Summary – The Greenland Ice Sheet in a Changing Climate

Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2009
This report presents a summary of the initial scientific findings of work conducted on the Greenland Ice Sheet (GRIS) component of the Arctic Council’s Cryosphere project – Snow, Water, Ice and Permafrost in the Arctic (SWIPA). It is a summary of the comprehensive and fully-referenced scientific and technical report entitled *The Greenland Ice Sheet in a Changing Climate: Snow, Water, Ice and Permafrost in the Arctic (SWIPA) 2009*.

The SWIPA project was established by the Arctic Council in April 2008 as a follow-up to the 2005 Arctic Climate Impact Assessment (ACIA). Its goal is to assess current scientific information on changes in the Arctic cryosphere, including the impacts due to changes in the cryosphere that have potentially far reaching implications for both the Arctic and the Earth as a whole.

The SWIPA project is coordinated by the Arctic Council’s Arctic Monitoring and Assessment Programme (AMAP) in cooperation with the International Arctic Science Committee (IASC), International Arctic Social Sciences Association (IASSA), International Polar Year, and WCRP-CliC Program (for further information see www.amap.no/swipa). The Greenland Ice Sheet component of the SWIPA project is led by Denmark.

This summary report is also available in Chinese, Danish, French, Greenlandic and Russian translations; however, the English language version constitutes the official version of the report. The SWIPA-GRIS reports, together with other SWIPA products, will be presented at the UNFCCC COP15 meeting in Copenhagen in December 2009. The results of the SWIPA project will also be provided to the UNFCCC Intergovernmental Panel on Climate Change (IPCC) for use in future IPCC assessments.

AMAP would like to thank all of the scientific experts that have contributed to this assessment. A list of the authors and contributors of the scientific background report is included in the colophon to this report. Thanks are also due to Carolyn Symon for preparing this summary of the scientific document and to Denmark for leading this component of the SWIPA work.

The support of the Arctic countries is vital to the success of SWIPA and AMAP work in general. Furthermore, the SWIPA-GRIS project could not have been conducted without the additional financial support received from Canada, Denmark, Norway, and the Nordic Council of Ministers.

Future SWIPA reports will include an update of the information concerning the Greenland Ice Sheet, in particular the sections dealing with potential impacts on biological systems and human populations. These potential impacts can only be fully addressed in relation to the combined effects of changes in all components of the cryosphere – and thus form part of the SWIPA integration assessment.
The Greenland Ice Sheet – an Arctic icon

Greenland’s ice sheet is the single largest body of freshwater ice in the Northern Hemisphere. It contains around 3 million km$^3$ of ice. If it were to melt completely this massive store of snow and ice would cause global sea level to rise by roughly 7 m. Globally, the Greenland Ice Sheet is second in size only to the much larger Antarctic Ice Sheet.

The Greenland Ice Sheet has expanded and contracted many times in response to changes in the Earth’s climate and will be highly susceptible to the strong global warming that is predicted to occur over the coming decades and centuries. Recent changes in the ice sheet suggest that it is already responding dramatically to the changing climate, but the extent to which it will shrink over the coming decades remains uncertain. A diminishing Greenland Ice Sheet will have local, regional and global impacts on the environment, as well as on ecosystems and human societies.

This assessment is the first with a comprehensive focus on the Greenland Ice Sheet under the currently changing climate. It forms an integral part of the Arctic Council project Climate Change and the Cryosphere: Snow, Water, Ice and Permafrost in the Arctic (SWIPA).

The SWIPA project (www.amap.no/swipa) will assess current scientific information on changes in the Arctic cryosphere that have potentially far-reaching implications for both the Arctic and the Earth as a whole.
Ice sheets form when the climate is cold enough for snow to accumulate. Over thousands of years, the annual layers of accumulated snow are compressed into ice by the weight of the overlaying snow. Ice sheets are constantly flowing, spreading out under their own weight from the areas where snow accumulates at the centre of the ice sheet to the melt zones on its flanks. Near the margins of the ice sheet, close to the coast, the ice melts or moves through relatively fast-moving ice streams and glaciers that end in the sea. There it either melts or breaks off (calves) into the sea to form icebergs. If an ice sheet accumulates about the same amount of snow as it loses it is said to be stable.

Past changes reflect natural variations in climate

Natural variations in global climate have been a feature of the Earth’s history over the past several million years. There have been periods of extreme cold during which large parts of the Earth’s surface were covered with ice (glaciations) and warmer periods with little or no ice. Extensive glaciations first began to occur in the Northern Hemisphere around 3 million years ago. Since then the Greenland Ice Sheet has expanded and diminished in accordance with the various glacial and interglacial periods.

