THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

STUDIES OF THE ARCTIC OCEAN SEA ICE COVER AND HYDROTHERMAL HEAT FLUXES

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ABSTRACT

Since reliable ice extent estimates from satellite data became available in 1979 the Arctic sea ice cover has followed a declining long term trend. Over the last decade the decline has accelerated with record low sea ice extents recorded in 2002, 2005, 2007 and 2012. In order to explain the mechanisms behind the observed ice cover decline it is critical to gain a better understanding of the climate system as a whole which in turn requires detailed studies of the involved processes. The main objective of the work presented in this thesis is to improve the knowledge of the Arctic ice cover sensitivity to climate change through detailed studies of some key processes involved.

The observed sea ice cover reduction has not been homogeneous over the Arctic Ocean. A typical pattern is that the thinning has been larger in regions with thick ice compared to regions with thinner ice. It has been argued that the ice thickness - ice growth rate feedback mechanism is the dominating process explaining these regional variations. The sea ice thickness response to variations in the atmospheric forcing is studied with a succession of increased model complexity. When the model realism is increased by the inclusion of processes such as ice divergence and variable surface albedo, the ice cover response properties become more complex with e.g. a very high sensitivity close to the transition between perennial and seasonal ice. These results imply that other mechanisms than the ice thickness - ice growth rate feedback might be more important for explaining the observed regional variations of the sea ice cover decline. It is suggested that temporal variations in the local ice divergence is one such mechanism and supporting observational data are presented.

Simulations of the present Arctic sea ice cover performed with coupled 3D models (both global and regional) show large inter-model scatter. Analyses of the mechanism behind this scatter point at differences in the surface albedo parameterization as one of the major factors. In the present thesis we address this problem by running a model with identical forcing and using a number of different albedo parameterizations taken from well-known global climate models. It is shown that the surface short wave radiation budget is strongly influenced by the choice of albedo parameterization. This means that for the same forcing the different parameterizations cannot all yield a realistic Arctic sea ice cover. Global climate models need then differences in e.g. the atmospheric composition in order to compensate for the different surface albedos such that they all produce ice covers that are fairly consistent with observations.

The effect on the Arctic sea ice cover of variations in solar insolation associated with Earth's orbital parameters is also studied. It is shown that the increased solar forcing in the Arctic during the early Holocene insolation maximum (~9500 years before present) had the potential to force the ice cover into a state dominated by seasonal ice. A compilation of available ice cover proxy data is also presented and the emerging picture is consistent with the model results.

The thesis also includes a separate study on hydrothermal plume modeling based on data collected during the AGAVE 2007 Expedition. An indirect method for estimating the heat flux of hydrothermal vents using buoyant plume dynamics in combination with water column observations is presented. The results show that one of the plumes investigated likely stems from a hydrothermal vent with a heat flux comparable to the largest known vents on Earth.

Keywords: Arctic Ocean, Sea ice, Sensitivity, Ice divergence, Albedo feedback, Ice export, Tipping point, Hysteresis, Milankovitch cycles, Holocene, Insolation, Climatic feedback, Gakkel Ridge, Hydrothermal vent, Hydrothermal plume, Hydrothermal heat flux

PREFACE

This thesis consists of a summary (Part I) and the following four appended papers (Part II), referred to by roman numerals in the text:

I. Stranne, C. & Björk, G. (2011). On the Arctic Ocean ice thickness response to changes in the external forcing. Climate Dynamics, doi: 10.1007/s00382-011-1275-y.
Stranne performed the modeling and all data analysis, had a leading role in writing the text and prepared all figures.

II. Björk, G., Stranne, C., Borenäs, K. (2012). The sensitivity of the Arctic Ocean sea ice thickness and its dependence on the surface albedo parameterization. Journal of Climate, In Press. doi: 10.1175/JCLI-D-12-00085.1
Stranne performed the modeling and all data analysis, had an active role in writing the text and prepared most figures.

III. Stranne, C., Jakobsson, M., Björk, G. (2012). Arctic Ocean perennial sea ice breakdown during the Early Holocene Insolation Maximum. Submitted to Scientific Reports.
Stranne performed the modeling and all data analysis, had a leading role in writing the text and prepared all figures except Fig. 3.

IV. Stranne, C., Sohn, R. A., Liljebladh, B., & Nakamura, K. (2010). Analysis and modeling of hydrothermal plume data acquired from the 85°E segment of the Gakkel Ridge. J. Geophys. Res., 115, C06028, doi:10.1029/2009JC005776.
Stranne performed the modeling and all data analysis, had a leading role in writing the text and prepared all figures. Stranne also participated in the AGAVE 2007 Expedition and was involved in collecting the data on which the paper is based.

OTHER RELEVANT PUBLICATIONS BY THE AUTHOR:

Sohn, R.A., Willis, C., Humphris, S., Shank, T.M., Singh, H., Edmonds, H.N., Kunz, C., Hedman, U., Helmke, E., Jakuba, M., Liljebladh, B., Linder, J., Murphy, C., Nakamura, K.-I., Sato, T., Schlindwein, V., Stranne, C., Tausenfreund, M., Upchurch, L., Winsor, P., Jakobsson, M., Soule, A. (2008). Explosive volcanism on the ultraslow-spreading Gakkel ridge, Arctic Ocean. *Nature*, 453(7199), 1236-1238. doi:10.1038/nature07075

Stranne, C. (2006). On the water exchange of small sill fjords – with application to the By Fjord, Uddevalla, Sweden. (M. Sc Thesis) *Earth Science Center*, University of Gothenburg, B495 2006, ISSN: 1400-3821

CONFERENCE PROCEEDINGS:

Upchurch, L., H. N. Edmonds, J. Resing, K. Nakamura, N. Buck, B. Liljebladh, C. Stranne, G. Tupper, and P. Winsor (2007). Geochemical characterization of hydrothermal plume fluids from peridotite- and basaltdominated regions of the ultra-slow spreading Gakkel Ridge*, Eos Trans. AGU,* 88(52), Fall Meet.

Stranne C., Winsor P., Sohn R. A., Liljebladh B. (2009). Heat flux estimates from the Gakkel Ridge 85E vent field from the AGAVE 2007 expedition, *Geophysical Research Abstracts*, Vol. 11, EGU2009-5441-1, EGU General Assembly 2009.

Björk, G. & Stranne, C. (2009). Response characteristics of the Arctic Ocean ice thickness on ice export perturbations. MOCA-09 (IAPSO) General Assembly, Montreal, Canada.

Stranne C. & Björk, G. (2010). A survey of forcing and albedo sensitivity of the Arctic Ocean ice cover. American Geophysical Union, Fall Meeting 2010, abstract #C43D-0568

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Part I

Summary

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1. Introduction and scientific background

1.1 A brief retrospect of Arctic exploration and research

Humanity has long been fascinated by the place in the north towards which the compass needle mysteriously points, the place we call the Arctic. Historically this region has been surrounded by myths. In the 14th century it was believed that ships could be drawn down and destroyed in the maelstrom, a huge rotating vortex that later reappeared in novels by Edgar Allan Poe and Jules Verne and more recently in the movie *Pirates of the Caribbean*. Another myth was that iron could be drawn out from ships by the Lodestone Mountain, an enormous magnetite mountain situated at the North Pole that was believed to attract all the compass needles of the world. In the early 19th century John Cleves Symmes Jr. (1779 – May 1829) proclaimed that the Earth consists of a hollow shell and four inner shells with openings, around 2300 km wide, at both poles. The Arctic myths have also spread in popular culture. For instance, Thomas Nast used the North Pole as the location for Santa Clause's home in his drawings. Jules Verne wrote the highly appreciated sci-fi book *A Journey to the Center of the Earth* on the Arctic opening into a hollow Earth theme. The monster in Mary Shelly's *Frankenstein* travels to the North Pole in search for peace and quiet and it is also the location for Superman's Fortress of solitude.

Before we continue it is important to stress that indigenous people have populated the Eurasian- and later the American coastline of the Arctic Ocean for thousands of years and that they have their own history of Arctic exploration of which unfortunately very little is known. Between the late 15th and early 20th centuries the motivation for Arctic exploration was primarily geographically oriented, first with shorter trade routes between Europe and the Far East as the main objective and later on with scientific curiosity and national pride perhaps being stronger driving forces. The first recorded attempt to find a passage through the Arctic was made by the Italian explorer John Cabot (c. 1450 – c. 1499) in 1497 and was followed by many failed attempts of which perhaps the most famous (and also tragic) was the British *Franklin Expedition* in 1845 where none of the 129 men onboard the two expedition vessels were ever to return. The many attempts to find pathways over the Arctic Ocean, both through the Northeast- and the Northwest Passages led to an increasingly detailed knowledge of the Arctic Ocean coastlines and islands but it wasn't until 1878 that Adolf Erik Nordenskiöld (1832 – 1901), a Finnish-Swedish explorer, made the first complete passage through the Northeast Passage with the sailing ship *Vega* (Fig. 1). Twenty-eight years later, in 1906, the famous Norwegian explorer Roald Amundsen (1872 – 1928), who later became the first human to set foot on the South Pole, conquered the Northwest Passage with a six man crew on board the small fishing vessel *Gjøa*. Due to the sometimes severe ice conditions and harsh weather in the Arctic, these routes never became economically viable, perhaps partly due to the opening of the Suez Canal in 1869. We will however return to this long sought after short cut through the Arctic in a later chapter since it has regained some attention over the last decade.

Figure 1. Adof Erik Nordenskiöld with *Vega* in the background. Painted by Georg von Rosen (1843–1923)

In the late 19th century the scientific interest in the Arctic started to awaken with Fridtjof Nansen (1861 – 1930) being one of the pioneers. Nansen became a world celebrity with the release of his book *Farthest North* where he describes his amazing adventures together with his crew on the *Fram expedition* 1893 – 1896 (Fig. 2). The scientific results from the *Fram expedition* was later published in 6 volumes and laid the ground for the modern understanding of the Arctic Ocean. Nansen contributed to the science of oceanography both with research articles and with development of new observational techniques. For instance, his studies of near surface currents later led to the discovery of the *Ekman Spiral* by the Swedish physicist Vagn Walfrid Ekman (1874 - 1954). The Nansen bottle for taking water samples is an example of his talent as an instrument developer and an improved version of the Nansen bottle (called Niskin bottle) is still used in oceanographic field work.

Nansen. Hendriksen.
Vannhenteren og termometerne er kommet op. (Fotografi 12. juli 1894.)

Figure 2. Fridtjof Nansen and college taking water samples during the Fram Expedition. Picture taken from the book *Farthest North*.

Nansen's idea to use drifting ice flows for the exploration of the Arctic Ocean, a method he himself successfully applied during part of the Fram expedition, was again utilized in 1937 when the first Soviet Union drifting ice station *North Pole-1* began to operate. This was the beginning of an extensive research program which was ongoing, with a couple of drifting ice stations usually running in parallel, until 1991 when the last Soviet station *North Pole-31* was closed. Twelve years later, in 2003, the program was resumed by Russian scientists through the launch of *North Pole-32*. Many important discoveries have been made as a result of the research program. Some of the most important include finding the Lomonosov Ridge and other bathymetric features of the Arctic Ocean, and the discovery of the large scale sea ice drift systems (although Nansen was a pioneer also in this respect).

