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There are indications that the Greenland ice sheet may respond more rapidly to global warming than anticipated even a few years ago (Zwally et al., 2002; Alley et al., 2005; Howat et al., 2005; 2007; Joughin, 2006; 2008; Das et al., 2008). The rise of sea level appears to have accelerated since 1993 (Nerem et al., 2006) and is now near the upper end of the range projected in recent estimates by the Intergovernmental Panel on climate Change (see Rahmstorf et al., 2007). Recent observations show changes in marine terminating glaciers with beds below sea level, where dynamical instabilities including rapid ice flow and calving are becoming more common. This has been documented for Greenland (Rignot and Kanagaratnam, 2006; Howat et al., 2007; Stearns and Hamilton, 2007), Antarctica (Rignot et al., 2008) and Alaska (e.g. Meier and Post, 1987). While the importance of the calving glaciers to the cryosphere's mass budget is thereby established, these dynamics have not yet been fully incorporated into ice flow models.

Linear extrapolation of sea-level rise since 1993 yields a rise of sea level of around 30 cm by the end of the 21st century. However, the geologic record of past sea-level rises in the last half million years suggests that ice sheets can deteriorate sufficiently rapidly to yield rates of up to 2 m per century for several centuries in a row. Sustained rates of more than 1 m per century are seen even for situations when the past sea level was close to the present high level (Rohling et al., 2008; Berger, 2008). Thus, the uncertainty of future sea-level rise is quite large at present (as also noted by IPCC, 2007), owing to a large degree of uncertainties in the dynamics of outlet glaciers draining the major ice sheets. Apparently, in Greenland, a few of such glaciers have a major effect in this respect. Many of the recent observations suggest these dynamics are intimately related to the changing conditions in the fjords into which the glaciers terminate (e.g. Motyka et al., 2003; Bindschandler, 2006). The question is what kind of information needs to be collected to decrease the range of uncertainty materially.

Workshop participants addressed this question from the point of view of detecting acoustic signals from calving glaciers and changes in the hydrography of the fjords into which the glaciers terminate. Participants were geophysicists specializing in hydro-acoustics, glaciologists, seismologists and marine geologists from Germany, the U.S.A., the Netherlands, Norway and Denmark.

The issue emerging in this context is the influence of ocean temperatures on the stability of the outlet glaciers. With the ongoing and anticipated rise of ocean temperature the question arises whether a rising rate of calving would engender an acceleration of glacier motion near the fjords and ultimately to an increase in the rate of draining of the ice fields upstream. As stated in the 4th Assessment Report of the IPCC, if such processes are not incorporated into the models, the possible future mass-loss on Greenland cannot be fully captured within the estimates. As a corollary, they provide for estimates of anticipated sea-level rise that tend to be on the low side of the possible range.

Accepting that ice-ocean interactions within Greenland fjords are a key element of ice-sheet stability (e.g. Motyka et al., 2003; Bindschandler, 2006), we propose that intensified studies of fjords with glacier termini can contribute substantially to improved understanding necessary for credible prediction of the future of Greenland ice sheet. In practice, this means that changes in the conditions in "glacier fjords" need to be recorded over a suitable time span (several years) and related to changes in the activity of the associated glaciers. The item of central importance in this context would seem to be the import of heat from the open sea into the fjord. The question is whether this parameter can be constrained by measurement, and just how this is to be achieved.

Clearly, the environment of fjords with glacier termini is not well suited for making series of routine measurements regarding temperature and salinity distributions and flow patterns as a function of seasons, tides, and changing weather conditions. The sites of observation are far from the research centers involved; and relatively large ships are necessary to get there. In addition, the weather and conditions are inclement at times, and there is non-negligible risk of losing equipment along with recorded data.

Considering the need for information from glacier fjords, and the difficulties for access and reliable deployment of instruments, there is much opportunity for novel approaches for quantitative observations, on which heat-transport estimates might be based. Such novel approaches could include the long-term deployment of hydro-acoustic instruments and pressure gauges in selected portions of a glacier fjord, in addition to traditional instruments for recording temperature and salinity. Hydro-acoustics could be employed both for passive listening (related for example to calving, iceberg collision, tidal flow and sediment transport, wind action) and active echo-sounding (e.g., Doppler detection of water and ice motions).

Presumably, with proper calibration, ice-generated sounds can be related to changing rates of calving events. Integration of simultaneously acquired hydroacoustic and land-based observations with ice-flow modeling efforts will reduce the uncertainties associated with the future behaviour of outlet glaciers and the Greenland ice sheet.

We propose a two-stage strategy for the study of ocean-ice interactions. The first strategy is process-oriented. Its goal is to establish ground rules regarding the most likely modes of interactions between outlet glaciers and the fjords that contain their termini. For this purpose it is necessary to concentrate on studying selected, well-chosen examples of glacier fjords with the proper size and setting and where complementary information is gathered, and has shown considerable activity. In such fjords, studies over a limited time can yield important insights for linking ocean and ice processes.

In the second stage, the calibrations obtained in the first stage are applied to long-term observations, where “long term” refers to periods between 5 years and a decade. These studies should still be regarded as pilot projects for the exploration of feasibility. They will have to be closely coordinated with investigators observing various aspects of the behavior of ice sheets, including seismic activity, and rates of flow of ice streams. The additional studies here proposed also need to be closely linked to the needs of the modeling community.

In summary, we propose that a comprehensive approach to the anticipated wasting of Greenland ice sheets includes increased attention to the processes occurring at the termini of outlet glaciers in marine fjords, with some emphasis on the heat import into the fjords involved. Because of difficulties in deploying instruments in that environment, we propose that novel approaches, using long-term recording on the sea floor and including acoustic devices, should be investigated.

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