Greenland’s climate has been particularly variable over the last 3 million years, and not all of these changes have been gradual. Ice cores from the Greenland Ice Sheet reveal 25 rapid changes in climate during the last glacial period – termed Dansgaard-Oeschger events. During each of these warming events temperatures increased by 10 to 15°C over periods of just a few decades. This increase in temperature was accompanied by a rise in global sea level of 5 to 20 m. The abrupt warming events were followed by long periods – lasting 1000 to 5000 years – in which temperatures gradually cooled, before the next rapid warming event occurred. The extent to which the Greenland Ice Sheet contributed to the rise in sea level during these rapid warming events of the last glaciation is not known.
Ice core drilling in Greenland. Ice cores – columns of ice obtained by drilling vertically through the ice sheet – have been used to reconstruct atmospheric conditions over the past 125 000 years. The cores are sliced into sections and the ice from each section is analyzed. Each section reflects atmospheric conditions at a particular period in history. Much of the information used to reconstruct the response of the Greenland Ice Sheet to past changes in climate has been obtained from ice cores.

**Predicting the future based on the past?**

After the last glacial period ended 12 000 years ago, the climate warmed into the present interglacial period (known as the ‘Holocene’). This has remained warm and has seen very small fluctuations in temperature.

The Eemian – the previous interglacial period – is a particularly interesting period to consider because in many ways it represents an analogue for what could happen to the present-day Greenland Ice Sheet as temperatures continue to rise. Air temperatures over Greenland during the Eemian were also relatively stable for several thousands of years but at about 5 °C higher than today. Sea level was roughly 4 to 6 m higher than today and reconstructions using data from ice cores suggest that a partial melting of the Greenland Ice Sheet may have been responsible for between 1 and 3 m of this increased sea level. This poses the question: Could the global warming that is projected to occur over the coming decades and centuries cause sea level to rise as high as it did during the previous interglacial period?
The Arctic is warming
The Arctic has warmed considerably over the past 50 years. While the average global temperature has increased by around 0.7 °C, average temperatures over Greenland have increased by more than twice that. Temperatures in the Arctic have also warmed at a far greater rate than those in much of Antarctica.

The UN Intergovernmental Panel on Climate Change (IPCC) predicts that by 2100, annual temperatures over the Arctic will be 3 to 8 °C higher than those observed during the 1951–1980 reference period, with winters warming at a greater rate than summers. A temperature increase of this size would be the largest the Greenland Ice Sheet had experienced for more than 100 000 years (i.e., since the end of the last interglacial period).

Warming trends around Greenland
Better information is needed about how the Greenland Ice Sheet is responding to current climate change before reliable predictions can be made about the way the ice sheet is likely to respond to future changes in climate.

The size and remoteness of the Greenland Ice Sheet make field measurements of climate difficult. However, some long-term datasets from different parts of the ice sheet do exist. The longest series of weather measurements have been collected by the Danish Meteorological Institute at eight coastal sites in southern Greenland. Some of these series cover 100 years or more. Data have also been collected at a network of automatic weather stations installed across the ice sheet since the 1990s.

The Ice Sheet today

Sea-ice occurs around much of the coast, especially during winter. To the east and southwest of Greenland the ice is carried south from the central Arctic by the East Greenland Current. To the west in Baffin Bay and Davis Strait the ice is seasonal, forming in the winter and melting the following summer.

Since 2003, some areas of the ice sheet have thickened (shown in white), others have thinned (blue shades), and others have shown little change (grey).

The predominant wind directions are from the west in summer and the southwest in winter.

The marine environment is dominated by the large-scale circulation. This has two main components: north-flowing waters originating from the warm salty water of the North Atlantic Current, and colder fresher waters flowing south from the Arctic.
Coastal records since 1840 show the highest temperatures to have occurred during the 1930s and 1940s. These coastal datasets also show a general warming of about 2 to 4°C since the end of the 1980s, mainly during winter. Recent warming at the western edge of the ice sheet is also clear in the automatic weather station data. However, there are too few datasets, and those that do exist are still too short, to establish temperature trends within the vast interior of the ice sheet.

The coastal warming since the early 1990s has occurred despite the global cooling effects of the vast quantities of ash released to the upper atmosphere by the eruption of the Mount Pinatubo volcano in the Philippines in 1991. This is different to the warming of the 1930s and 1940s which occurred during a period of unusually low volcanic activity.

The weather data confirm that the climate in, around and over the Greenland Ice Sheet varies widely; from north to south, from east to west, and with changes over the central ice sheet very different to those on the coast. Attempts by scientists to model these local variations in temperature have been relatively unsuccessful. Differences between what the models predict and what the temperature measurements show indicate that a better geographical spread of climate measurements is needed to drive the models. Longer datasets are also important and it is essential that existing time series are continued and where possible extended backwards, for example using data from ice cores.
Whether the ice sheet is growing or shrinking depends on the balance between the processes that add or remove ice. The overall balance between the mass gain by snow accumulation and the mass loss through iceberg calving and runoff from melting each year is known as the ‘total mass balance’. This is effectively a measure of the ‘health’ of the ice sheet. If, over time, the ice sheet loses more mass than it gains then the total mass of the ice sheet will gradually decrease.

