What can we learn from the ice sheets?

Guðfinna Aðalgeirsdóttir, Danish Climate Centre, Danish Metorological Institute; Denmark

Introduction

Climate models show that greenhouse gas induced climate change is amplified in the Polar Regions. The Arctic shows high sensitivity to increased temperatures and it is vulnerable because the change from subzero to above zero temperatures has a large impact on the environment, ecosystems, people, transport and infrastructure. Glaciers and ice caps are sensitive to climate and respond to changes in temperature and precipitation at time scales that are currently observable. Observations are, however, scarce and it is expensive and often difficult to obtain information about the current state, to assess the already resulting impact, and to validate the models that are used to predict the possible future evolution. Here, a brief overview of current knowledge concerning the state of balance of glaciers and ice sheets in the world is given, followed by a more detailed discussion of the state of the Greenland Ice Sheet and the Icelandic ice caps. Then a few model efforts, aiming at simulating the present and future surface mass balance of the Greenland Ice Sheet to project future climate in and around Greenland and predict the likely response of the Icelandic glaciers to a given climate change, are presented. It is not a comprehensive overview of modelling efforts, but reflects the author's focus of research.

Observations

Measurements of glacier mass balance started relatively recently, during the 20th century, and there are only a few glaciers that have been monitored continuously over long periods. Despite this limitation in observations extrapolations from existing data have been made and the best estimate for the total volume of glaciers and ice caps outside the Greenland Ice Sheet and Antarctica is equivalent to 0.65 ± 0.16 m of sea-level rise (Dyurgerov and Meier, 2005). The contribution of these glaciers to sea level rise has also been estimated and is found to have accelerated during the 20th century. Kaser et al. (2006) found the global total balance of glaciers outside Greenland and Antarctica to be -0.38 ± 0.19 mm SLE a^{-1} for the period 1961-1991 and -0.98 ± 0.19 mm SLE a^{-1} for the period 2001-2004. A recent study has found their estimate to be too low for the glaciers on the Antarctic Peninsula so those numbers are probably a minimum estimate (de Woul, 2008). For the period of 1991-2004 this glacier contribution is about 20-30% of a recent estimate of total sea-level rise for 1993-2005 (Kaser et al., 2006), the rest is due to contribution from the large ice sheets (Greenland and Antarctica) and thermal expansion of the ocean caused by increased temperatures. A study of glaciers in Alaska also indicates increasing wastage of glaciers; from 0.14 ± 0.04 mm SLE a^{-1} from the mid-1950s to the mid-1990s to 0.27 ± 0.10 mm SLE a^{-1} during the last decade of the 20th century (Arendt et al., 2002). A satellite based study covering about 85% of the Antarctic ice sheet indicates that most of the ice sheet is near balance during the period of 1992-2006, apart from three exceptional areas, where a large increase in melting has occurred. These areas are the Antarctic Peninsula and the areas that flow into the Bellinghausen and Amundsen Seas, and cause the net balance of the ice sheet to become increasingly negative from -112 ± 91 GT a^{-1} in 1996 to -196 ± 92 GT a^{-1} in 2006 (Rignot et al., 2008). Observations therefore indicate that large portions of the glaciers in the world are presently melting and the rate of the loss of mass is increasing.

Greenland Ice Sheet

The total volume of ice stored in the Greenland Ice Sheet contains a potential sea-level rise of about 7 m. This ice sheet covers an area of about 1.7 million km^2 and has only been monitored for a short time. Due to its size, it has been difficult to get a comprehensive overview, but in recent years an increasing number of observations, including data gathered by satellites, have improved the knowledge of the current state of the Greenland Ice Sheet. An extensive American project sponsored by NASA and NSF, Greenland Climate Network (GC-NET, http://cires.colorado.edu/ science/groups/steffen/gcnet/) has set up a number of automatic weather stations (AWS) that have been run since 1995, and since the 1999 field season there are 18 stations on the ice sheet. These stations collect climate information and send the data via satellite transmitters that enable a near-real time monitoring of weather conditions on the ice sheet. Another program launched by the Danish Ministry of the Environment in 2007 aims at estimating the annual loss of mass from surface melting, with similar AWS, as well as from ice berg calving. This project combines modelling with in situ data collection. It is designed and operated by the Geological Survey of Denmark and Greenland (GEUS). Both these monitoring programs provide data necessary to validate models of the surface mass balance.