1.2 Modern Arctic research

Judging from the increasing Arctic tourism (with for example North Pole tourism with Russian ice breakers and weekend packages to Svalbard gaining in popularity) the public interest seems to thrive also in present time. But what about the scientific interest in the Arctic? Is it perhaps quantifiable? If we use the number of published peer reviewed research articles per year with a title including the word *Arctic*, as a proxy for the scientific interest it appears to be increasing exponentially with time (Fig. 3a). This is however a deceiving proxy since the overall production volume of research articles appears to be following the same exponential trend as here exemplified by plotting the corresponding curves for published articles with titles including the words *Atlantic* and *Pacific*.

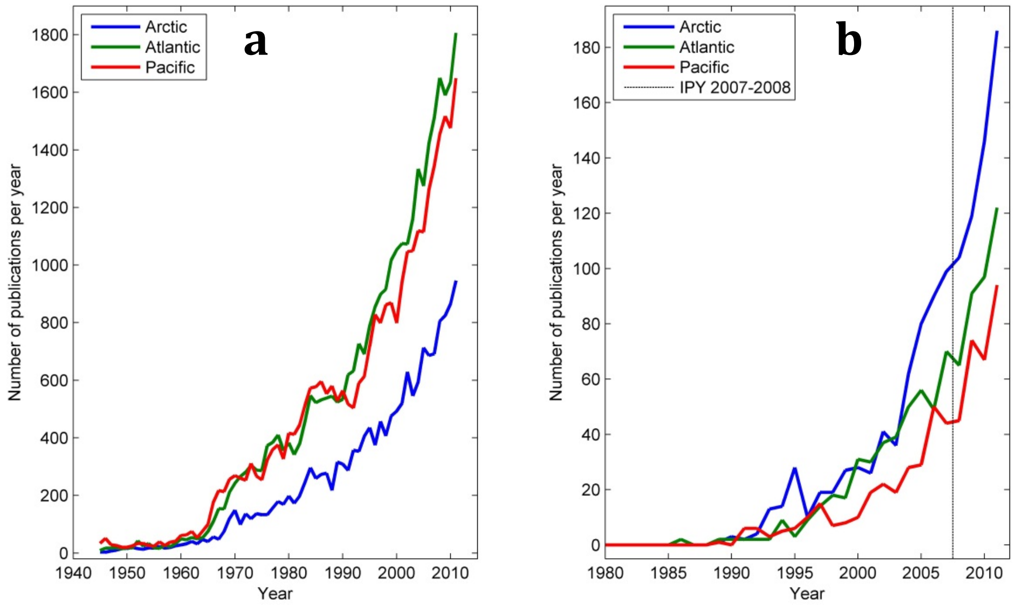


Figure 3. Number of published peer review articles per year, taken from the ISI Web of Science - Science Citation Index Expanded data base, plotted against time. Panel a) with the word Arctic (blue), Atlantic (green) and pacific (red) included in the title and panel b) the same as previous but with the additional phrase "climate change" as part of the topic. Also shown in panel b as a vertical black line, is the International Polar year 2007-2008.

Is the notion that the Arctic is a region of increasing scientific interest completely wrong then? The answer is no; the Arctic region is definitely a hot scientific topic and subject to intense (and intensified) research efforts. The research is however mainly associated with a fairly narrow range of question formulations. When constructing the same curves as in Fig. 3a but adding the phrase *"climate change"* with quotation marks as a required topic, we get an entirely different result which should give us a clue (Fig. 3b). Apart from the fact that the phrase *climate change* seems to start appearing in the research literature in the early 90s, we see that the number of research articles per year with titles including the word *Arctic* actually exceeds both corresponding *Atlantic* and *Pacific* curves from around 2003 and onward. During 2011 there were actually twice as many articles published with a topic including the phrase *"climate change"* and with the word *Arctic* in the title compared to the corresponding number but with the word *Pacific* in the title. This would be very surprising statistics if only considering for instance the number of people living along the coast lines or the relative size of the three oceans. The picture becomes however less surprising after a glance at Fig. 4.

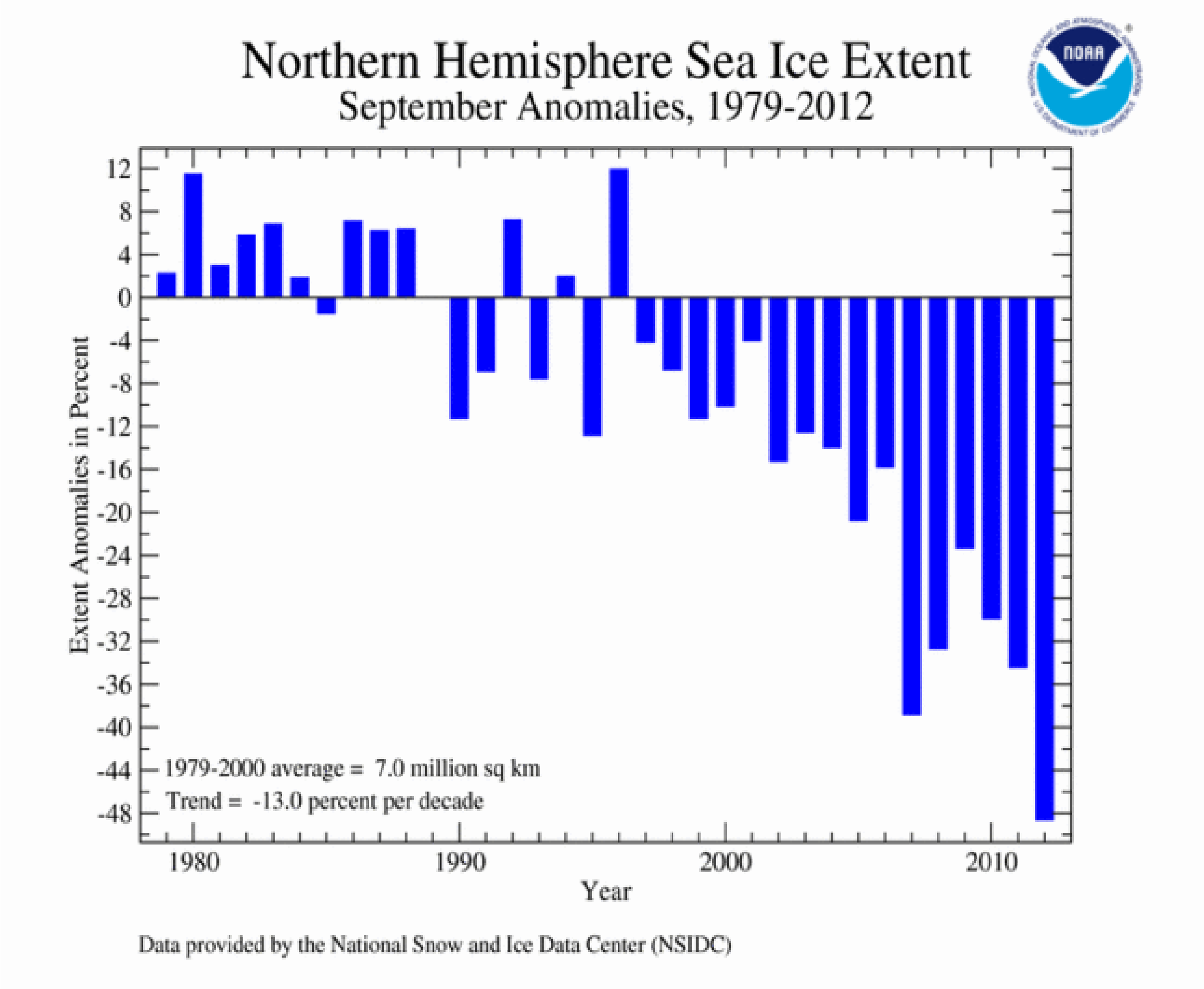


Figure 4. September sea ice extent anomalies in the Arctic from 1979 to present based on satellite data..

1.3 The recent Arctic sea ice cover decline

As illustrated in Fig. 4-5, the Arctic ice cover extent in summer has experienced a series of record lows over the last decade. A record low September ice extent was recorded in 2005. In 2007, after a slight recovery in 2006, the ice extent fell to a new record low, more than 20 % below the previous 2005 record (Stroeve et al. 2008). Since then, the ice cover has not recovered and a new record low was again recorded in 2012.

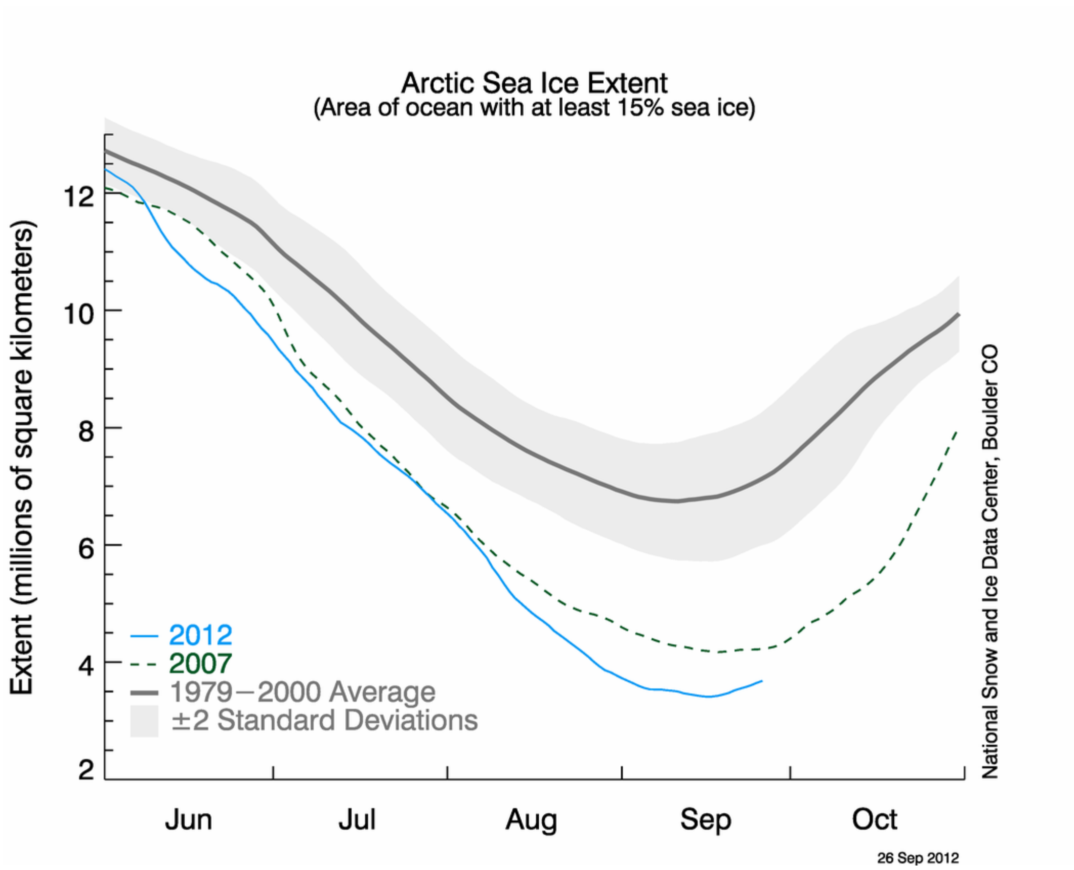


Figure 5. Arctic summer sea ice extent for the 1979-2000 average and the two record minimum years 2007 and 2012.

