European Science Foundation
SETTING SCIENCE AGENDAS FOR EUROPE

Exploratory Workshops Scheme

Standing Committee for Life, Earth and Environmental Sciences (LESC)

ESF Exploratory Workshop on

Improving Estimates of the Rate of Sea-Level Rise from the Greenland Ice Sheet

Cala Millor, Mallorca, Spain, 27-29 May 2008

Convened by:
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Main Objectives of the Workshop:

The Greenland Ice Sheet (GrIS) is changing rapidly, and contributing to global sea level rise. Greenland's outlet glaciers have thinned dramatically, mainly because of poorly understood ice dynamic and surface processes. The ice sheet models used to predict sea-level do not include these processes, and consequently under-estimate Greenland's future contribution to sea-level rise. This ESF Exploratory Workshop brought together Europe's leading observational glaciologists, remote sensing experts, ice sheet modellers and meteorologists to assess the current state of knowledge in the mass balance of the GrIS, and to prioritise research needs in order to improve model predictions of the rate of future sea-level rise from the Greenland Ice Sheet. The workshop is expected to lead to the development of proposals, including a European Framework 7 proposal, to address these research priorities.

Executive summary (approx. 2 pages)

Introduction and aims

An annual average temperature rise of >3 ºC is likely to cause an irreversible melting of the Greenland Ice Sheet (Gregory *et al.* 2004), which would eventually raise sea-level by ~6.7 m. Most reasonable emission scenarios result in a 5-7 ºC temperature rise in the Arctic by the end of the 21st century (ACIA 2005; IPCC 2007). Already the decade of the 1990s was the warmest in the Arctic since instrumental records began (ACIA 2005). Current models suggest the deglaciation of Greenland in response to such elevated temperatures should occur slowly over 1000s of years (e.g., Alley *et al.* 2005), but the models used do not include recent observed changes in ice dynamics, "because a basis in published literature is lacking" (IPCC 2007). Our lack of understanding of these ice dynamic processes means that these models will consistently under-predict the rate of sea-level rise from Greenland.

This workshop brought together 23 researchers, who included Europe's leading observational glaciologists, remote sensing experts, ice sheet modellers and meteorologists to assess the current state of knowledge in the mass balance of the Greenland Ice Sheet, and to prioritise research needs in order to improve model predictions of the rate of future sea-level rise from the Greenland Ice Sheet. Attendees mixed those currently working on Greenland, with those with proven expertise, but not yet working on Greenland, and with early career scientists. The workshop was considered a great success by attendees and is expected to lead to the development of proposals, including a European Framework 7 proposal, to address these research priorities.

Current state of knowledge

The margins of the Greenland Ice Sheet have in the last decades shown dramatic and unexpected shifts in the balance of ice discharge, surface melt, and accumulation. These shifts have included glacier thinning at rates of more than ~1.5 m yr^{-1} (Krabill *et al.* 1999, 2000, 2004), and in some cases up to 10 m yr^{-1} (Abdalati *et al.* 2001), rapid glacier accelerations and decelerations of up to ~100% (e.g., Howat *et al.* 2005, Rignot & Kanagaratnam 2006, Luckman *et al.* 2006, Howat *et al.* 2007), and increases in the area of the ice sheet subject to summer melt (Steffen *et al.* 2004). In the same period, the central portion of the ice sheet has remained approximately in balance (Krabill *et al.* 2000) or thickened slightly (Johannessen *et al*. 2005). Overall, however, water storage in the Greenland Ice Sheet appears to be dominated by the ice marginal areas, and the ice sheet is losing mass, and therefore contributing to global sea-level, at an accelerating rate (Cazenave 2006, Chen *et al.* 2006, Luthcke *et al.* 2006, Velicogna & Wahr 2006; Fig. 1). However, the observations on which these estimates are based have largely come from remote sensing studies which are of very short duration, so that we do not know whether the changes are profound or simply represent short term fluctuations.