Satellite and remote sensing methods, such as altimetry measurements from aircrafts, have in recent years given a good coverage of the whole ice sheet. Elevation measurements made in

1993 and repeated in 1999 indicate that the highest part of the ice sheet is in balance, or thickening, while the coastal areas are thinning (Krabill et al., 2000; Thomas et al., 2001; Krabill et al., 2004). The loss of mass has been increasing during the measurement period (Thomas et al., 2006).

Independent satellite based measurements that derive the total mass of the ice sheet by making detailed measurements of Earth's gravity field (Gravity Recovery and Climate Experiment, GRACE, http://www.csr.utexas.edu/grace/), yield similar results. GRACE measurements have revealed that in just four years, from 2002 to 2006, Greenland lost between 150 and 250 km^3 of ice per year. That is enough melting ice to account for an increase in global sea level of as much as 0.5 mm a^{-1} (Velicogna and Wahr, 2005; Velicogna and Wahr 2006; Chen et al., 2006; Luthcke et al., 2006). The current estimate for the Greenland ice sheet loss of mass is somewhat different between the various groups processing the data, but all agree that the rate of loss of mass is increasing.

The GRACE measurements have a large footprint so it is possible to locate regions of greatest loss, but it is not possible to observe individual glaciers. Other kinds of measurements, where the speed of individual outlet glaciers is measured, show a widespread increase in discharge in the southern part of Greenland (Rignot and Kanagaratnam, 2006). In particular, the speed of three of Greenland's fastest glaciers, Jakobshavn Isbræ, Helheim and Kangerdlugssuaq, approximately doubled since 2000 (Joughin et al., 2004; Luckman and Murray, 2005; Luckman et al., 2006; Howat et al., 2005), although the last two have partially slowed down since then (Howat et al., 2007). Jakobshavn Isbræ on the other hand shows no signs of slowing down. The outlet glacier increased its speed from 5.7 km a^{-1} to 12.6 km a^{-1} between 1992 and 2003 (Joughin et al., 2004) after rapid thinning and break up of its floating tongue (Thomas et al., 2003). Ongoing work on this glacier shows that the glacier is maintaining high speed; during the summer of 2007 it was measured to be 14.6 km a^{-1} close to the calving front (M. Lüthi, personal communication 2008).

An estimate of the surface mass balance of the Greenland Ice Sheet for the years 1958 – 2007 combined with measurements of the temporal variability in ice discharge shows that the ice sheet was losing 110 ± 70 GT a^{-1} in the 1960s, 30 ± 50 GT a^{-1} or near balance in the 1970s-1980s, and 97 ± 47 GT a^{-1} in 1996 increasing rapidly to 267 ± 38 GT a^{-1} in 2007 (Rignot et al., 2008). A more detailed study of the south eastern coast of Greenland using ICESat-derived surface elevation changes with difference ASTER digital elevation models indicates that the ice sheet is not only losing mass through the large fast-flowing glaciers; the two largest glaciers, Kangerdlugssuaq and Helheim account for only about 28% of the total loss of mass (Howat et al., 2008).

Using spaceborne microwave brightness temperatures it is possible to observe areas that show a melting of the ice sheet. During the summer of 2007 a record melting was observed with an up to 25-30 days longer melting season and estimated at 30% more melting than the previous year. Within the last 18 years of performed measurements the five highest years of melting all occur after 1998 (Tedesco, 2007).