The reason for the Arctic sea ice decline is a complicated yet central question and a subject we will return to in later chapters. But first let us ask ourselves if Fig. 5 provides an adequate picture of the actual ice cover decline in the Arctic over the last decades. The curve is based on estimates of the sea ice concentration from satellite imagery and tells us essentially nothing about the variations in ice thickness. What if the ice covered area was reduced at the same rate as the mean ice thickness was increasing? Then Fig. 5 would not provide a fair representation of recent trends of the Arctic sea ice cover, especially not if we are interested in the change in sea ice volume. In the early 2000's voices were raised that this might in fact be the case (e.g. Winsor, 2001; Holloway & Sou, 2002). For this reason the thickness of the Arctic sea ice cover and its change over time is of great scientific interest. Reliable ice thickness estimates are however somewhat more problematic to gather compared to ice extent estimates, largely due to the much lower accuracy of satellite derived ice thickness. Most of the available records of ice thickness estimates are compiled in the *Unified Sea Ice Thickness Climate Data Record* (Lindsay, 2010). The database consists of Upward Looking Sonar (ULS) records from US and UK submarine tracks sporadically available from 1975 to present. Thickness estimates from ULS are also available from a number of different mooring projects since the early 2000's. The ICESat satellite provide laser-altimeter freeboard measurements and ice thickness estimates are available sporadically from 2003. Other estimation methods include using age of sea ice as a proxy (Rigor & Wallace, 2004), measurements of the dispersion of ice swell with seismometers (Marsan et al., 2012) and the new Soil Moisture and Ocean Salinity (SMOS) Satellite which provides data since summer 2010 (Kaleschke et al., 2012). If considering all the available ice thickness records it becomes quite clear that there has been a real and significant negative volume trend of the Arctic Ocean sea ice cover over the last several decades. For instance, through a range of observations and modeling approaches, including in situ ice thickness measurements and ICESat retrieved ice thickness, Schweiger et al. (2011) presented an estimate of the Arctic ice volume trend of −2.8 ± 1 $\cdot 10^3$ km^3 $decade^{-1}$ since the late 70's (Fig. 6, note that the figure has been updated since the publication and that the present linear trend is -3000 km^3 $decade^{-1}$).

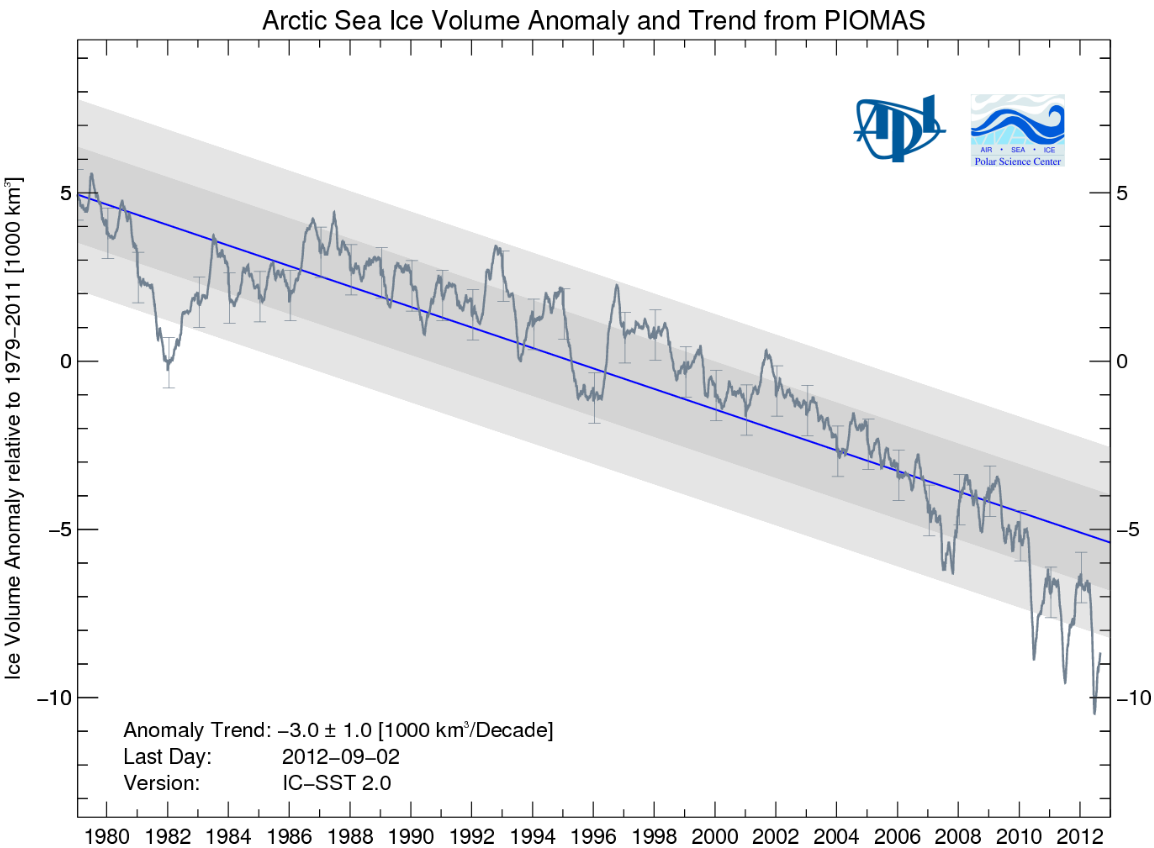


Figure 6. Estimated Arctic sea ice volume anomaly relative to 1979 – 2011 average.

There are no doubts that the Arctic Ocean ice cover is being reduced and that the reduction has been ongoing, more or less continuously, since the late 70's. The knowledge of the variations of the Arctic sea ice cover prior to the satellite era is however considerably more limited. We do know that the ice cover has been highly variable on multi-millennial time scales (a subject we will return to) but judging from the many failed attempts to conquer the passages through the Arctic over the last several centuries, the present state and rate of change of the ice cover might very well be exceptional in terms of more recent history. By combining findings from various excavation sites with climate proxy data, Archaeologists have developed scenarios of how past climate changes have affected human life within the Arctic. One of the clearest examples of such links was the expansion of indigenous bowhead whaling and the rapid spread of the whaling based coastal Eskimo cultures from northern Alaska across the central Canadian Arctic to Baffin Island and Greenland around 1000 years ago, associated with the so called *Medieval Warm Period.* Based on recent radiocarbon dating and paleoenvironmental data, this substantial shift in population and economy took place within less than 200 years and was caused at least partly by the declining sea ice conditions in the Arctic (IASC, 2012). The driving mechanisms behind this apparently rapid change of the Arctic sea ice cover are not yet fully understood. Comparisons between Scottish and Moroccan climate proxy data suggest that it might have been associated with a period dominated by a persistent and strong positive mode of the North Atlantic Oscillation (Trouet et al., 2009). This would then mean that Earth during the *Medieval Warm Period* was not subject to a global mean temperature rise but rather a large scale redistribution of heat.

1.4 The resurrected quest for faster trade routes

The first successful journey through the Northeast Passage in 1834 was followed by several successful expeditions of both scientific and exploratory nature. However, the so called *Northern Sea Route* (Fig. 7) through the Northeast Passage did not find economic viability until the Soviet era and was then largely politically motivated. In 1932, a Soviet expedition led by Professor Otto Yulievich Schmidt was the first to sail all the way from Arkhangelsk to the Bering Strait in one summer and three years later the Northern Sea Route was officially opened for commercial exploitation. After the breakup of the Soviet Union in the early 1990s, commercial navigation in the Siberian Arctic went into decline. The Northern Sea Route was officially reopened in 2005 due to the favorable ice conditions and in 2009, the first western company sailed through the Arctic without assistance from icebreakers, cutting 4000 nautical miles off the journey between South Korea and Holland (Ho, 2010). Gains from shipping on the Northern Sea Route might become quite substantial if the observed sea ice decline continues. Ice free navigation through the Northeast Passage would mean reduced number of days at sea and more than a doubling of the vessel fuel efficiency when shipping between northern European and northern Pacific ports (Schöyen & Bråthen, 2011).

Figure 7. A graphical comparison between the Northern Sea Route (blue) and the route through the Suez Canal (red) between South Korea and Holland, a 4000 nautical mile difference.

2. The CCAM model – a versatile tool

Papers I-III are based on modeling results from the Coupled Column Arctic Model (CCAM). The model has been developed by Göran Björk (e.g. Björk, 1989; Björk, 1992; Björk, 1997). The atmospheric part of the model is a stand-alone version of the CCSM3 radiative module (Collins et al., 2006) which was coupled to the ice and ocean models by the present author. Below we will explain the model in some detail and discuss the basic model assumptions.

The Arctic is a complex climate system characterized by intimate couplings between the atmosphere, the sea ice cover and the ocean. The individual processes and mechanisms of the system are in climate models formulated as mathematical functions of one or several variables. The ice growth rate, for example, can be formulated as a function of the ice thickness, the atmospheric surface temperature, the ocean salinity and temperature close to the ice interface, and the internal ice temperature. Such mathematical formulations of various processes can be more or less sophisticated, they can be based on empirical as well as theoretical arguments, and constitutes the foundation of the model computer code. In climate models we also find so called parameterizations. While also being mathematical formulations, parameterizations refer to a method of replacing processes that are too small scale or complex to be physically represented in the model by a simplified function, often based on empirical knowledge. Typical parameterizations used in climate models are e.g. the cloud formation and precipitation processes. The potential importance of one specific parameterization (the surface albedo) is investigated in *paper II*.

Changes in the state of the modeled system are caused by changes in the model forcing. The climate system is influenced by spatial and temporal variations in the forcing on a wide spectrum of time- and length scales. However, by considering only the horizontally integrated properties of the system components, the spatial variations can be hidden in a presumably meaningful horizontal average which simplifies the model complexity considerably. This approach is always applied to some extent in climate modeling since the smallest length scale of the real system can be on the order of millimeters. It is however taken to its extreme in the present model where the horizontally averaged domain includes the whole Arctic Ocean. This is however not entirely true since a so called sub-grid ice thickness distribution is applied. The influence of this ice thickness distribution is investigated and discussed in some detail in *paper I*.

