remaining melt water may stay in depressions to form swamps accelerating the methane emission. A quantitative estimate of the melt of permafrost in the near future, and its hydrological consequences are urgently needed.

A realistic estimate of future sea levels will by achieved by the cooperation between scientists investigating the above and other aspects of the Earth’s cryosphere and the ocean.

The IPCC 4th Assessment report (IPCC, 2007) devoted considerable attention to the Earth’s cryosphere. There are several important issues including Arctic sea ice, permafrost, mountain glaciers, ice caps and the large land ices on Greenland and Antarctica.

A possible melting of the land ices would lead to innumerable problems for the world as this would mean the sea level will rise some 70 m setting huge amount of land under water. The summary given by IPCC is based on climate model experiments that calculate the changes in the mass balance.

The results for Greenland (IPCC, 2007, table 10.7) give a rather modest sea level rise due to a negative mass balance between the last decades of the 20th and 21st century. The results in sea level rise for all models fall between 0.01m and 0.12m (5-95% probability). This is more or less compensated for by increasing mass balance for Antarctica due to larger net accumulation at higher temperatures.

However, irrespective of curbing the emission of greenhouse gases at the end of the 21st century the melting of Greenland will continue reaching some 0.90 m at 2300 while the net accumulation at Antarctica will reduce this to 0.60 m (Result from the ECHAM5 model at the Max Planck Institute in Hamburg using scenario A1B). (Fig. 1). For a longer term assessment see (Charbit et al., 2008).

The somewhat sobering results from IPCC, 2007 has recently been questioned (e.g. Thomas et al., 2006, Velicogna and Wahr, 2006). A series of satellite and aircraft based measurements indicate a rapid melting on Greenland during recent years related to processes not yet included in the models used by IPCC. These are related to rapid thinning and retreat of Kangerdlussuaq and Helheim glaciers in the south-east and Jakobshavn in the south west of Greenland (Joughin et al., 2004; Howat et al., 2007; Holland et al., 2008; Nick et al., 2009; Kerr, 2009). Possible mechanisms such as hydraulic acceleration of the ice sheet due to continued warming remains incompletely understood, including the infiltration of surface melt water (via moulins) providing a dynamical effect of the movement of the ice (Zwally et al., 2002; Joughin et al., 2008; Das et al., 2008; van de Wal et al., 2008; Shepherd et al., 2009).

The observational studies include gravimetric satellite date (GRACE), satellite radar interferometry and laser altimetry from airplanes suggesting an overall loss of 100 Gton/year over the last decade 1995-2005 (Shepherd and Wingham, 2007) and in some years more than twice that amount (Rignot and Kanagaratnam, 2006). The largest mass losses are generally indicated as being from low elevation (<2000m) and especially in southeast Greenland, with partly compensating mass gains at higher elevations (>2000m) (Luthcke et al., 2006). Other altimetry data suggests that there appears to have been a substantial growth of the ice in the interior 1992-2003 (Johannessen et al 2005, Thomas et al, 2005, Zwally et al 2005).
Whereas satellite observations have shown enhanced melting associated with increase of melt extent and melt-season length (e.g., Steffen et al., 2004; Hall et al 2006, 2008; Tedesco 2007; Mernild et al., 2009).

Modeled data of mass balance based on ECMWF operational and re-analysis products also indicate rising trends in both precipitation and runoff (Box et al., 2006; Hanna et al., 2008; Fettweis, 2007).

Johannessen has stressed the large internal variability related to storm track variations. Recent high resolution global modeling (MPI, Hamburg, unpublished) using a resolution of some 30 km indicate considerable mass balance variations for the years 1979-2001 (fig 2) (net gains of 60km$^3$ and net losses of 120km$^3$) which statistically are in agreement with recent result, Johannessen et al 2008 (in verbatim)

Needless to say, the report of rapidly retreating glaciers on Greenland has attracted both media and political interest and created a view that the situation is serious and urgent (Hansen, 2007). We do not know yet whether this is the case. A key purpose with the ISSI workshop is to increase our knowledge and to provide a strategy towards improving our knowledge. Due to the high internal variability in the storm tracks around Greenland there are considerable inter-annual variations in the net mass balance. Furthermore there are also reasons to believe that many of the glaciers on Greenland undergo chaotic variations with occasional rapid movements. The fact that this has only recently been possible to observe from space might have created an impression that what has happened in recent years is unique.