All these measurements have been carried out for a relatively short time (less than two decades). Before the satellite era the view was that the Greenland Ice Sheet had a long response time and would not respond rapidly to changes in climate. The new data show rapid dynamical changes and a large annual variability in the loss of mass that had not been anticipated. The modelling community is now working hard to understand the observed processes and incorporating them into the models to improve predictions of the future evolution of the ice sheet.

Icelandic Ice Caps

Glaciers cover about 11% of Iceland. The three largest ice caps, Vatnajökull, Hofsjökull and Langjökull, have volumes of about 3000 km^3, 200 km^3 and 195 km^3, respectively (Björnsson and Pálsson, 2008). This is about the same amount as 20 years of precipitation in Iceland, stored in the ice caps. Regular mass balance measurements on these ice caps started 1988 on Hofsjökull (Sigurðsson, 1989-2004), 1991 and 1992 on Vatnajökull depending on location (Björnsson et al., 1998), and 1997 on Langjökull (Björnsson et al., 2002). The net balance on Hofsjökull was positive in 1988/1989 and in the period 1991-1994, in other years it was negative. All outlet glaciers from Hofsjökull have been retreating since 1995 and the total area of the ice cap has shrunk by approximately 3.5% since 1986. The net balance on Vatnajökull was positive the first 3 years of measurements, but has been negative since 1995. Langjökull has had negative mass balance since 1997. Most of the measured termini of glaciers in Iceland have been retreating during the 20th century (Sigurðsson, 2005). Therefore all the glaciers are presently losing more ice every year than is added in the form of snow.

Modelling efforts

Scarcity of data on the surface mass balance of the Greenland Ice Sheet makes it necessary to simulate it with models. A number of efforts have been made to model the surface mass balance and these models broadly indicate similar trends. The surface mass balance responds rapidly on an annual basis to changing meteorological forcing. Significantly increasing production of melted water has been partly offset by increasing precipitation causing negligible or only small negative trends in total surface mass balance during the last part of the 20th century (Hanna et al., 2005; Box et al., 2006; Fettweis, 2007). The satellite observations discussed above indicate, however, an increasingly negative mass balance. The increased ice flux observed near the ice margins, and the possibly enhanced iceberg calving, which is hard to monitor or model, have led to a more negative mass balance than only melting can account for. The significantly increasing Greenland summer warmth (the three warmest summers since 1958 were 2003, 2005 and 2006) and Greenland Ice Sheet melting and runoff since 1990 has been attributed to atmospheric warming (Hanna et al., 2008) and is likely to continue in the coming decades.

A model study with the regional climate model HIRHAM on a 25 km grid covering Greenland and the surrounding seas has been conducted for the period 1950-2080. The model is forced with observations until year 2000 and the IPCC emission scenario A1B thereafter (Stendel et al., 2008). Compared to a 30 years reference period 1961-1990 the model predicts that in about 30 years from now the general winter temperature will increase by about 3°C and summer temperature by 2°C. Locally a 6°C and 4°C temperature increase is predicted on the west and east coast, respectively. For the same period the precipitation is predicted to increase by 15% over West Greenland and 40% over the interior and East Greenland. Towards the end of the model period, about 70 years from now, the temperature is predicted to increase by 7-8°C over most of the model's domain during the winter months and about 3°C during summer. As much as 12°C temperature increase is predicted along the northeast coast. This amplification of temperature increase along the east coast is primarily caused by the retreat of sea-ice during the whole year in this area. The precipitation is predicted to increase up to 40% over the interior and West Greenland and up to 60% over East Greenland. There is, however, a decrease in the amount and frequency of snowfall along the southern coast with more snow predicted to fall on the lower parts of the ice sheet. According to the model experiment an increase in extreme precipitation events can be expected in the climate in the future (Stendel et al., 2008).