The ice cover response to temporal forcing variations is a complex issue partly due to different inertial timescales (or response time scales) of the various components of Arctic climate system. For instance, thick ice reacts more slowly to forcing perturbations than thin ice; the response in cloud formation is usually faster than the ocean deep water response and so on. To further complicate things there is a wide spectrum of time scales associated with the different feedback processes e.g. surface albedo feedback associated with vegetation and glaciers works on longer time scales than the feedback related to atmospheric water vapor content. By applying identical seasonal cycles of the forcing the modeled Arctic will eventually reach a quasi-steady state, meaning in this context that the seasonal cycles of the model state variables are identical each year. In this way the temporal variations in the forcing (other than the seasonal cycle) is "filtered out" so that only the average seasonal cycle of the climate system is considered. The notion that the actual average state of the Arctic climate can be simulated by applying average forcing might not however be entirely accurate and the reason for this is discussed in section 3.5.

Through the assumption that the Arctic climate can be described in a meaningful way as a horizontally integrated system in quasi-steady state and with a number of processes parameterized we arrive at the present Coupled Column Arctic Model (CCAM) based on around 10,000 lines of computer code. Although rather basic in that it is one dimensional (regional and global 3D models are more commonly used in climate modeling), this model is still fairly sophisticated and could be termed as state-of-the-art in its class, at least in some respects. But more importantly - it is a very useful and versatile tool.

However, just because we do not consider spatial (and to an extent temporal) variations in the forcing in this modeling approach, it does not necessarily mean that the effect from such variations can or should be ignored. Some aspects of temporal and spatial forcing variations can however be investigated further from this basic column model set up. For instance, by assuming a smaller horizontally integrated model domain we can apply "local" forcing and in this way assess the importance of spatial variations. This was done to some degree in *paper I* where local variations of ice divergence (related to the local ice export) is considered and similarly in *paper II* where latitudinal variations in solar insolation is studied. Also the transient sea ice response to temporal forcing perturbations of different magnitude and length can be systematically investigated from this model set up. In section 3.5 we present a concept of how such studies could be performed without going particularly deep into the subject.

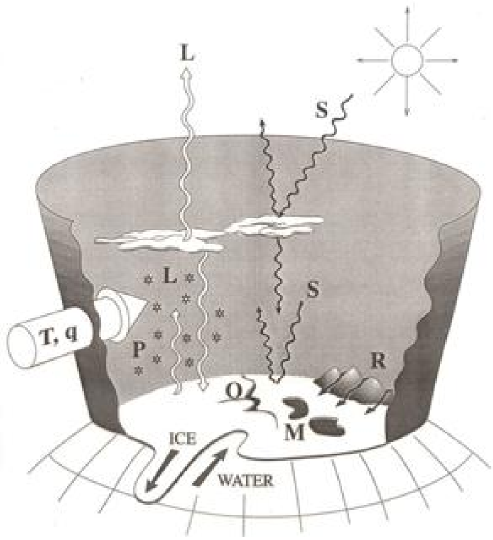
3. The sensitivity of the Arctic Ocean sea ice cover

3.1 Introduction

A natural question to ask in the light of the recent Arctic sea ice decline is how sensitive the ice cover is to changes in the atmospheric and oceanic conditions. This is also a central question in the present thesis. The sensitivity of the ice cover to climate change can be tested by varying the model forcing and study how the ice cover reacts. It is often convenient to perform such tests on the external forcing since it is always explicitly specified in the boundary conditions of the model. There are three dominating forcing quantities in the Arctic climate system: the net atmospheric advection (or transport) of energy into the Arctic (F_{wall}), the incoming solar radiation and the long wave radiation back to space. The incoming solar radiation is independent of climate change (on shorter time scales) and the radiation back to space is an internal quantity in this respect which is highly dependent on F_{wall}. For these reasons and also for consistency, the sensitivity of the Arctic sea ice cover is mainly tested through variations in F_{wall}. In *paper II* we also use, in addition to F_{wall}, the solar radiation (in terms of latitude) as a variable forcing quantity while in *paper III* the sensitivity of the Arctic sea ice cover to changes in solar radiation on inter-millennial time scales (associated with changes in Earth's orbit and rotational angel in relation to the Sun) is investigated.

In this chapter we will first present the main constituents of the Arctic energy budget and their seasonal cycle, followed by a brief discussion regarding the implications of these seasonal variations on the sea ice cover. We will then proceed to discuss different kinds of processes and their relative importance for the modeled Arctic sea ice sensitivity. The transient ice thickness response to forcing perturbations of different length and magnitude is then discussed in the context of the quasi-steady state approach applied in the present thesis. We end the chapter with a discussion regarding Arctic sea ice cover variations on inter-millennial time scales, related to the findings in *paper III*.

3.2 The Arctic energy budget



R = Runoff (freshwater)
L = Long wave radiation
S = Short wave radiation
O = Ocean heat
M = Melt (snow and ice)
P = Precipitation
T = Temperature (heat transfer)
q = moisture

Figure 8. Schematic sketch of the Arctic heat budget. Image provided by National Snow and Ice Data Center, University of Colorado, Boulder.

The atmospheric part of the model domain can be visualized in a schematic cartoon (Fig. 8) where the different constituents of the Arctic energy budget are shown as arrows. Note that the big arrow including T and q corresponds to the F_{wall} parameter discussed above. The Arctic climate system is heavily influenced by seasonal variations in the Arctic energy budget. For instance, solar insolation (at the top of the atmosphere) changes from a maximum in late June reaching over 700 Wm^{-2} to zero (i.e. complete darkness) for more than 100 days during winter. The impact on the ice cover from these seasonal variations becomes apparent when considering the typical seasonal cycle of the sea ice concentration (Fig. 9).

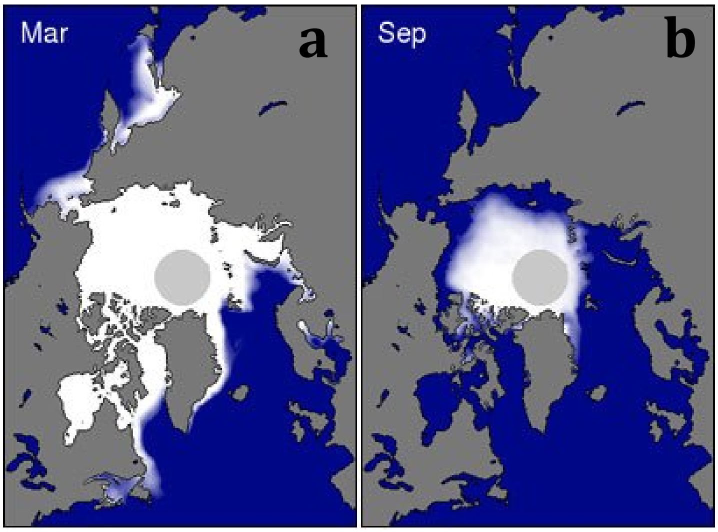


Figure 9. Arctic sea ice concentration climatology from 1979-2000, at the approximate seasonal maximum (a) and minimum (b) based on passive microwave satellite data. Image provided by National Snow and Ice Data Center, University of Colorado, Boulder.

Having knowledge of the seasonal cycles of the different constituents of the Arctic energy budget is essential when trying to understand and to model the system. The dominating components can be separated into horizontal atmospheric energy transports (F_{wall}), net radiation at the top of the atmosphere and net heat transfer between the ocean/ice – atmosphere interface (Fig. 10). The sign of the heat budget constituents are defined as positive when adding energy to the Arctic atmosphere. The ocean then loses heat to the atmosphere during winter and gains heat during summer with a net heat loss of about 11 Wm^{-2}. F_{wall} is around 100 Wm^{-2} and is fairly constant over the year. The net energy flux at the Top Of the Atmosphere (TOA) is dominated by outgoing long wave radiation in winter and during summer the outgoing long wave radiation is on about equal footing with the incoming short wave insolation.

The data presented in Fig. 10 as well as some the forcing parameters used in the CCAM are based on so called reanalysis data products. Reanalysis a systematic method of producing organized data sets from data assimilation i.e. incorporating observed data into a computer model of the real system. The sources, techniques and amount of observational data that goes into the assimilation often vary with time and region. This is one of the problems with reanalysis products since such inhomogeneities can result in artificial variability and trends in the data set. It is however often the best option for constructing climatologies (as here used for some of the model forcing). The sources for atmospheric assimilation data include e.g. satellites, buoys, aircrafts and ship reports. In the NCEP/NCAR reanalysis product (which is one of the more commonly used atmospheric reanalysis) approximately 7-9 million observations are assimilated at each time step (with a temporal resolution of 6 h).

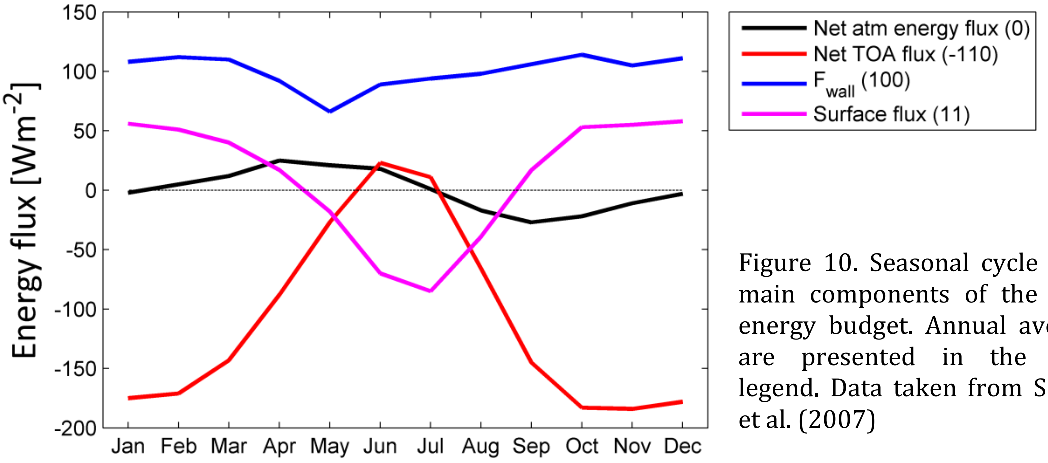


Figure 10. Seasonal cycle of the main components of the Arctic energy budget. Annual averages are presented in the figure legend. Data taken from Serreze et al. (2007)

3.3 Important processes and mechanisms

Various assumptions and simplifications are always necessary when attempting to model a climate system. If we limit the discussion to the category of coupled column models in the Arctic, the degree of simplification spans between simple analytical "one equation" thermodynamic models to the present quite sophisticated numerical model. But seeking the highest model complexity shouldn't necessarily become a purpose of its own. The level of model complexity should rather be adapted to the kind of questions we want answers to. For instance if we want to study the basic thermodynamic effect of increased oceanic heat flux, a simpler model where this forcing is a prescribed parameter would perhaps be preferable to the present CCAM where the oceanic heat flux is an internal quantity. On the other hand, if we want to study the effect of a certain process this process must, for obvious reasons, be included in the model e.g. in order to investigate the role of brine production on the ocean mixed layer depth, the model must include brine production and an active mixed layer to begin with. For this reason, a sophisticated model such as CCAM becomes a very versatile tool in that it includes a large number of processes.