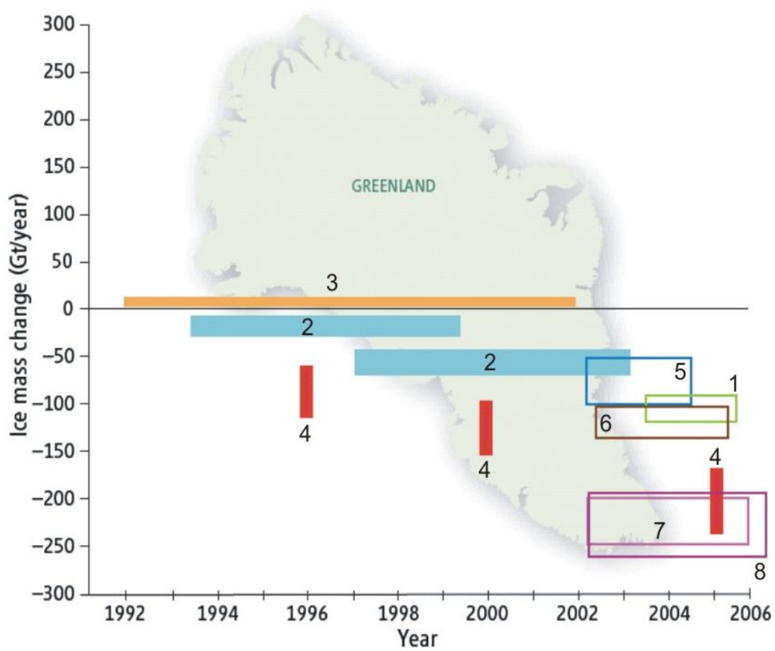

Fig. 1: Estimates of the overall mass balance of Greenland. Almost all estimates are negative (mass loss) and the mass loss appears to be accelerating through time. 1=Luthcke *et al.* 2006; 2=Krabill *et al.* 2004; 3=Zwally *et al.* 2005; 4=Rignot & Kanagaratnam 2006; 5=Velicogna & Wahr 2005; 6=Ramillien *et al.* 2006; 7=Chen *et al.* 2006; 8=Velicogna & Wahr 2006. Open boxes (1, 5, 6, 7, 8) use GRACE data; closed bars are from other techniques. Note the differences between estimates, even those using the same data, and the short duration of all these estimates. After: Cazenave 2006.

Change in the amount of water stored in a glacier or ice sheet is known as the mass balance. The mass balance depends on mass loss or gain due to ablation and accumulation (the so-called surface mass balance, SMB), as well as the ice dynamics which control how rapidly ice is transported down glacier from regions of mass accumulation to lower elevations where the ice can melt or be calved as icebergs. In Greenland about a third to a half of the mass loss is through surface melt and runoff, while the remainder is controlled by the ice dynamics and is calved from the fast flowing outlet glaciers (Ohmura & Reeh 1991, Rignot & Kanagaratnam 2006).

The surface mass balance of Greenland is known to be highly variable, for example, 2002–03 was a year of unexpectedly high snowfall in south-east Greenland (Krabill *et al.* 2004), and 2005 was a year of record melt (http://cires.colorado.edu/science/groups/steffen/). Even so the difference between snow accumulation and meltwater run-off cannot account for the thinning rates that have been measured on many glaciers (e.g., Thomas *et al.* 2000) and changes in ice dynamics are thought to be the cause (e.g., Rignot & Kanagaratnam 2006). In west Greenland, Jakobshavn Isbrae seems to have crossed some threshold causing this previously stable ice mass to become unstable (Echelmeyer and Harrison, 1990, Joughin *et al.* 2004, Luckman & Murray 2005), whereas Helheim and Kangerlugdssuaq, in east Greenland speeded up by around 50-100% for several years and have now slowed down again (Howat *et al.* 2005, Luckman *et al.* 2006, Howat *et al.* 2007). While these dynamic changes have surprised glaciologists, two processes are likely to be involved: firstly, seasonal surface meltwater reaching the glacier bed can reduce basal friction and induce changes in flow rates (Zwally *et al.* 2002); secondly, changes in marginal conditions of tidewater glaciers affect the backstress and hence the glacier flow rate. Neither of these processes is included in the ice sheet models currently used to estimate future rates of sea-level rise.