A number of model studies of Icelandic ice caps have shown that they are sensitive to changes in climate, and predictions indicate that most of the ice will disappear within the next 2 centuries. A degree-day mass balance model has been coupled to dynamic ice cap model for the 3 ice caps in Iceland and the coupled model has been forced with a specified climate scenario defined for the Nordic countries (Aðalgeirsdóttir et al., 2005; Björnsson et al., 2006).

When imposing a temperature increase of about 0.2-0.4°C per decade the simulations predict that Langjökull will disappear within 150 years from now and the higher elevated Hofsjökull and Vatnajökull will almost vanish within 200 years from now. The runoff is predicted to increase, as the climate gets warmer, but peak after 40-60 years and then decrease due to the reduced area of the glaciers. Another model study, with a prescribed warming rate of 2°C per century, simulated ice cap area and volume to reduce by 12-15% and 18-25% within 100 years, respectively. Individual outlet glaciers experience 3-6 km retreat in the first 100 years and a total retreat of 10-30 km over 200 years (Flowers et al., 2005). These model experiments are relatively simple approaches that perturb the present climate and apply low order ice sheet models, but give an idea of the time scale for the response of the Icelandic ice caps to the predicted warming climate.

Conclusion

Glaciers and ice caps are responding to an increasing temperature with increased rates of loss of mass. Observations on the Greenland Ice Sheet indicate that the ice is moving faster, the ice sheet is discharging more ice to the ocean than before, and that the increased temperature is causing longer melting seasons. Changes are happening at a faster rate than the models that have been used until now have predicted. In order to improve predictions for the future evolution of the Greenland Ice Sheet, beyond the conservative approach taken by the fourth assessment of IPCC (IPCC, 2007), work on improving the ice sheet models and coupling them with climate models is necessary. Recent observations have made it clear that present ice sheet models cannot simulate the rapid dynamical changes and glacier thinning that is a response to a warming climate. Work is in progress to improve the models and couple model results from climate models to improved ice sheet models of surface mass balance and ice dynamics.

By considering the smaller ice caps and glaciers in the Arctic as a model for the Greenland Ice Sheet in warmer climate conditions, lessons can be learned about response of ice sheets to climate change. This has to happen soon as it is predicted that most glaciers and ice caps in the Nordic countries, will almost disappear during the next 100-200 years. The runoff from presently glaciated areas may increase by 25-100% in a period of 30-100 years from now. There will be large changes in runoff seasonality and in the diurnal runoff cycle and, in some cases, changes related to migration of ice divides and sub-glacial watersheds. These changes will have an impact on existing and planned hydropower plants, infrastructure, and people utilizing the runoff from the glaciers.

References

Aðalgeirsdóttir, G., T. Jóhannesson, H. Björnsson, F. Pálsson, and O. Sigurðsson (2006), The response of Hofsjökull and southern Vatnajökull, Iceland, to climate change, *Journal of Geophysical Research*, 111, F03001, doi10.1029/2005JF000388

Arendt, A., K. Echelmeyer, W. Harrison, C. Lingle, and V. Valentine (2002), Rapid Wastage of Alaska Glacier and Their Contribution to Rising Sea Level, *Science*, 297, 382-386.

Björnsson, H., and F. Pálsson (2008), Icelandic glaciers, *Jökull*, 58, 365-386.

Björnsson, H., F. Pálsson, M. T. Guðmundsson, and H. Haraldsson (1998), Mass balance of western and northern Vatnajökull, Iceland, 1991-1995, *Jökull*, 45, 35-58.

Björnsson, H., F. Pálsson, and H. Haraldsson (2002), Mass balance of Vatnajökull (1991-2001) and Langjökull (1996-2001), Iceland, *Jökull*, 51, 75-78.