There are probably limits to what degree a model can be simplified while still producing meaningful results. In *paper I* we look into this problem from a sea ice thickness sensitivity point of view, by comparing model results from the CCAM with results from the analytical version of Thorndike's *Toy Model* (1992). When some of the more important processes that are not included in the Analytical Toy Model (ATM) are switched off in the CCAM, the two models turn out to produce very similar results in terms of sea ice thickness response properties. This tells us basically that the ~10,000 lines of computer code that make up the CCAM are more or less interchangeable with one single equation in this respect. Apart from evidence of Thorndike's fundamental understanding of the Arctic climate system, this is also a verification of the CCAM model. A natural continuation from here is to pinpoint the additional processes included in the CCAM and to determine their relative importance.

But let us first consider the basic response properties of this simplified Arctic sea ice cover. The response properties of the ice cover to steady state perturbations in the forcing can be visualized in what we define as a *response curve* where the annual mean steady state ice thickness H_{ice} is plotted against the steady state forcing perturbation *p* from the baseline forcing. The gradient of the response curve, $dH_{ice}(p)/dp$ is then a measure of the ice thickness sensitivity at a steady state $H_{ice}(p)$. In this case we use F_{wall} as a forcing perturbation parameter. The ATM response curve (Fig. 11) shows that the ice cover sensitivity is a strong function of the steady state ice thickness: thin ice is significantly less sensitive than thick ice.

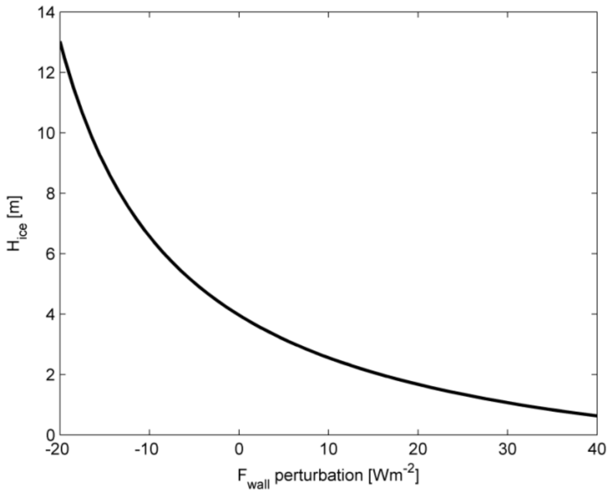


Figure 11. The ATM response curve.

The simplest way to explain the mechanism behind this non-linear relation between ice thickness and ice thickness sensitivity is perhaps through a conceptual figure. Following Thorndike (1992) the growth rate integrated over the whole year, *G* can be described as a non-linear function of mean ice thickness H_{ice} (Fig. 12, note that this is a conceptual figure with an arbitrary non-linear curve). We assume steady state meaning that the total annual growth *G* equals the total annual melt *M*. Now, if we increase *M* by increasing the solar insolation the ice thickness will be reduced every year until *G* has increased enough to match the new *M*. Consider two scenarios, one with relatively thick (Fig. 12a) and one with relatively thin (Fig. 12b) steady state ice thickness. When perturbing *M* by the same amount in the two cases, the sea ice thickness must be adjusted significantly more in the “thick ice scenario” compared to the “thin ice scenario”. This is a well-known thermodynamic property of sea ice, described by Bitz & Roe (2004, hereafter abbreviated as B&R) as an ice thickness - growth rate feedback.

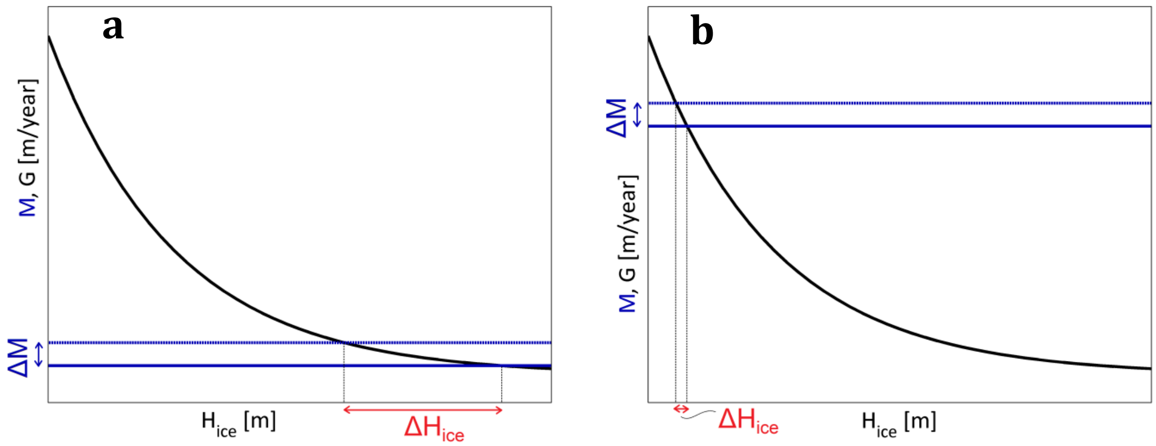


Figure 12. Conceptual figure showing annual ice growth G (black line) and annual melt M (blue line) as a function of ice thickness for a "thick ice scenario" panel *a* and a "thin ice scenario" panel *b*. A perturbation in M results in a larger ice thickness change (indicating high sensitivity) in the "thick ice scenario" compared to the "thin ice scenario".

The ice thickness – growth rate feedback implies that the sensitivity of the ice cover is reduced with declining ice thickness. One can attempt to use this feedback to explain the observed spatial variability of the Arctic sea ice reduction and this is exactly what was done by B&R. By examining ice thickness estimates from submarine freeboard measurements during two periods, 1958-1976 (defined as "initial ice thickness") and 1993-1997 they found a clear correlation between initial ice thickness and ice thickness reduction (or sensitivity) which match the ATM response curve fairly well. This provides quite a strong argument that the ice thickness growth rate feedback is the dominating mechanism explaining the observed relation between ice thickness and sensitivity. We will however argue that this might not be a correct conclusion.

In *paper I* we recognize four potentially important processes that are absent in the ATM and we investigate their relative influence on the Arctic ice cover in terms of ice thickness sensitivity. The absent processes are:

i) Ice deformation through a parameterization representing ice ridging. The ridging process gives rise to a "sub-grid" Ice Thickness Distribution (ITD) rather than the uniform slab of ice assumed in the ATM.

ii) Ice export out of the Arctic Ocean. The effect of ice export on the Arctic sea ice cover is investigated by a few different ice export parameterizations with different degree of realism.

iii) Snow precipitation. The effect of snow precipitation is also investigated in some more detail in *paper II*.

iv) A dynamic surface albedo parameterization dependent on the surface properties. The importance of the details of the albedo parameterization is treated in *paper II*.

For an in-depth discussion regarding the results the reader is referred to *paper I*. We will however discuss some of the implications of the results here. We show that two of these processes have a substantial influence on the shape of the ice thickness response curve: the sea ice export and the dynamic surface albedo parameterization.

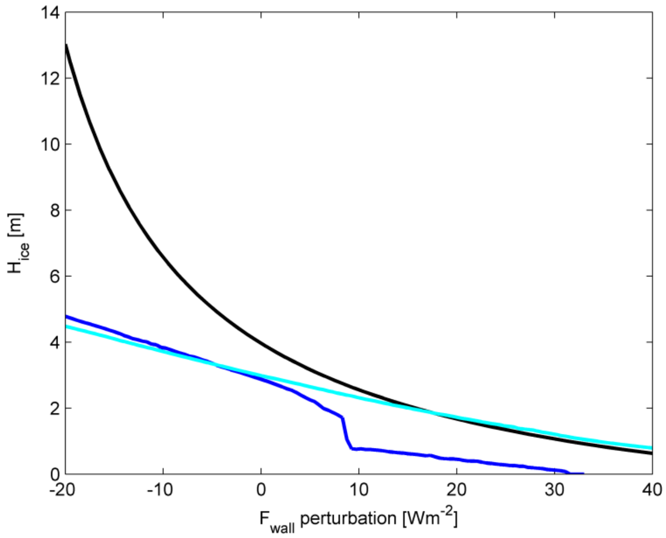


Figure 13. Response curves for the ATM (black), CCAM without surface albedo feedback (cyan) and CCAM including surface albedo feedback (blue).

Different ways to parameterize ice export are discussed and we argue that a reasonable way to do it is through an assumption of a seasonally dependent sea ice area export (linked with the typical large scale atmospheric circulation). This implies that the thicker the ice cover becomes the larger volume is exported, a linear relation which has a strong stabilizing effect on the ice cover sensitivity. This means that the ice export mechanism works as a so called negative feedback on the ice thickness sensitivity. A feedback is in this context defined as a change in the sensitivity, of in this case the average ice thickness, when a mechanism is included in the model compared to when it is not. It can however be slightly more complicated than that. For instance, the strength of a feedback can be non-linear such that it is stronger for e.g. positive forcing perturbations than for negative. A feedback mechanism can also be highly dependent on the state of the climate system meaning for instance that it might be weaker in a colder climate and stronger in a warmer climate or vice versa.

When plotting the response curve for the case with a seasonally dependent ice area export the ice thickness sensitivity becomes constant and independent of ice thickness rather than non-linear as the ATM response curve indicates (cyan curve, Fig. 13). Adding a variable surface albedo dependent on ice thickness, the shape of the response curve is altered again (blue curve, Fig 13). Now the response curve can be divided into two linear regimes, a *perennial* and a *seasonal* sea ice cover regime, separated by a steep transition. By perennial sea ice cover we mean an ice cover that never completely disappears in summer (although it might be significantly reduced) as opposed to a seasonal sea ice cover where all ice is lost during a period in summer. The present day sea ice cover is perennial as shown in Fig. 9, but as we will discuss in *paper III* things might have been different 9000 years ago. Perhaps even more interesting, especially when considering the recent sea ice decline of the Arctic Ocean, is the fate of the perennial ice cover in the near future.

Considering the CCAM response curve with all processes included (blue curve, Fig. 13) the sensitivity as a function ice thickness is quite different from the ATM response curve (black curve, Fig. 13). More importantly it does not agree with the ice thickness sensitivity inferred from submarine observations any longer. In *paper I* we argue that the additional processes included in the CCAM rest on solid theoretical grounds and should add to the realism of the response curve. Moreover, support for the CCAM response curve, with the two ice cover regimes separated by a steep transition, can be found in General Circulation Model (GCM) studies. Although not directly comparable to our study, Holland et al. (2006) demonstrate a similar steep transition of the Arctic sea ice cover when simulated with a GCM under increasing CO_2 forcing. There are indeed some problems with this comparison but the basic mechanism behind the transition is the same in both studies and is often referred to as *surface albedo feedback*. We will discuss this feedback in more detail in section 3.4 since it is the topic of *paper II* but let us first return to the discrepancy between the CCAM response curve and the inferred sea ice sensitivity from submarine observations.