Processes that add ice
Precipitation adds mass at the surface of the ice sheet. Most precipitation (roughly 96%) that falls onto the ice sheet is snow; with the remainder falling as rain. Snowfall on the Greenland Ice Sheet has significantly increased over the past 50 years, mainly due to warmer near-surface air temperatures causing increased moisture in the air which leads...
to increased precipitation. Since 2000, the high interior of the ice sheet (the part above 2000 m) has thickened, gaining around 5 cm in height each year through this increase in snowfall. There were particularly heavy snowfall years in 2002/2003 (southeast Greenland) and 2004/2005 (West Greenland). Some scientists have suggested that heavy snowfall years may become more frequent in a climate with warmer winters.

**Processes that remove ice**

The Greenland Ice Sheet loses mass through surface melting and, at the margins of the ice sheet, through icebergs and melting from ice surfaces in contact with warmer ocean water.

**Surface melting**

Air temperature and winds just above the surface of the ice sheet are the most important factors influencing surface melting. Another important factor is the reflectivity of the ice surface to incoming sunlight – a property known as surface albedo. Particles of dust and soot (black carbon) in the atmosphere can be deposited directly onto the surface of the ice sheet and can reduce albedo in the melt zone.

Melting in the ablation zone has been measured at a few sites around the margins of the ice sheet. How representative these few sites are and how well the surface processes are understood is uncertain. Some meltwater will run off directly, some will drain through cracks in the ice and some will refreeze.

Data from satellites show that the areas experiencing summer melting have increased significantly since 1979, with a record-breaking area of surface melting measured in 2007.

**Ice loss from the margins**

The speed with which ice flows away from the accumulation zone on the upper part of the ice sheet becomes extremely variable as it approaches the margins – with areas of slow flow separated from fast-flowing outlet glaciers and ice streams.

Vast amounts of ice are discharged into the sea from the ends of glaciers. These outlet glaciers (shown in red on the figure on page 8) usually flow through deep and narrow fjords before releasing ice in the form of icebergs and meltwater from ice surfaces in contact with the seawater. Icebergs are the main source of ice loss from the margins of the ice sheet.

The largest outlet glacier on the Greenland Ice Sheet is Jakobshavn Isbræ.

One of the results of recent scientific studies that has caused particular concern is the finding that annual ice discharge for the Greenland ice sheet as a whole increased by 30% over the past decade: from 330 Gt in 1995.

Jakobshavn Isbræ (Sermeq Kujalleq in Greenlandic) is a large outlet glacier on Greenland’s west coast. The ice flows through a deep subglacial trough that starts roughly 50 km inland from the current ice front and extends to 1500 m below sea level. The trough is relatively narrow (~5 km) but channels ice from an area draining ~7% of the Greenland Ice Sheet. Recent estimates of ice discharge from Jakobshavn Isbræ show a big increase in ice loss within the past few years. Around 10% of Greenland’s icebergs are calved from Jakobshavn Isbræ. The iceberg that sank the Titanic in 1912 is thought to have originated here. Jakobshavn Isbræ has retreated 15 km in the past eight years.
to 430 Gt in 2005. This increase was due to faster ice flow by the outlet glaciers and ice streams.

Many outlet glaciers, including Jakobshavn Isbræ on the west coast and Kangerdlugssuaq Glacier and Helheim Glacier on the east coast, have experienced recent and dramatic increases in the amount of ice discharged each year. Ice discharge from many southern outlet glaciers increased rapidly between 1995 and 2000, often doubling, and by 2005 this pattern had extended to outlet glaciers in northern areas. There is some regional variation, however, with discharge from the Helheim and Kangerdlugssuaq glaciers falling back to previous levels in 2007, while the high loss of ice from Jakobshavn Isbræ has continued.

Faster flowing ice in outlet glaciers is causing widespread retreat of these glaciers, as discharge continues to outstrip supply. This out-of-balance loss of ice to the sea from many southern glaciers has caused extensive areas of thinning (‘drawdown’) near the edge of the ice sheet.

Many reasons have been suggested for the speeding-up of outlet glaciers. It is likely that some types of ice-ocean interaction are involved because all the major changes occur first near the ocean and then propagate inland into the ice sheet. Because major sections of the ocean-terminating glaciers are floating, relatively warm ocean currents are believed to be particularly important.