Björnsson, H., G. Aðalgeirsdóttir, S. Guðmundsson, T. Jóhannesson, and F. Pálsson (2006), *Climate change response of Vatnajökull, Hofsjökull and Langjökull ice caps, Iceland, in European Conference on Impacts of Climate Change on Renewable Energy Sources*, Reykjavik, Iceland, June 5-9, 2006.

Box, J. E., D. H. Bromwich, B. A. Veenhuis, L. Bai, J. C. Stroeve, J. C. Rogers, K. Steffen, T. Haran, and S. Wang (2006), Greenland ice sheet surface mass balance variability (1988-2004) from calibrated Polar MM5 output, *J. Climate*, 19, 2783-2800.

Chen, J. L., C. R. Wilson, and B. D. Tapley (2006), Satellite gravity measurements confirm accelerated melting of Greenland ice sheet, *Science*, 313, 1958-1960.

de Woul, M. (2008), *Response of glaciers to climate change. mass balance sensitivity, sea level rise and runoff*, Ph.D. thesis, Stockholm University, Department of Physical Geography and Quaternary Geology.

Dyurgerov, M. B., and M. F. Meier (2005), *Glaciers and the changing earth system: A 2004 snapshot, INSTAAR, Occasional Paper No. 58*.

Fettweis, X. (2007), Reconstruction of the 1979-2006 Greenland ice sheet surface mass balance using the regional climate model mar, *The Cryosphere Discussions*, 1(1), 123-168.

Flowers, G. E., S. Marshall, H. Björnsson, and G. K. C. Clarke (2005), Sensitivity of Vatnajökull ice cap hydrology and dynamics to climate warming over the next two centuries, *Journal of Geophysical Research*, 110, F02011, \doi10.1029/2004JF000200.

Hanna, E., P. Huybrechts, I. Janssens, J. Cappelen, K. Steffen, and A. Stephens (2005), Runoff and mass balance of the Greenland ice sheet: 1958-2003, *Journal of Geophysical Research*, 110, D13108, \doi10.1029/2004JD005641.

Hanna, E., P. Huybrechts, K. Steffen, J. Cappelen, R. Huff, C. Shuman, T. Irvine-Fynn, S. Wise, and M. Griffiths (2008), Increased runoff from melt from the Greenland Ice Sheet: a response to global warming, *J. Climate*, 21, 331-341.

Howat, I. M., I. Joughin, S. Tulaczyk, and S. Gogineni (2005), Rapid retreat and acceleration of Helheim Glacier, east Greenland, *Geophysical Research Letters*, 32, L22502, \doi10.1029/2005GL024737.

Howat, I. M., I. Joughin, and T. Scambos (2007), Rapid changes in ice discharge from Greenland outlet glaciers, *Science*, 315(5818), 1559-1561.

Howat, I. M., B. E. Smith, I. Joughin, and T. Scambos (2008), Rates of southeast Greenland ice volume loss from combined ICESat and ASTER observations, grl, 35, L17505, \doi10.1029/2008GL034496.

IPCC (2007), *Climate Change 2007*: The Physical Science Basis. contribution of working group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, [S. Solomon and D. Quin and M. Manning and Z. Chen and M. Marquis and K.B. Averyt and M. Tignor and H. L. Miller (Eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Joughin, I., W. Abdalati, and M. Fahnestock (2004), Large fluctuations in speed on Greenland's Jakobshavn Isbræ glacier, *Nature*, 432, 608-610.

Kaser, G., J. G. Cogley, M. B. Dyurgerov, M. F. Meier, and A. Ohmura (2006), Mass balance of glaciers and ice caps: Concensus estimates for 1961-2004, *Geophysical Research Letters*, 33, L19501, \doi10.1029/2006GL027511.

Krabill, W., W. Abdalati, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, W. Wright, and J. Yungel (2000), Greenland Ice Sheet: High-elevation balance and peripheral thinning, *Science*, 289, 428-430.