In *paper I* it is suggested that the match between the observed ice thickness sensitivity and the thermodynamic ice thickness - growth rate feedback is coincidental, a possibility that is also recognized by B&R. What are then the alternative explanations to the spatial variation of the Arctic sea ice cover reduction? In *paper I* we show that the sea ice sensitivity is a function of local ice export (or ice divergence): low divergence gives a thicker but also more sensitive ice cover. We then proceed by studying observational divergence data and we establish that there are indeed significant spatial variations in the average divergence of the Arctic Ocean. But perhaps more importantly, we show that the divergence has undergone a quite substantial change over time. Such dramatic regional changes in divergence should, at least in theory, have an effect on the local ice thickness (*paper I*, Fig. 4). From this notion alone we can assume that the observed regional variations of the Arctic Ocean ice cover reduction was not solely caused by the thermodynamic ice thickness – growth rate feedback. The shift in divergence is likely connected to the large scale atmospheric circulation. Numerous studies have shown that the ice export through Fram Strait correlates well with the North Atlantic Oscillation (NAO) index (e.g. Hilmer and Jung 2000, Kwok et al. 2004). When looking at the long term average of the NAO we see that the 60s (defined as the initial state of the Arctic ice cover in B&R) was dominated by a negative mode while the 90s (used to calculate the ice thickness change in B&R) was dominated by a positive mode (Fig. 14). Without going deeper into this subject we conclude that the mode of the large-scale atmospheric circulation of the Arctic seems to have shifted between the 60s and the 90s and that this shift might have influenced the regional variations of the Arctic sea ice reduction.

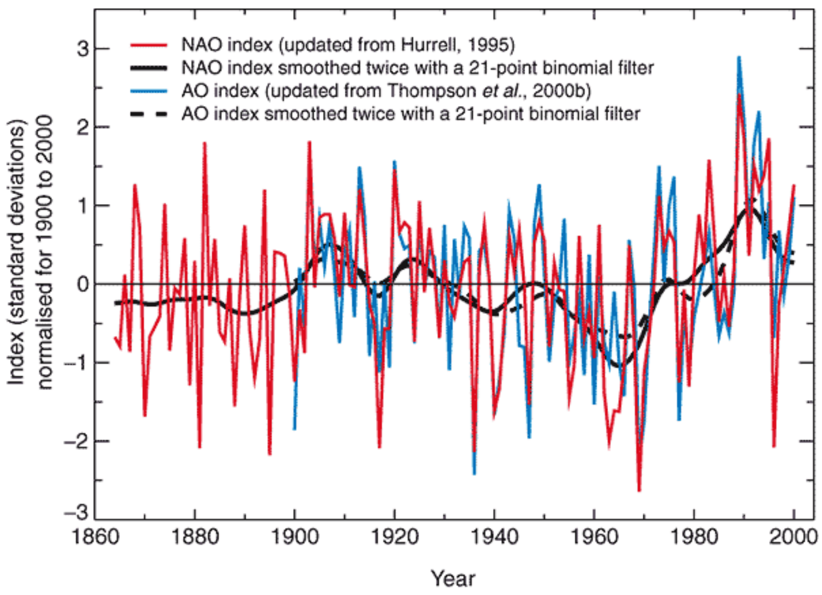


Figure 14. The Arctic Oscillation index plotted against time. Figure taken from IPCC AR3 (2001)

3.4 The influence of the surface albedo parameterization on the modeled sea ice

Simulations of the present and future Arctic sea ice cover performed with coupled 3D models (both global and regional) have shown a large inter-model scatter. Analyses of the reason behind the inter-model scatter point at the surface albedo parameterization as one of the major factors (Holland et al. 2010; Wyser et al., 2008). The sensitivity of the modelled ice cover to the details of the surface albedo parameterization has also been demonstrated for stand-alone basin scale dynamic - thermodynamic 2D ice models (Liu et al. 2007), in single column models (Holland & Curry 1999); and in more idealized model concepts (Eisenman & Wettlaufer 2009). The explanation to this large sensitivity lies in the fact that variations in snow/ice albedo is one of the dominating factors influencing the Arctic energy budget (e.g. Curry *et al*., 1995; Houghton *et al*., 2001). In reality the surface albedo is a rather complex function of surface characteristics including snow depth, ice thickness, area fraction and depth of melt ponds on the ice, and snow crystal structure. It is also dependent on solar zenith angle and on the atmospheric properties. In climate models we find a wide variety of surface albedo parameterizations of different types and level of complexity.

In *paper II* we look at the surface albedo parameterization problem from an ice thickness sensitivity point of view. Is the modeled ice thickness sensitivity itself sensitive to alterations in the albedo parameterization? More specifically we ask the question: how does the shape and gradient of the ice thickness response curve (discussed above) change when the surface albedo is altered between different parameterizations taken from a number of well-known global climate models? For an in-depth discussion on the details of the results the reader is referred to *paper II*. Here we will discuss one aspect of the results that is not directly related to basic question formulation presented above. Our results show that not only does the gradient of the response curve change, but the absolute ice thickness for a given forcing also turns out to change (and quite dramatically) between the different parameterizations (Fig. 15). For this reason the question regarding what we call *compensating factors* in global climate models becomes an interesting discussion topic. The reasoning goes basically as follows. In our study we show that the change in the surface radiation budget when altering between the different parameterizations give rise to significantly different mean ice thicknesses spanning between over 3 m for the albedo parameterization used in the CSIRO mk3 model, to less than 0.7 (which is well into the seasonal ice cover regime with completely ice free summers) for the parameterization used in CCSM3, when baseline forcing is applied. Even though there are differences in the respective global climate model output in terms of present day Arctic sea ice cover thickness and extent, both these models produce a reasonably realistic sea ice cover. Thus, there must be one or several factors in the models that compensate for the differences in the surface radiation budget (caused by the different albedo parameterizations) such that the output from the models still becomes realistic.

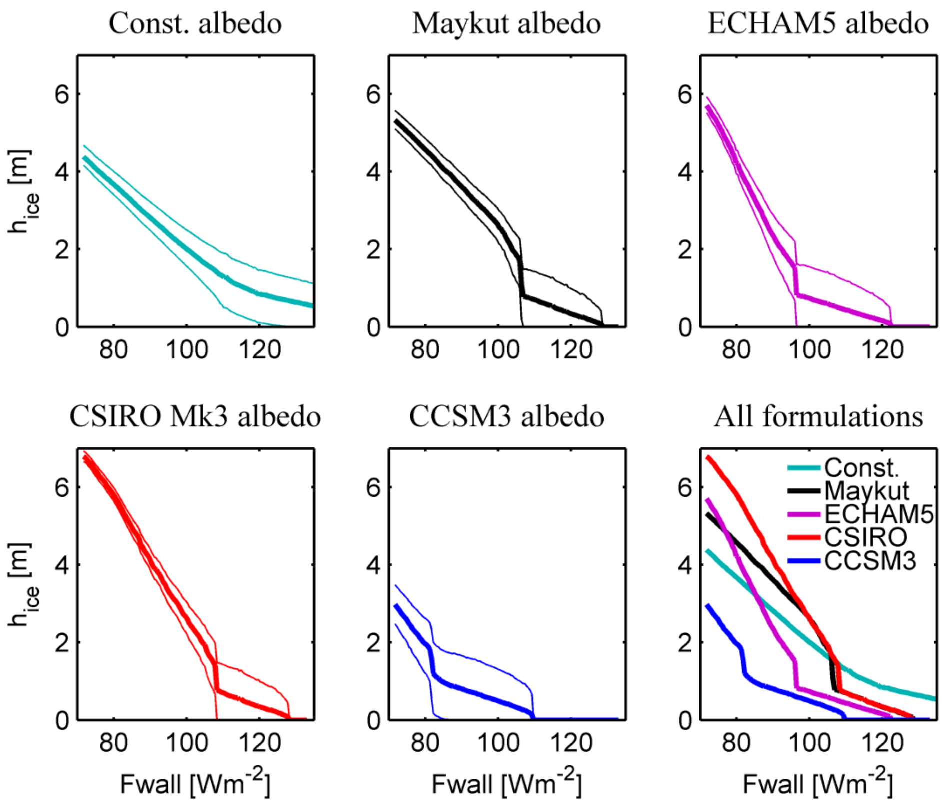


Figure 15. CCAM response curves for different albedo parameterizations (thin curves show annual maximum/minimum sea ice thickness). Figure taken from *paper II* (see the appended paper for details of the different parameterizations).

One way to compensate for a low present day surface albedo is to have a relatively high cloud albedo. Gorodetskaya et al. (2008) show that indeed the CCSM3 model (having a comparably low surface albedo) also has a relatively high cloud albedo reflecting 40-60 Wm^{-2} more of the incoming solar radiation in June compared to other global climate models. This comes from generally higher cloud water content (the amount of liquid water droplets and ice crystals) with a summer maximum of close to 200 gm^{-2} compared to observationally derived estimates of around 100 gm^{-2}. This means that while still producing realistic Arctic sea ice conditions the simulated atmospheric conditions can differ substantially between models.

Do these differences have any serious consequences for the simulated sensitivity of the Arctic sea ice cover? After *paper II* was accepted for publication a paper by Kay et al. (2012) was published discussing some differences between the two latest versions of the atmospheric part of the CCSM model; the Community Atmosphere Model (CAM) version 4 and 5. One key difference between the two model versions is actually the cloud water content. It is reduced significantly in the pre-industrial control runs from a maximum summer value of over 200 gm^{-2} for the CAM4 (similar to the coupled CCSM3 values shown in Gorodetskaya (2008)) to less than 40 gm^{-2} in the new improved CAM5 version (significantly less than estimates based on satellite observations of around 100gm^{-2}). Kay et al. (2012) show that both model versions increase the cloud liquid water content under 2xCO_2 experiments. The annual mean cloud liquid water content increase is however almost 5 times larger for the CAM4 compared to the CAM5. This indicates that the sensitivity of the Arctic climate system is indeed influenced by the initial pre-industrial state of the atmosphere. The present author suggests that the differences in the typical present day atmospheric properties between models and model versions as exemplified above are an indication that the scientific understanding of the Arctic atmosphere and response properties perhaps are not yet thoroughly understood at the time of writing (although such understanding is surely approached in a fast pace).

3.5 Temporal variations in the model forcing

The transient response of the sea ice cover to temporal forcing perturbations of different magnitude and length can be systematically investigated from the present model set up. Let us take cloud forcing as an example, which also serves to illustrate the complexity of the system. The amount and vertical distribution of clouds is important for the state and behavior of the Arctic climate system. The importance lies in the radiative properties of clouds. Changes in the cloud cover influence the surface radiation budget but as we will see, the net effect depends on for example the sign and the altitude of the cloud cover alteration. The reason is related to the fact that the dispersive, reflective and absorptive properties of clouds are strong functions of the radiation wavelengths. For instance, a cloud with increasing liquid water content becomes whiter in color and thus increases the albedo (*reflecting* a higher percentage of the short wave radiation) while it at the same time increases the *absorption* of long wave radiation. In the present model, clouds are present at three different pressure levels (corresponding to three different altitudes) and are described by two parameters: the water content (or the Cloud Water Path, CWP) and the horizontal cloud cover fraction. If we concentrate on the CWP, it is in the Arctic often a mixture of water droplets and ice crystals (so called mixed phase clouds). The fraction between ice and liquid water is important for the radiative properties of the cloud and is in this model parameterized as a function of the atmospheric temperature. As to illustrate the complexity of the model it can be mentioned that a clouds emissive properties is also a function of the diameter of the ice crystals which is parameterized as a function of pressure. But let us return to the discussion of temporal variations in the forcing and their potential effect on the Arctic sea ice cover. By spinning up the model to a quasi-steady state, as described in section 2, we can then systematically apply perturbations of different length, time of year and magnitude. It is then straightforward to observe the response of the ice cover and the relaxation time scale (Fig. 16).