During glacier movement some energy is released in the form of seismic emissions originally thought to be due to the interaction with the bed, but now known to be associated with iceberg calving events. Ekström *et al.* (2003, 2006) located the source of long period seismic waveforms seen on the global seismological network that were not included in standard international earthquake catalogues. A large number of these events originate from beneath outlet glaciers in Greenland, and they vary seasonally, with more being detected in the summer months when surface meltwater would be expected (Ekström *et al.* 2006). They are thus ascribed as “glacial” earthquakes, and they potentially provide a record of the location, timing, amount and mechanism of ice movement. Such geophysical measurements, together with seismic and radar surveys, have strong potential for informing us about changes at the glacier bed beneath outlet glaciers, the key unknown in ice dynamics.

Future changes of the Greenland Ice Sheet under projected climate warming are based on 3D ice sheet models that include ice dynamics, thermodynamics and glacial isostacy (e.g., Huybrechts 2002). These models currently include the effects of SMB changes on ice dynamics through changes in geometry alone (ice thickness and slope; Huybrechts *et al.* 2004) and use the outputs of GCM simulations as the mass balance forcing. However, the rapid changes in outlet glacier dynamics that have been observed in recent decades cannot be reproduced and are not included. Both the 2005 Arctic Climate Impact Assessment and 2007 IPCC Report identify improved projections of the future mass balance of Greenland, and in particular of the controls on outlet glacier dynamics, as critical research needs.

Need for an ESF Workshop to co-ordinate a European response

These critical research needs are of great importance to society in predicting the rate of future sea-level rise. This is a key time for Europe to mobilise its great research strength in this area, and we believe this ESF workshop was the ideal catalyst for this process. Europe's considerable expertise on the Greenland Ice Sheet has never been targeted in such a way. Yet in the USA, programmes such as PARCA (Program for Regional Climate Assessment), show the power of combining research expertise, with the sum contribution greatly exceeding that which can be generated by individuals or isolated groups.

Three International Polar Year (IPY) 2007-8 umbrella projects address this research area, all co-ordinated solely or jointly within Europe: "Glaciodyn" (co-ordinated Oerlemans), "MARGINS" (joint co-ordinator Murray) and "The Greenland Ice Sheet – Stability, History and Evolution" (co-ordinator Dahl-Jensen). The ESF workshop in May 2008 occurred about half-way through the International Polar Year allowing assessment of the status quo. This is critical to determining future research priorities. The three IPY project convenors were invited to the workshop, although only one attended. The workshop timing should allow submission of projects for funding calls with closing dates in 2008.

The overall workshop aim was to lead to collaborations that would produce a set of proposals that address the critical research gaps that are needed to improve predictions of sea-level rise from the Greenland Ice Sheet. These proposals will include one to EU Framework 7.

Scientific content of the event (minimum 1 page, no abstracts)

The summary below is based on bullet points agreed by all members of the meeting. In many cases the discussions highlighted the data or knowledge required to improve our estimate of the contribution of the Greenland Ice Sheet to sea level.