Weighing the balance – the fate of the Greenland Ice Sheet

Up until 1990 – before the recent speeding-up of ice flow in the outlet glaciers and the trend towards increased mass loss from surface melting – the Greenland Ice Sheet seemed to be roughly in balance. The total amount of ice added and lost each year seemed to be around 500 Gt; of the 500 Gt added in snowfall ~50% was lost in run-off from surface melting and ~50% was discharged in icebergs.

Recent measurements show that this balance has now shifted and that there have been quite large and rapid changes in surface melt-
Estimating total mass balance

There are three techniques for estimating or observing changes in total mass balance: the mass budget approach, repeat altimetry, and changes in gravity. Only gravity measurements directly measure changes in ice mass, the first two approaches measure changes in other quantities (e.g., melt, surface height) and then convert these to changes in ice mass.

- The mass budget approach calculates the total mass balance from individual estimates of ice gains (snowfall) and ice losses (melt and icebergs).
- Satellite radar altimetry and laser altimetry from airplanes have been widely used to measure changes in the height of the ice sheet. Changes in the height of the ice sheet reflect changes in the total amount of ice it contains.
- Changes in the Earth’s gravity field are directly related to changes in mass. Since 2002 the GRACE (Gravity Recovery and Climate Experiment) mission has measured changes in the Earth’s gravity field.

A wide range of different approaches all indicate a decrease in the total mass balance of the ice sheet. The ‘boxes’ on the figure indicate the range of the mass loss estimate (vertical axis) and the time period for which the estimate is made (horizontal axis). The big spread in the data illustrates the uncertainty of the estimates.

1 Gt = 1000 000 000 tonnes.

1 Gt of ice roughly corresponds to a block of ice 1.1 km$^3$ in size. An iceberg discharge of 430 Gt in 2005 (see text) corresponds to enough freshwater to provide each person on Earth with 174 liters of clean drinking water each day of the year.
Predicting future changes in the Greenland Ice Sheet

The response of the Greenland Ice Sheet to a changing climate is complex. It depends on the interactions between the ice sheet, the atmosphere, and the ocean. Only recently have complex mathematical models been developed that describe this system as a whole and this has improved our ability to model the natural system as a whole.

Improving estimates of the balance at the ice sheet surface, now and in the future, relies on being able to downscale regional atmospheric models and to understand the processes controlling the fast-flowing ice streams. Additional uncertainties concern our understanding of the influence of meltwater below significant parts of the Greenland Ice Sheet.

It is important to remember that all models rely on assumptions and that as a result all model projections come with a level of uncertainty. Uncertainties tend to increase the further the projections extend into the future. However, as long as the uncertainties are properly understood, models provide perhaps the only tool currently available for predicting what the future will bring.

Despite their limitations, it is clear from the mathematical models that the Greenland Ice Sheet is very sensitive to climate warming.

A temperature threshold for ‘irreversible’ change?

The Greenland Ice Sheet is losing mass in response to recent climate warming. Even if temperatures stabilize, the ice sheet will continue to melt for some time. Beyond a certain point the ice sheet may even enter a state of ‘irreversible destabilization’ leading to a complete melting of the ice sheet – as happened to the ice sheets that covered much of northern Europe and North America at the end of the last ice age. Under this scenario, Greenland would lose its ice sheet until such time as a new glaciation occurred. The surface warming at which the melting of the ice sheet would become ‘irreversible’ is a so-called ‘threshold’.

Some scientists believe that if the average global warming were to rise by 3.1 °C (corresponding to a warming over Greenland of 4.5 °C) thinning of the ice sheet would reinforce the decay of the ice sheet as a whole. Drawdown of the ice sheet due to rapid glacial discharge would make it impossible to reverse the decline, even if temperatures were stabilized.

Despite a lack of knowledge on the exact temperature rise that would constitute this threshold, it is agreed that well before the threshold is reached, the mass balance for the ice sheet as a whole would have started to decline – something that has already started during the 1990s and 2000s.

Some of the best models currently available – including several used by the IPCC – lend credence to this suggestion of a ‘threshold’. Based on model results, scientists have suggested that cumulative emissions of greenhouse gases equivalent to 3000 Gt of CO$_2$ could lead temperatures past the threshold for irreversible melting of the Greenland Ice Sheet. Current CO$_2$ emissions from human activity could therefore cause several centuries of sea level rise.

It should be noted that even though air temperatures over Greenland during the last interglacial period (the Eemian – see page 3) were 5 °C higher, complete melting of the Greenland Ice Sheet did not occur.
The role of the Greenland Ice Sheet in global climate change

The changes in the ice sheet described above are driven by changes in regional weather systems over and around the ice sheet, by ocean conditions, and by ice sheet processes. At the same time, the characteristics of the ice sheet itself play a major role in shaping local and regional climate. Changes in the ice sheet also have the potential to influence global climate and ocean circulation.