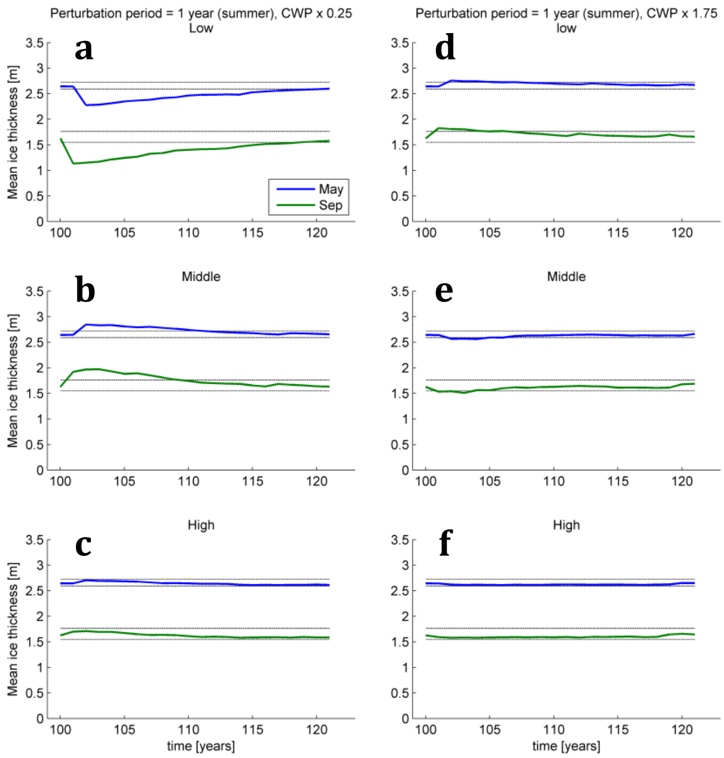


Figure 16. Example of how the mean ice thickness for the month with thickest (May) and thinnest (September) ice cover reacts to a sudden decrease (a-c) and increase (d-f) of 75 % of the summer (May – October) cloud water path after a 100 year spin up period. Black dotted lines show the max/min monthly averages from a 500 year control run.

Fig. 16 illustrates a few interesting things. One is that the ice cover reacts differently depending on where in the atmospheric column the perturbation occurs; a negative perturbation in low clouds has the opposite effect compared to the same perturbation in middle clouds while the ice cover seems less sensitive to perturbations in high clouds. Another interesting detail is that the ice thickness sensitivity depends on the sign of the forcing perturbation (comparing the left and right columns of Fig. 16).

The length and magnitude of a forcing perturbation can be expected to influence the ice cover response to the perturbation. This is exemplified in Fig. 17 where we plot the ice thickness at the maximum deviation from a 500 year control run average, for different kinds of perturbation lengths and magnitudes. Here the non-linear ice thickness response to the perturbation sign and magnitude is illustrated quite clearly (Fig. 17a-c). Such non-linear responses to forcing perturbations have implications on the "quasi-steady state approach" applied in this thesis. Let us assume that the deviation from the average annual cycle of the low level cloud CWP forcing is large and distributed symmetrically around the average. Then the average ice thickness would become smaller than the steady state ice thickness produced by average forcing due to the stronger response to the negative forcing fluctuations compared to the positive. The magnitude of this effect is however also a function of the perturbation frequency spectrum; high frequency variations have less effect than low frequency variations as shown in Fig. 17d-f.

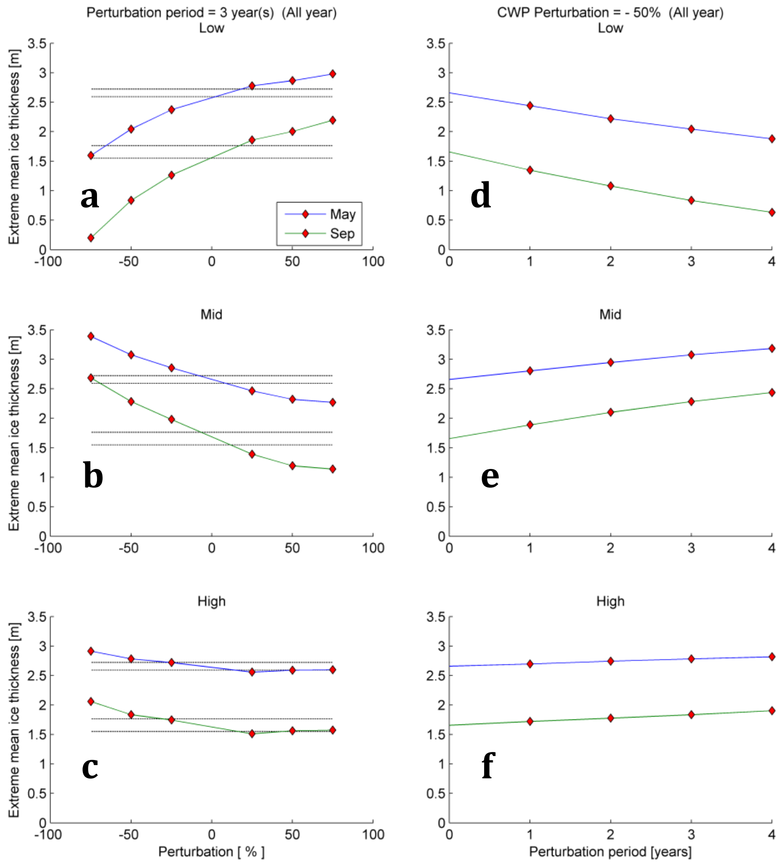


Figure 17. The extreme mean ice thickness defined as the maximum deviation of the monthly mean ice thickness from a 500 year control run average, plotted against perturbation magnitude (a-c) and against perturbation period (d-f). Black dotted lines show the max/min monthly averages from a 500 year control run.

3.6 The Arctic sea ice cover on inter-millennial time scales

Studies of Arctic Ocean sea ice proxies suggest a reduction in both thickness and extent during parts of the early and middle Holocene (~6,000 - 10,000 years BP) compared to present day conditions (Fig. 18b). The cause of this sea ice minimum has been attributed to the northern hemisphere Early Holocene Insolation Maximum (EHIM) associated with Earth's orbital cycles. In *paper III* we investigate the transient effect of insolation variations during the final part of the last glaciation and the Holocene by means of continuous simulations with the CCAM.

Our results show that the increased insolation in the Arctic during the EHIM has the potential to drive the system into a state dominated by ice free summers (Fig. 18a). There are however two very basic assumptions made here: we look at the Arctic climate as an isolated system not influenced by changes in the global climate system (i.e. the oceanic circulation and F_{wall} are not influenced by EHIM) and the atmosphere does not respond to the climate change induced by the EHIM (i.e. the seasonal cycle of cloudiness and atmospheric water vapor contents do not change). None of these assumptions can be expected to be compatible with reality. We argue however that these results are still useful with the basic argument being that the global and local feedback processes at the time of writing are not thoroughly understood. Taking the net effect of changes in local Arctic cloud formation in a warming climate as an example, not even the sign of this feedback is known, much less the strength (e.g. Verlinde et al. 2007; Soden and Held 2006; Cai and Lu, 2010).

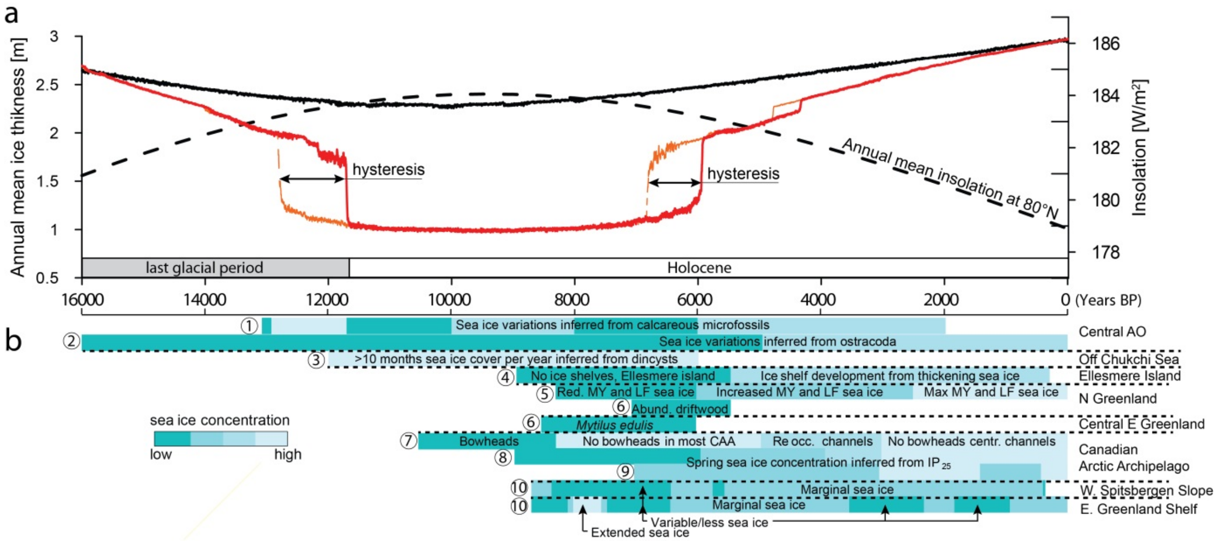


Figure 18. Annual mean sea ice thickness for three different simulations (Panel a) compared with results from published paleo-sea ice studies (Panel b). Black curve: constant surface albedo; red curve: dynamic surface albedo parameterization. The simulation implemented with a dynamic surface albedo parameterization was run from present time and backwards in terms of short wave forcing to address the importance of the initial state of the sea ice cover, orange curve. The figure is taken from *paper III*.