Krabill, W., E. Hanna, P. Huybrechts, W. Abdalati, J. Cappelen, B. Csatho, E. Frederick, S. Manizade, C. Martin, J. Sonntag, R. Swift, R. Thomas, and J. Yungel (2004), Greenland Ice Sheet: increased coastal thinning, *Geophysical Research Letters*, 31(L24402).

Luckman, A., and T. Murray (2005), Seasonal variation in velocity before retreat of Jakobshavn Isbræ, Greenland, *Geophysical Research Letters*, 32, L08501, \doi10.1029/2005GL022519.

Luckman, A., T. Murray, R. de Lange, and E. Hanna (2006), Rapid and synchonous ice-dynamics changes in East Greenland, *Geophysical Research Letters*, 33, L03503, \doi10.1029/2005GL025428.

Luthcke, S. B., H. J. Zwally, W. Abdalati, D. D. rowlands, R. D. Ray, R. S. Nerem, F. G. Lemoine, J. J. McCarthy, and D. S. Chinn (2006), Recent Greenland ice mass loss by drainage system from satellite gravity observations, *Science*, 314, 1286-1289.

Rignot, E., and P. Kanagaratnam (2006), Changes in the velocity structure of the Greenland ice sheet, *Science*, 311, 986-990.

Rignot, E., J. L. Bamber, M. R. van den Broeke, C. Davis, Y. Li, W. J. van de Berg, and E. van Meijgaard (2008), Recent Antarctic ice mass loss from radar interferometry and regional climate modelling, *Nature Geoscience,* \doi10.1038/ngeo102.

Rignot, E., J. E. Box, E. Burgess, and E. Hanna (2008), Mass balance of the Greenland ice sheet from 1958-2007, *Geophysical Research Letters*, 35, L20502, \doi10.1029/2008GL035417.

Sigurðsson, O. (1989-2004), Afkoma Hofsjökuls 1987-1988, ... 2002-2003 (Mass balance of Hofsjökull 1987-1988, ... 2002-2003), *National Energy Authority*. (Technical reports in Icelandic).

Sigurðsson, O. (2005), In Caseldine, Russell, Harðardóttir and Knudsen (eds.) Iceland - Modern processes and past environments, chap. Variations of termini of glaciers in Iceland in recent centuries and their connection with climate, Elsevier, London, 241-255, 335-397 (references), 408 (map).

Stendel, M., J. Christensen, and D. Petersen (2008), In: H. Meltofte, T.R. Christensen, B. Elberling, M.C. Forchhammer and M. Rasch (eds.): High Arctic Ecosystem Dynamics in a Changing Climate. Ten years of monitoring and research at Zackenberg Research station, Norheast Greenland. Advances in Ecological Research, vol. 40, chap. Arctic climate and climate change with a focus on Greenland, pp. 13-43, Academic Press.

Tedesco, M. (2007), A new record in 2007 for melting in Greenland, *Eos*, 88(39), 383.

Thomas, R., B. Csatho, C. Davis, C. Kim, W. Krabill, S. Manizade, J. McConnell, and J. Sonntag (2001), Mass balance of higher-elevation parts of the Greenland ice sheet, *Journal of Geophysical Research*, 106(D24), 33,707-33,716.

Thomas, R., W. Abdalati, E. Frederick, W. Krabill, S. Manizade, and K. Steffen (2003), Investigation of surface melting and dynamic thinning on Jakobshavn Isbraed, Greenland, *Journal of Glaciology*, 49, 231-239.

Thomas, R., E. Frederick, W. Krabill, s. Manizade, and C. Martin (2006), Progressive increase in ice loss from Greenland, *Geophysical Research Letters*, 33, L10503, \doi10.1029/2006GL026075.

Velicogna, I., and J. Wahr (2005), Greenland mass balance from GRACE, *Geophysical Research Letters*, 32(L18505).

Velicogna, I., and J. Wahr (2006), Acceleration of Greenland ice mass loss in spring 2004, *Nature*, 443, 329-331.