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EDITORIAL

Foreword: International Space Science Institute (ISSI) Workshop on the Earth's Cryosphere and Sea Level Change

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Rising sea level is perhaps the most severe consequence of climate warming, as much of the world's population and infrastructure is located near current sea level (Lemke et al. 2007). A major rise of a metre or more would cause serious problems. Such possibilities have been suggested by Hansen and Sato (2011) who pointed out that sea level was several metres higher than now during the Holsteinian and Eemian interglacials (about 250,000 and 120,000 years ago, respectively), even though the global temperature was then only slightly higher than it is nowadays. It is consequently of the utmost importance to determine whether such a sea level rise could occur and, if so, how fast it might happen.

Sea level undergoes considerable changes due to natural processes such as the wind, ocean currents and tidal motions. On longer time scales, the sea level is influenced by *steric* effects (sea water expansion caused by temperature and salinity changes of the ocean) and by *eustatic* effects caused by changes in ocean mass. Changes in the Earth's cryosphere, such as the retreat or expansion of glaciers and land ice areas, have been the dominant cause of sea level change during the Earth's recent history. During the glacial cycles of the last million years, the sea level varied by a large amount, of the order of 100 m. If the Earth's cryosphere were to disappear completely, the sea level would rise by some 65 m.

The scientific papers in the present volume address the different aspects of the Earth's cryosphere and how the different changes in the cryosphere affect sea level change. It represents the outcome of the first workshop held within the new ISSI Earth Science Programme. The workshop took place from 22 to 26 March, 2010, in Bern, Switzerland, with the objective of providing an in-depth insight into the future of mountain glaciers and the large land ice areas of Antarctica and Greenland, which are exposed to natural and anthropogenic climate influences, and their effects on sea level change. The participants of the workshop are experts in different fields including meteorology, climatology, oceanography, glaciology and geodesy; they use advanced space-based observational studies and state-of-the-art numerical modelling.

Present assessments of sea level height reported in this volume (Church and White 2011; Woodworth et al. 2011) show that sea level rise has been going on at least since the

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middle of the nineteenth century, with a tendency towards an acceleration during the last decades. The global averaged increase in sea level during the last 150 years amounts to 20–25 cm. The sparse and irregular observational records and difficult sampling due to local variations, such as caused by wind and ocean currents, complicate the accuracy of this estimate. Accurate estimates are also compromised by geodetic changes, including an ongoing rise of the land, especially in areas that were glaciated during the last ice age.

Since 1993, sea level height has been monitored from space by radar altimetry measurements that have led to a significant improvement in accuracy. There is a general agreement (e.g., Nicholls and Cazenave 2010; Church and White 2011) that the mean sea level rise during the last 17 years is approximately 3 mm/year. There are minor variations from year to year, but no significant change in the trend has been determined for the period during which we have space observations. Thanks to the recent development of gravity measurements made from space and vertical temperature soundings of the oceans, it has been possible to identify separately the mass and volume changes of the oceans; the steric and eustatic components of sea level change have thus been quantitatively determined.

Observations show that sea level rise is slowly accelerating, and the present trend is well above the mean trend of the last century. The latest results, including those obtained using space-based gravity techniques, show in fact that the present sea level rise is dominated by the increase in ocean mass due to melt water (about two-thirds) and the remaining third by thermal expansion of seawater. The melt water comes from mountain and coastal glaciers and parts of the large land ice masses. Present observations and model studies show ongoing mass losses of glaciers worldwide, together with a net loss of mass of the land ice from both Greenland and Antarctica. Whether this is only a temporary effect cannot yet be determined because of the short observational record. The storage of water on land in lakes, dams and aquifers also undergoes changes, but the gains and losses broadly compensate each other.

A particular concern in recent years has been the indications of the rapid acceleration of some of the large glaciers on Greenland and Antarctica which suggest larger net losses than previously estimated. These indications have been supported by different space measurements including those from ICESat and GRACE. Although the mechanisms are not fully understood, it appears that higher ocean temperatures at the outlet of the glaciers at the coast is a dominant process, while the percolation of melt water through the land ice is seen as being of secondary importance.

Recent modelling results with a more detailed representation of non-linear dynamical effects influencing the deformation of the ice flow seem to imply counteracting processes that swiftly can decelerate the flow. Thus, *periodically accelerating and decelerating glaciers might be part of their natural behaviours*. Needless to say, this must be further explored; it justifies the continuous monitoring of the dynamics of the land ice masses as well as their detailed modelling.

Under the assumption of a continued warming as a consequence of increasing concentrations of greenhouse gases in the atmosphere, the sea level is expected to continue to rise. Most model estimates suggest a modest acceleration of sea level rise towards the end of the twenty-first century compared to now. In this respect, recent studies reported at the workshop support the IPCC report (2007) giving likely values for a middle-of-the-line-scenario of 20–50 cm. The view of the workshop is that detailed numbers are difficult to justify as both climate models and the scenarios are changing. There are no scientific reasons that the range might narrow; rather it might widen as more aspects of the climate system are considered. *Instead, it is more sensible to make risk assessments, not predictions.*

However, there are severe worries what might happen in the next century and later. In the case of Greenland, model studies indicate several equilibria, with different amounts of land ice maintained at higher temperatures but also *different thresholds of irreversibility* where the land ice after a major melt is unable to recover. It is thought that the first of such thresholds might occur after a 10% loss of the mass of ice on Greenland.

While global sea level rise is an integrated measure of climate change, the concern of sea level change is foremost an issue affecting specific local areas that could be a consequence of natural processes. Here, sea level is influenced by ocean currents and wind patterns as well as by ongoing tectonic processes. There are regions where sea level has been rising and others where the sea level has been falling over longer periods of time. Such local trends over the last decades might be *several times larger* than the global mean trend of 3 mm/year.

A fundamental problem facing virtually all Earth system studies today is the need for long-term observations and monitoring as well as better and more relevant observations. *The dilemma is that the time scale of the internal mode of variability of the system is significantly longer that the lifetime of a dedicated space mission, which makes it extremely difficult to separate a climate signal from the noise of natural processes*. We are, for example, not able to establish whether the recent marked mass losses noted by GRACE and ICESat on Greenland are robust signals or not. This calls for a dual strategy combining new space missions with continued and extended measurements by space instruments whose performance and value has already been proved.

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