Feedback mechanisms linking the Greenland Ice Sheet to the Arctic and global climate systems are at the core of concerns about the implications of future changes in the ice sheet. The risks and likely future changes in the ice sheet are very strongly related to how fast the changes (and hence sea level rise) will occur. These are still very uncertain as they depend on the processes that are speeding up the ice streams and fast-moving glaciers, which are as yet imperfectly understood. These topics need to be studied much more intensely.

Sea level rise

Sea level rise is an issue that is high on the agenda in any discussion of global climate change. Estimating the extent to which sea level may rise as a result of changes in the Greenland Ice Sheet in this century and beyond is therefore a key question and a major source of uncertainty in projections of future sea level rise.

It is clear that the melting ice sheet is already contributing to global sea level rise (although melting of the Greenland Ice Sheet is only one of the factors contributing to global sea level rise – see box). At present, the annual loss of ice from the Greenland Ice Sheet (160 ±50 Gt) corresponds to a rise in sea level of about half a millimeter per year, which is 10–20% of the observed 3 mm annual rise in global sea level.

Model projections to 2100

Most current models suggest that ice loss from the Greenland Ice Sheet will contribute about 5-10 cm to the rise in global sea level by 2100. However, higher estimates have also been made.

If climate warming were to cause a widespread speeding-up of ice discharge from the outlet glaciers, as recent observations indicate may be occurring, then the contribution from the Greenland Ice Sheet to global sea level rise could be as high as 20 cm by 2100, and perhaps even more under extreme warming scenarios.

Recent projections for global sea level rise by 2100 that include the contributions from thermal expansion of the oceans and the rest of the world’s ice masses, in addition to meltwater from the Greenland Ice Sheet, are as high as 1.0 (±0.5) m.

Global warming causes the water of the oceans to expand and the ice masses on land to melt. Both of these processes contribute to global sea level rise. Currently, the most important process driving sea level rise is thermal expansion of the ocean water.

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The projected future rise in global sea level is calculated from a global warming of 3 °C in the 21st century. The dotted line indicates the prediction by the UN Intergovernmental Panel on Climate Change. The purple shade indicates the degree of uncertainty of the calculations.
Model projections to beyond 2100

Moving the time-horizon much further into the future – a thousand years – current models suggest that with a regional warming of 3 to 4 °C, melting of the Greenland Ice Sheet alone could add as much as 1 m to global sea level rise by year 3000, while a warming of 5 to 6 °C could add as much as 2 m. However, the further into the future we look, the more uncertain the model projections are.

Complete melting of the Greenland Ice Sheet has the potential to raise sea levels by up to 7 m, a devastating prospect for coastal populations around the world. While most climate change models suggest that complete melting would take 3000 years or more, it is possible that ‘thresholds’ for destabilizing change will be approached on a much shorter time-frame. Steps need to be taken to avoid changes due to global warming that might exceed our capacity to adapt to them – and one such change could be associated with an irreversible melting of the Greenland Ice Sheet.

Ocean circulation – the spectre of ‘abrupt’ climate change

The effect that melting Arctic ice may have on ocean circulation patterns – and in particular the suggestion that altered ocean circulation may be associated with ‘abrupt’ changes in climate – is another issue that has received much attention in the climate debate in recent years.

The climate of northwestern Europe, in particular, is strongly influenced by ocean circulation patterns – as warm surface currents carry heat across the Atlantic Ocean and up into the Norwegian and Barents Seas from much lower and warmer latitudes. Without this warming influence, winter conditions in northwestern Europe would be similar to those experienced in Labrador in Eastern Canada.

As the surface waters are cooled in the Arctic seas the water becomes heavier, sinking and flowing back out to the southern oceans as cold deep water ocean currents. This process is effectively the engine that drives the global thermohaline circulation – also called the great ocean conveyor belt (see above). This major feature of the Earth’s climate system intimately links the Arctic with the rest of the world and illustrates the global importance of Arctic climate. Evidence suggests that in a warmer Arctic the cooling effect that makes the surface waters sink, combined with additional inputs of fresh surface waters from melting ice and increased Arctic river flow, could cause this circulation to weaken or even, some scientists have suggested, to shut down altogether. Paradoxically, in a warming global climate, the reduced northern transport of heat by ocean currents could cause strong regional cooling across the Nordic Seas and Barents Sea, as well as some degree of cooling over the entire Northern Hemisphere. Evidence indicates that such changes in ocean circulation in the past have occurred over very
short periods (decades) – leading to so-called ‘abrupt’ changes in regional climate.