The situation for Antarctica is more complex. The mass balance of Antarctica is determined from the difference between two competing processes of ice discharge into the ocean by glaciers and accumulation of snowfall constituting two large numbers with significant uncertainties undergoing considerable variations on different time scales. An example of the variability in net accumulation mainly due to atmospheric circulation can be seen in Fig 3. The most estimates of mass balance using altimetry and GRACE measurements indicate mass gain and mass loss respectively in East and West Antarctic (e.g. Davis et al., 2005; Zwally et al., 2005; Ramillien et al., 2006). Strong warming has been observed in the Antarctic Peninsula region, contributing to the break-up of the Larsen B and Wordie ice shelves and associated ice-flow acceleration (e.g. Scambos et al., 2004; Shepherd et al., 2004). Comparison of regional models and radar interferometry (Rignot et al., 2008) indicates both the progress of ongoing work as the complexity of the processes.

**Sea level change**

Since the Last Glacial Maximum around 20,000 years ago, MSL has risen worldwide by about 120 meters. A consensus seems to have been achieved that the 20th century rise in global sea level was closer to 2 than 1 mm/year, with values around 1.7 mm/year having been obtained recently for the past century (Cazenave and Nerem, 2004; Church and White, 2006) or past half-century (Church et al., 2004; Holgate and Woodworth, 2004). However, the rate of change was far from constant, with an acceleration around 1920-1930, a deceleration after 1960, and a relatively recent acceleration in the 1990s (e.g. Woodworth et al., 2008; Douglas, 2008). The high rate in the latter period of over 3 mm/year was observed not only by tide gauges but also by satellite altimetry (Beckley et al., 2007). A longer-term acceleration
appears to have taken place between the 18th and 19th centuries into the 20th century, based on the small number of available long European tide gauge records (Woodworth, 1999; Jevrejeva et al., 2008) and on complementary data from salt marshes (e.g. Gehrels et al., 2006). However, there are considerable spatial and temporal sampling issues connected to all of these reported rates (cf. Figure 1 of Wunsch et al., 2007).

MSL is often described as an 'integrator parameter', providing an integration of many climate-change related processes i.e. global warming leading to oceanic thermal expansion, glacier and ice cap melt, modifications to hydrological exchanges between land and ocean etc. Consequently, if MSL is changing, it points to major changes in one or more of the drivers of that change. Ultimately, anthropogenic climate change appears to be the fundamental issue, although the attribution of the ‘budget’ of sea level rise remains a major research question (Bindoff et al., 2007). Potential effect of ice sheets on sea level rise is considered, e.g., in Pfeffer et al., 2008; Mitrovica et al., 2009; Stammer, 2008.

**Sea level budget**

Recently Cazenave et al., (2009) have undertaken studies including the use of data from GRACE as to the different contributions to sea level rise in the period 2003-2008. Results are summarized in the table 1. Values in mm/year.

<table>
<thead>
<tr>
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<th>Value ± Error</th>
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<tbody>
<tr>
<td>Sea level (altimetry)</td>
<td>2.5 ± 0.4</td>
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<tr>
<td>Ocean mass (GRACE)</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td>Ice sheets (GRACE)</td>
<td>1.0 ± 0.15</td>
</tr>
<tr>
<td>Glaciers and ice caps (Meier et al., 2007)</td>
<td>1.1 ± 0.24</td>
</tr>
<tr>
<td>Terrestrial waters</td>
<td>0.17 ± 0.1</td>
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<tr>
<td><strong>Sum of ice and waters</strong></td>
<td><strong>2.2 ± 0.28</strong></td>
</tr>
<tr>
<td>Sea level (altimetry – GRACE)</td>
<td>0.31 ± 0.15</td>
</tr>
<tr>
<td>Steric sea level(Argo; 04-08)</td>
<td>0.37 ± 0.1</td>
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While these figures broadly agree it is important to recognize that this depends a lot on the GIA, (Glacial Isostatic Adjustment) in GRACE. However, by alternative methods to estimate some of the terms the accuracy should be possible to improve.

Finally it is important to note that the largest contribution comes from the eustatic part perhaps because as significantly less energy is needed to melt ice than to warm the bulk of the oceans. Other indications are from the freshening of sea water (Munk, 2003)

**ISSI Book**

The outcome of the workshop will be published by ISSI following the same procedure as used for its Space Science Series which are reprinted from Space Science Reviews or Surveys in Geophysics (See [http://www.issibern.ch/publications/ssi.html](http://www.issibern.ch/publications/ssi.html))
Fig 1 Change in sea level. Contribution from Greenland (red), from Antarctica (blue). Total contribution (black). ECHAM5 model, IPCC Scenario A1B, MPI, Hamburg
Fig 2 Annual mass balance for Greenland during 22 years. T319 equivalent to ca 30 km grid. Model driven by SST from a model run at lower resolution (T63).

Fig 3 Annual mass balance for Antarctica during 22 years. T319 equivalent to ca 30 km grid. Model driven by SST from a model run at lower resolution (T63).
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