Surface mass balance:

The surface mass balance was acknowledged to be poorly constrained, and the different models and compilations produce very different results (**Edward Hanna**, **Jon Bamber**), especially in some key areas such as the south-east coastal region (**Michiel van den Broeke, Roderik van de Wal**). Despite this **Edward Hanna** emphasized the significant areas of agreement between models (Hanna, Fettwies, Box and McConnell time series). The talks and discussion in this session emphasized the uncertainties in the contribution from land-ice in Greenland to sea level rise, and they recognized that this estimate must include both local glaciers and ice caps as well as the main ice sheet. Many processes are still poorly constrained, and therefore cannot yet be included in models (**Carl Egede Bøggild**). **Niels Reeh** presented a new melting / refreezing model. These processes can also be studied on other Arctic ice caps, such as those in Svalbard, where logistics may be simpler (**Jon-Ove Hagen**, **Carl Egede Bøggild**).

- SMB not well constrained, needs testing especially in critical areas (such as SE coast where accumulation/ablation gradients differ in different models); scenarios very different especially using different melt schemes
- Spatial albedo + 'background' dataset
- Acknowledge the uncertainties in all land ice contributions to sea level rise
- Need to understand both local glaciers and ice sheet in Greenland
- Arctic ice caps can help explain Greenland small glaciers and improve process understanding
- Analogue and process studies needed

Remote sensing of volume changes:

Discussions in this session highlighted a number of limitations of current data sources. The first was that the **length of many of the records is very short** especially those from satellites, including

GRACE). Thus we do not as yet have a good feeling for the natural variability of the system versus any climate driven trend. The need for longer term records (such as those derived from historical aerial photographs – a technique presented by **Tim James**) was highlighted as a research priority. The second was the differences in the estimates from different groups processing GRACE data (**Jon Bamber**), although it was also stressed that the gap between different methods is closing (**Anny Cazenave**), and often differences are the result of averaging over different periods of time. Aircraft altimeters provide a time series that is of significantly longer in scope and provides coverage of the marginal areas that are too steep to image using satellite sensors (**Rene Forsberg**). Systematic differences between different satellite altimeters were presented by **Kirill Khvorostovsky**. Overall records show thickening of the interior of the ice sheet and shrinkage around the margins, suggesting increases in both accumulation and ablation rates.

- Length of time scale and understanding of variability (trend vs. cycle)
- Need to establish longer timescale records, for example those from archival photographs
- Better estimation of runoff to close sea level budget, need for process understanding of the signal (for interpretation)
- Better cooperative understanding of the difference between processing and satellite methods

Remote sensing of glacier dynamics:

Talks in these sessions emphasized the differences between controls on tidewater-terminating and land-terminating outlets, and emphasized the need to study both outlet types (**Adrian Luckman**, **Andy Shepherd**). The need for a database of ground observations to record ground-based observations was recognized, which can act as ground-truth for satellite and remotely sensed data. The latter were recognized to be the only methods to achieve wide-scale coverage. It is clear that we do not as yet know the seasonal response of the margins (both tide-water and land-terminating glaciers **Adrian Luckman**) and it is important to study these so that changes in velocity from remotely-sensed data can be put into context. **Kilian Scharrer** presented the latest velocity and volume change estimates from airborne altimetry of Helheim and Kangerdlussuaq Glaciers. Finally there was considerable discussion of the data required to characterize the processes controlling the dynamic response of glaciers. The need for specific study sites where these processes are studied and where the boundary conditions are known (or are established by future projects) was emphasized. **Tazio Strozzi** presented a summary of sensors and techniques for deriving glacier dynamics from SAR satellite data as well as results from a new land-based interferometry technique for measuring glacier dynamics.

- Need to understand seasonal forcing and response
- Establish a database of ground-based observations
- Study separately tidewater and land terminating outlets
- Process studies of: bedrock, temperature/viscosity, basal boundary conditions, parameterize from established 'study areas'

Geophysics, calving and tidewater interactions:

The controls on the dynamics of tidewater glaciers is one area that recent satellite observations have highlighted as poorly constrained. One aspect of tidewater terminating glaciers now seems to have been clarified: **Morten Langer Andersen** presented data that convincingly demonstrated that glacial earthquakes are the result of calving events. However, many aspects of outlet glaciers require further investigation before outlet dynamics can be fully incorporated into models. Overall neither the external controls (atmospheric and ocean / fjord controls, effect of sea ice), nor the internal controls (subglacial hydrology and basal geometry) are well understood. In order to include outlet glacier dynamics into ice sheet models, the bed geometry is needed for major Greenland outlet glaciers, which is a challenging task and various solutions to this problem were discussed. **Tavi Murray** showed results from Antarctica that demonstrate how radar can be used to image aspects of the basal hydrological system.