In its Fourth Assessment Report, the IPCC concluded that the main current that transports warm water up into the Arctic (the Atlantic Meridional Overturning Circulation), is ‘very likely’ to decrease in the 21st century, but that this is not expected to lead to cooling over Europe – and that the changes are ‘very unlikely’ to be abrupt. However, none of the models used as the basis for these statements considered the effects of melting ice sheets. Because the global thermohaline circulation is driven by density differences, there is clearly the potential for increasing quantities of meltwater from Greenland to have at least some impact on ocean circulation; and, by extension, global climate.

In the few studies where ocean circulation models have been linked with ice sheet models, most results suggest that meltwater from the Greenland Ice Sheet is having little effect on the Atlantic Meridional Overturning Circulation. This is mainly because the amount of freshwater added by discharge from the Greenland Ice Sheet is around ten times smaller than that from the large north-flowing rivers that enter the Arctic Ocean, such as the Mackenzie in North America and the Ob, Yenisey and Lena in northern Russia. However, a better understanding of the impact of freshwater from the Greenland Ice Sheet remains important for assessing the stability of the North Atlantic circulation under future climate change scenarios, and also for understanding more local-scale effects on ocean circulation patterns around Greenland.

Sea ice

Meltwater entering the seas around Greenland increases the stability of the sea surface layers and encourages freezing. This suggests that increasing amounts of meltwater released from the Greenland Ice Sheet are potentially ‘pre-conditioning’ ever larger areas of the sea surface for ice production during winter. However, observations show that sea-ice cover around Greenland has actually decreased in recent years. This illustrates how difficult it is to predict the overall combined effect of higher air temperatures and higher freshwater inputs.

The presence of sea ice that is joined to the land at the coast (fast ice) also appears to affect the advance and retreat of glaciers that flow into the sea. While sea ice cannot actually halt the flow of these enormous glaciers, it seems that it can temporarily prevent icebergs calving. At the 79-glacier in northeast Greenland, a period of permanent fast ice cover where few icebergs were formed was followed by enhanced iceberg formation as several years’ worth of accumulated ice suddenly broke away as the fast ice disappeared.
Little is known about how a melting Greenland Ice Sheet is impacting the marine ecosystem around Greenland and this is the subject of various ongoing scientific studies. However, it will be hard to attribute particular changes in the ecosystem to changes in the ice sheet, because the ecosystem is a reflection of the combined effects of many different factors. The Greenland Ice Sheet is just one of several components of the Arctic cryosphere that are likely to affect the marine ecosystem under a changing climate. Changes in sea ice will be particularly important. This section provides examples of how changes in the Greenland Ice Sheet are likely to affect marine biological systems. To address this topic properly will require an integrated assessment involving more than just the Greenland Ice Sheet and so, by its very nature, the material presented here is of a very different type to that presented earlier for the physical environment.

**Effects cascade through the food web**

Climate change is having pronounced effects on marine systems around the world. For Greenland, the strong outflow of freshwater from the melting ice sheet is an additional factor that is causing widespread changes in the physical environment. These changes may have important consequences for food webs and could well be extremely significant for the Greenland economy, which is highly dependent on fisheries. A particular focus of attention is the influence that climate-induced change is having on the primary producers upon which the rest of the marine food web depends.

As warmth and sunlight return to the Arctic at the end of the long cold polar winter, a burst of algal growth (the ‘spring bloom’) is triggered in the ocean’s sunlit nutrient-rich surface layer. How much primary production occurs each year depends on a number of fac-
Calanus copepods are a key group in the Arctic marine ecosystem, transferring energy up the food web from the primary producers at the bottom. This fat-based transfer of energy is one of the main reasons for the large stocks of fish, birds and marine mammals in Arctic waters.

A prerequisite for successful energy transfer up the food chain is that Calanus migrate towards the sea surface as the developing phytoplankton bloom at ice break-up (upper plot). In years with an early break-up or no sea ice at all, the spring bloom may develop early and the copepods may arrive in the surface waters after it has peaked (lower plot). If a mismatch occurs, energy transfer up the food chain will be limited.
Northern Shrimp, *Pandalus borealis*, currently the most important marine resource in Greenland, is responsible for over 70% of the total fisheries revenue. Catches have gradually increased and are now roughly 150,000 tonnes per year, with 90% to 95% harvested off West Greenland.

Greenland Halibut, *Reinhardtius hippoglossoides*, has been caught off Greenland since the late 19th century when a small inshore fishery developed around Ilulissat. Offshore fisheries in East and West Greenland developed much later beginning around 1970. Recent catches (66,000 tonnes in 2007) are about equally divided between inshore West Greenland, offshore West Greenland and East Greenland.

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**Fisheries are the mainstay of Greenland’s economy**

The seas around Greenland are important fishing grounds, especially for the Northern Shrimp and Greenland Halibut fisheries which play a major role in Greenland’s economy.