Martin Luethi presented a simplified 3D model of Jakboshavn Isbrae that reproduces some aspects of the recent behaviour of the ice stream simply by incorporating geometrical length changes into a finite element model. **Doug Benn** showed the results of a new 2-D process-based model of calving glacier dynamics that reproduces the past behaviour of Helheim Glacier convincingly. Analogues from other locales, such as Iceland, were also discussed (**Throstur Thorsteinsson**).

- Atmospheric vs. ocean/fjord controls on calving glaciers
- Sea ice effect on calving
- Better understanding of fjord processes
- Basal conditions, drag and hydrology
- Glacial earthquakes relate to iceberg calving

- Need for outlet bed geometry (use of active seismics, gravity or submarines)
- Develop and test models of calving glacier dynamics

Current ice sheet models of Greenland and their inclusion in Earth System models

Guðfinna Aðalgeirsdóttir gave an excellent summary of the state of knowledge regarding climate forcing of ice sheet models and their inclusion into Earth System models. Key aspects highlighted for development included the need for:

- Development of data bases/standards for model verification
- Interactive ice sheet-climate model
- Improved surface mass balance
- Improved ice dynamics
- Improved estimate for future sea level rise

Two areas which the attendees at the meeting felt should also be addressed in more depth were highlighted: these were modeling and oceanography.

Assessment of the results, contribution to the future direction of the field, outcome

Feedback on the meeting was consistently positive (one attendee said it was the best meeting he had ever attended).

Immediate Actions from the Workshop:
Were agreed by the participants to be

- This report on the workshop and its content for ESF
- An EOS report on the workshop
- ESF Research Networking Programme, 4-5 year programme, bid to be co-ordinated by Bøggild, Murray and van de Wal. Bamber also signaled that he would be happy to help. Deadline for this proposal is 23 October 2008. We recognize that these programmes are funded by the member organisations, so pre-warning of these organizations and some advance politicking would be wise!

Final programme

Talks were allocated 15 minutes, and in general discussion was not time limited. This produced a much more discussion-rich format than is usual at scientific meetings. There was also a frank admission of the limitations of various techniques, which greatly increased understanding of attendees who worked in complimentary areas of science.

Tuesday 27 May 2008

Morning Arrival at Hotel Sumba, Cala Millor and registration

12.30-14.00 Lunch

14.00-14.15 Introduction and domestic arrangements
Tavi Murray, Carl Egede Bøggild and Timothy James

14.15-15.00 Remote sensing observations of Greenland volume changes and mass balance

15.00-15.30 Coffee break

15.30-17.30 Remote sensing observations of Greenland volume changes and mass balance (continued)

19.00 Dinner and evening discussion (Hotel Sumba)

Wednesday 28 May 2008

09.00-10.00 Remote sensing observations of Greenland glacier dynamics

10.00-10.30 Coffee break

10.30-12.00 Remote sensing observations of Greenland glacier dynamics (continued)

12.00-12.30 Current ice sheet models of Greenland and their inclusion in Earth System models

12.30-14.00 Lunch

14.00-15.00 Surface mass balance, melt extent and runoff

15.00-15.30 Coffee break

15.30-17.00 Surface mass balance, melt extent and runoff (continued)

19.00 Dinner and evening discussion (Hotel Sumba)

Thursday 29 May 2008
09.00-10.00 Outlet glaciers, calving and tidewater interactions

10.00-10.30 Coffee break

10.30-11.00 Outlet glaciers, calving and tidewater interactions (continued)

11.00-12.30 Geophysical observations of Greenland outlet glaciers including glacial earthquakes

12.30-14.00 Lunch

14.00-15.00 Geophysical observations of Greenland outlet glaciers including earthquakes (continued)

15.00-15.30 Coffee break

15.30-15.45 Presentation of the European Science Foundation (ESF)
Olgeir Sigmarsson (ESF Standing Committee for Life, Earth and Environmental Sciences)

15.45-17.30 Discussion and planning of follow-up research activities and/or collaborative actions or other specific outputs

Departure or
19.00 Dinner and evening discussion for participants not travelling (Hotel Sumba)

Friday 30 May 2008
Morning Departure

Final list of participants (names and affiliations)

Many attendees gave presentations in more than one session. A rapporteur was chosen to summarise each topic (Anny Cezenave, Jon Ove Hagen, Adrian Luckman, Edward Hanna, Niels Reeh).

Remote sensing observations of Greenland volume changes and mass balance

Jonathan Bamber (University of Bristol, UK)
Anny Cazenave (Centre National d'Etudes Spatiales, FR)
Rene Forsberg (Danish National Space Center, DK)
Louise Sørensen (Danish National Space Center, DK)
Timothy James (Swansea University, UK)
Kirill Khvorostovsky (University of Bergen, NO)

Remote sensing observations of Greenland glacier dynamics

Adrian Luckman (Swansea University, UK)
Niels Reeh (Technical University of Denmark, DK)
Kilian Scharrer (Ludwig-Maximilians University, DE)
Andy Shepherd (University of Edinburgh, UK)
Tazio Strozzi (GAMMA Remote Sensing, CH)

Current ice sheet models of Greenland and their inclusion in Earth System models

Guðfinna Aðalgeirsdóttir (Danish Meteorological Institute, DK)

Surface mass balance, melt extent and runoff

Michiel van den Broeke (Utrecht University, NL)
Carl Egede Bøggild (The University Centre in Svalbard, UNIS, NO)
Jon-Ove Hagen (University of Oslo, NO)
Edward Hanna (University of Sheffield, UK)
Roderik van de Wal (Utrecht University, NL)

Outlet glaciers, calving and tidewater interactions

Doug Benn (The University Centre in Svalbard, UNIS, NO)
Throstur Thorsteinsson (University of Iceland, IS)
Martin Luethi (ETH Zurich, CH)

Geophysical observations of Greenland outlet glaciers including glacial earthquakes

Morten Langer Andersen (GEUS, DK)
Tavi Murray (Swansea University, UK)

Invited but unable to attend at last minute

Peter Jansson (Stockholm University, SE)

Tonie van Dam (University of Luxembourg, LU)

ESF representative
Olgeir Sigmarsson (University of Iceland)

Local Support
Nick Selmes (Swansea University, UK)

Statistical information on participants (age bracket, countries of origin, etc.)

24 people attended the meeting, of whom 20 were official invitees, one provided local support for running the meeting, two were self-funded and one was the ESF representative funded directly by the ESF. Of the 20 invitees who could attend, 3 (15%) were women. One woman could not attend because of child care responsibilities (ill health of her partner) at the last minute.

	Invitees	**Plus helpers, self-funded & ESF**
Denmark	4 RF, NR, GA, MLA	1 LS
France	1 AC	
Germany	1 KS	
Iceland	1 TT	1 OS
Netherlands	2 MvdB, RvdW	
Norway	3 CB, JOH, DB	1 KK
Switzerland	2 TS, ML	
UK	6 JB, AL, AS, EH, TM, TJ	1 NS

Age bracket	**Number of invitees in age bracket**
30-34	3
35-39	4
40-44	5
45-49	3
50-54	1
55-59	2
60-64	1
65-69	1