The presence of sea ice is a significant factor for these fisheries. Some of the important shrimp fishing grounds are periodically inaccessible due to ice cover, while the offshore Greenland Halibut fishery is constrained by sea ice in both East and West Greenland. Sea ice also affects traditional subsistence hunting and fishing in inshore areas; especially when the ice is too poor to support fishermen and dogs but too thick for small boats to break through. It is not yet clear how a melting Greenland Ice Sheet is likely to affect the thickness and extent of sea ice (see page 13).

Overall, the direct effects of increased meltwater from the Greenland Ice Sheet on Greenland’s fish stocks are thought to be of little importance compared with those from increasing sea temperature, especially on the offshore fishing grounds. But there may be a number of indirect effects. Environmental changes resulting in a mismatch between the hatching of the shrimp larvae and the timing of the spring algal bloom (shrimp food) could affect the strength of the Northern Shrimp fishery. Whereas for Greenland Halibut, which spawn in deep ocean waters and then drift as larvae to shallower more favorable habitats, changes in ocean currents could be important.
Impacts on human society

The Greenland Ice Sheet is such a dominating feature of Greenland that, ever since the island was first inhabited, the effects of climate fluctuations on the ice sheet have had enormous impacts on the human populations living around its margin. The history of Greenland’s early Paleoeskimo cultures and that of the later Thule culture, which gradually transformed into the present-day Inuit society in Greenland, has been one of constant adaptation to changes in climate and increased interactions with European culture (see pages 20/21).

Although archeological evidence shows that many of the major changes in Greenland society coincided with major environmental changes, the interaction is complex and the socio-economic and cultural changes caused by changes in the physical environment themselves affect how society responds to future changes in the ice sheet. Links from the past cannot be used to project the direct or indirect impacts of future changes in the ice sheet on modern Greenland society.

A long history of adapting to change
Arctic societies, including those of Greenland, have always changed and have always shown a great resilience in their ability to adapt to change. This is still the case today, with major transitions in Greenland’s economy during the 19th and 20th century at least partly linked to changes in the physical environment.

How successfully a society responds to changes in the physical environment reflects the interaction between environmental change and changes in socio-economic structures. For example, a society with an economy based on a range of different resources is less vulnerable to climate change impacts than a society with an economy based on a single resource (such as a single species of fish). In Kangas-siaq in West Greenland, the local economy has been diverse enough that the community has been able to respond quickly to environmental change by switching between a range of different activities over the past 70 years: sealing and caribou hunting – cod fishing – salmon fishing – seal harvesting with nets – catfish fishing – shrimp trawling – caribou hunting using former fishing vessels for transportation to and from the hunting grounds – snow crab harvesting – lumpfish catching – cod fishing. Other examples are in Uummannaq and Upernavik also in West Greenland, where changing sea ice conditions have made hunting and fishing on and from the sea ice so difficult that the communities have responded by switching to more open-sea activities using boats.

With improved transport and communications, new activities such as tourism have introduced new sources of income, replacing to some extent the dependence on subsistence hunting and fishing.
Changing conditions, on land and at sea, affect everyday life in most Greenland communities, particularly for people who rely largely on a subsistence economy. Being able to travel at sea, and sea transport to and from Greenland, are very important for hunting, fishing, and tourism. Abandoned settlements show that not all communities have been able to adapt to change. People in remote rural communities seem particularly vulnerable. Hunting land mammals such as caribou and muskox is important in some communities and changes in the ice sheet that affect meltwater drainage patterns may in turn affect animal migrations. Subsistence hunting for marine mammals and seabirds is also important, especially in the small and remote settlements. Changes in sea ice and sea temperature will probably result in changes in food-web structures that decrease the availability of some species while increasing the availability of others.

Modern society is evolving rapidly in Greenland with around 80% of the population now involved in service sectors such as administration, education, and other such activities. These patterns are particularly pronounced in the major population centers, such as Nuuk – the capital of Greenland. Although fisheries are still generating much of the country’s revenue, there is growing interest in Greenland’s considerable raw material potential, including the potential for oil and gas, minerals, and in hydroelectric power exploitation (based on meltwater from the Greenland Ice Sheet). Renewable resources such as fish will be affected by climate change mainly as a result of its direct influence on the environment in which they live. The effects of climate change on non-renewable resources, on the other hand, will mostly be through its indirect effects on accessibility and transport.

The increasing quantities of meltwater from
Hydroelectric power is a resource that is increasingly being used in Greenland. This hydroelectric power is based entirely on water basins supplied by meltwater from the Greenland Ice Sheet. Greenland’s three operational hydropower plants currently produce enough electricity to cover 43% of domestic energy consumption. A fourth plant will open shortly near Sisimiut and a fifth plant is planned near Ilulissat.

More than 11 million tonnes of ore were extracted from the Black Angel zinc-lead mine in Maarmorilik, West Greenland, between 1973 and 1990. This mine, at the margin of the ice sheet, made an important contribution to the local economy until the accessible ore was exhausted. Although more high-grade ore was located in the near-by area, the over-lying ice made it difficult to access. A significant melt-back of the ice margin has recently eased access and made it possible to mine ore that was formerly ice-covered.

Greenland society is changing at an unprecedented rate, mainly due to the influences of globalization. In this context, the direct impacts of changes in the Greenland Ice Sheet are thought likely to be minor, at least in the near future. Whether this will be the case over the longer term, especially if climate change in general brings about major changes in, for example Greenland’s economic dependence on fisheries vs. non-renewable resources, remains to be seen.
Changes in the Greenland Ice Sheet and human occupation in the Ilulissat area

The Ilulissat Glacier/Sermeq Kujalleq and the Ilulissat Ice Fjord/Kangia have had an enormous impact on the development of human occupation in the region. Excellent hunting and fishing conditions in the Disko Bay area, resulting from the nutrient-rich meltwater draining into the ice fjord, have been the basis for life here and prehistoric hunting areas and settlements were established and abandoned as the position of the glacier front advanced and retreated.

**Inuit settlements, cultural changes and role of the Ilulissat Ice Fjord**

Various groups arrived in the region, settled for periods ranging from a few to many hundreds of years, and then disappeared. At several times, therefore, the region has been uninhabited. The area has been permanently settled since people of the Thule culture arrived around 1200 AD with the establishment of two flourishing communities, Sermermiut and Qajaa. These are among the largest prehistoric Inuit settlements discovered in Greenland and indicate the availability of rich, stable and plentiful resources over very long periods.

**Ilulissat Ice Fjord and present-day socio-economic effects**

In 1741, Jakobshavn (today Ilulissat) was established and this led to the depopulation of Sermermiut around 1850. Today, Ilulissat has a population of 4000 and is the third-largest town in Greenland. Half of Greenland’s coastal fisheries are centered here.

Abundant resources and the ability of the traditional culture to adapt to changing environmental conditions have been crucial to the prosperity of the region. But, it seems the current environmental changes may be less predictable and more challenging than they were. This may imply profound changes in the availability of nutrients, ultimately leading to changes in stocks of Greenland Halibut and Northern Shrimp. These species are extremely important, not just for human harvesting, but also for seals and whales that also form a major part of the daily food supply for people in the area, and for their sled dogs. Seabirds are also an important part of the traditional diet. The breeding success and distribution of some seabird species is very susceptible to the influences of climate change. As food webs change, other species may enter the region, offering both new and potentially prosperous options for economic activities, but also bringing uncertain consequences for existing species. Adapting to such changes is more complicated in today’s society, as fisheries are now highly industrialized and establishing new types of production is costly and requires international involvement and regulations applied to managing, accessibility and rights. Changes in sea ice cover – especially the reduction in winter sea ice – will inevitably affect subsistence hunting and fishing. It is also likely to affect marine transport and could increase access to commercial fish stocks, also causing changes in the fisheries. In this, changes in the Greenland Ice Sheet due to climate change cannot be divorced from changes to other components of the cryosphere.

The unpredictable nature of changes in the Greenland Ice Sheet makes it difficult to plan for and manage the impacts. At the same time, poor management may lead to serious and irretrievable damage.

**The ice fjord and its impact on science, politics and tourism**

The Ilulissat Ice Fjord contains one of the world’s best-studied glaciers. The ice fjord was first studied by H.J. Rink in the mid-19th century and his work formed the basis for the theory of the Quaternary glaciations. The ice fjord is still the subject of international research owing to the exceptional changes it is experiencing as the climate warms.

The Ilulissat Ice Fjord was nominated a UNESCO World Heritage site in 2004, in recognition of the uniqueness of the area and the extensive interplay between nature and culture in this region. This has made it one of Greenland’s leading tourist destinations, with over half the tourists visiting Greenland staying in this region.

*Chronology of the different cultures that have colonised Greenland and a generalised climate curve for the last 4500 years.*
The Greenland Ice Sheet is just one of many components of the Arctic cryosphere that is manifesting changes linked to a warming climate. The potentially far reaching implications of changes in the various components of the Arctic cryosphere, for both the Arctic and the Earth as a whole, are being addressed through the SWIPA project (www.amap.no/swipa).

The work under SWIPA is organized into three major components (Arctic Sea Ice, Greenland Ice Sheet, Terrestrial Cryosphere), with the terrestrial component further divided into four modules (Snow, Permafrost, Glaciers and Ice Caps, Hydrology). Assessment reports for each of these components/modules will be produced during 2010 and presented to the Arctic Council in Spring 2011. An integrated assessment report based on the key findings of the individual assessment reports will also be produced during 2010 for presentation to the Arctic Council in Spring 2011.