There are a number of feedback processes not included in CCAM that are believed to be important in this context. A few examples are feedbacks associated with the lapse rate (i.e. the vertical temperature gradient in the atmosphere), cloud formation, water vapor, large scale oceanic and atmospheric circulations, and continental (vegetation) albedo. There are other more intrinsic feedbacks associated with for instance methane release from Arctic Ocean continental shelf and Siberian tundra, and CO2 sequestration (in organic material e.g. through vegetation changes from tundra to pine forest, or in the ocean e.g. associated with changes in deep water formation). Several climate simulations show that the albedo feedback associated with vegetation is positive at high latitudes, but further south (or in a significantly warmer climate) the situation can be reversed if deciduous forests replace evergreen forests which would then work as a negative surface albedo feedback (Miller et al., 2010). The examples above are mentioned to give the reader an idea of how complicated the Earth climate system is in reality. Moreover, different feedback mechanisms work on different timescales, they are complicated to study and difficult to verify. Nevertheless, they are all subject to intense research and knowledge is gained in a fast and steady pace. There are however still many question marks that need to be straightened out and in the meantime, simplified studies like *paper III* can give important insight in the potential effect of increased solar radiation.

How did the atmospheric circulation react to the EHIM? According to modeling efforts by Crucifix et al. (2002) the atmospheric circulation did not change much in terms of atmospheric heat transport. In *paper III* we show however that even a small change can be a decisive factor in determining whether or not the modeled ice cover falls into seasonal ice or not during the EHIM. We show that a reduction of the annual mean atmospheric heat transport of less than 1% (or about 1 Wm^{-2}) would be enough to change the model outcome so that the ice cover stays perennial throughout the whole Holocene to present day. This corresponds to a change in the annual mean surface heat budget of around 0.5 Wm^{-2} if we assume that about 50 % of the atmospheric heat transport radiates directly out to space (following Thorndike, 1992).

If we believe that we can trust our model results under the assumptions above, this means that the sign of the net effect of the remaining feedback mechanisms not considered in CCAM would render the verdict on whether or not we had ice free summers in the Arctic during the EHIM. A future outlook here would then be to compile a list of the individual feedbacks and the estimated sign, strength and error. If the estimated net effect would prove to be overwhelmingly positive for instance this would provide strong and (partly) independent evidence of seasonal ice cover conditions in the Arctic during the EHIM, in addition to climate proxy data and global climate modeling efforts.

4. Hydrothermal heat fluxes in the Arctic

The research presented in *Paper IV* deals with a method of estimating hydrothermal heat fluxes by means of a numerical plume model. This paper is thus not related to the previous papers other than that it is based on observations made in the Arctic Ocean. It was led by the present author as a side project since I was onboard the ice breaker Oden as a part of the CTD team collecting the data (on which the research is based on) during the *AGAVE 2007 expedition*. We will begin this chapter with an introduction to hydrothermal vent systems. We will then explain how hydrothermal plumes are created by the emanating warm vent water and how we can make crude estimates of the vent thermal power from observations of these plumes.

4.1 Introduction

A hydrothermal vent is a fissure on the ocean sea floor from which so called hydrothermal fluid emanates. Hydrothermal fluid is created in hydrothermal circulation systems where seawater find its way through cracks in the oceanic crust and is heated in the vicinity of a magma chamber leading to an expansion of the fluid and an associated increase in pressure. The hydrothermal fluid is then injected back into the ocean either through focused high temperature venting (~ 100 - 400°C) or through lower temperature diffuse venting (Fig. 19).

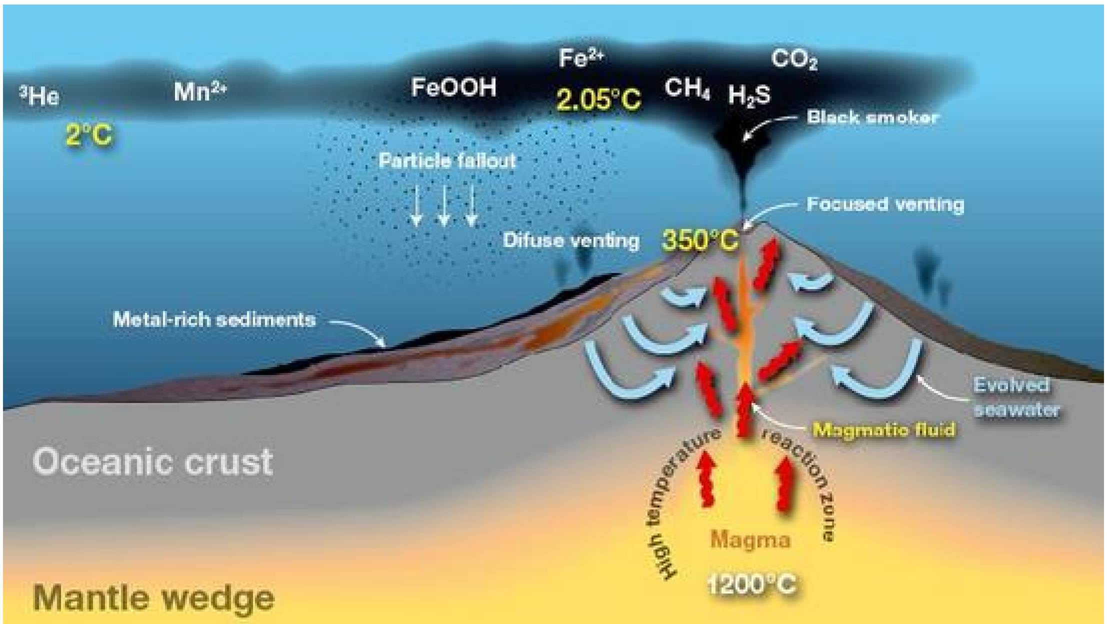


Figure 19. Schematic sketch of a hydrothermal circulation system and plume. Courtesy of Dr Cornel de Ronde at GNS Science.

When the sea water is heated it interacts with rock which then changes the chemical and physical characteristics of the fluid. Since the hydrothermal fluid is warmer than the ambient sea water (which is typically around -1°C in the Arctic) a buoyant plume is created much like smoke emanating from a factory chimney. The color of the plumes range from colorless through white to black depending on the temperature and chemical properties of the vent fluid. The color comes from mineral particles that precipitate rapidly as hot (usually quite acidic) hydrothermal fluids mix with the cold adjacent seawater at the vent orifice (Fig. 20).

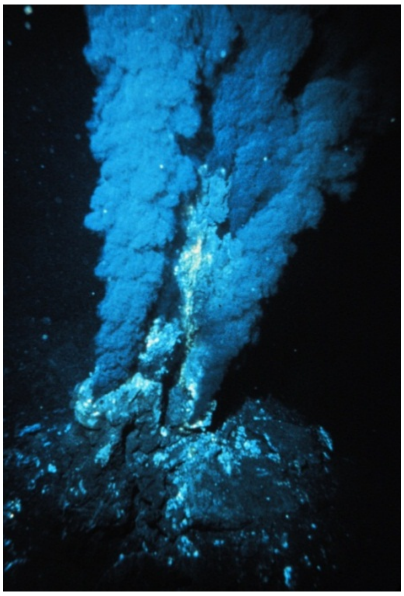


Figure 20. Black smoker at a mid-ocean ridge hydrothermal vent. Courtesy of National Oceanic and Atmospheric Administration. Photographer: P. Rona.

Hydrothermal vents are commonly found near volcanically active places and areas where tectonic plates are moving apart, so called mid-ocean ridges. As can be seen in Fig. 21, the Mid-Atlantic Ridge connects to a spreading ridge in the Arctic Ocean. This continuation of the Mid-Atlantic Ridge is called the Gakkel Ridge (formerly known as the Nansen Ridge) and is the slowest known spreading ridge on Earth with a spreading rate of less than one centimeter per year.

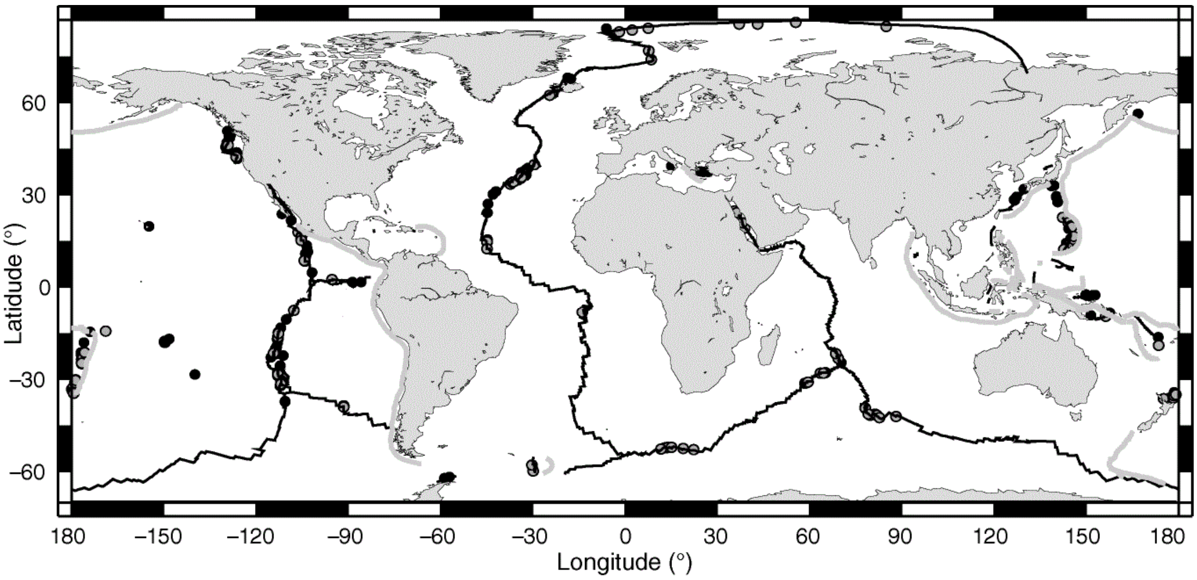


Figure 21. Distribution of 144 known (black dots) and 133 inferred (gray dots) hydrothermal fields. Black lines are the mid-ocean ridges and transform faults, gray lines are subduction zones. Taken from Baker & German (2004).

Compared to the typical deep sea conditions, the areas around hydrothermal vents are biologically much more productive. The biological production comes from archaea (a kind of single-celled organisms) that uses chemosynthesis from chemical components of the vent fluids to build organic matter and thus forming the base of a food chain supporting specialized ecosystems around the vent fields. Since the discovery of the first hydrothermal vent in 1977 (Weiss et al., 1977) there have been many speculations and even indications that the origin of life in fact might have been associated with hydrothermal venting (e.g. Bernhardt & Tate, 2012; Nitschke & Russell, 2009). Since the Arctic deep water is isolated from the other oceans of the world by a 2550 m deep sill at the Fram Strait (Thompson et al, 2012) the vent ecosystems along the Gakkel Ridge (with depths of the axial valley ranging 3000 – 5000 m) might very well have been separated from the rest of the world for millions of years. It is then quite possible that species associated with the Gakkel vent fields might have followed a separate parallel evolution and this was one of the main reasons why the AGAVE 2007 expedition was planned and executed.

4.2 The AGAVE 2007 Expedition

The Arctic Gakkel Vents (AGAVE) expedition was a 40-day cruise with the ice breaker Oden during summer 2007. It was funded mainly by NSF and was led by researchers from Woods Hole Oceanographic Institution. The main objective was to use autonomous underwater and under-ice vehicles (AUV's) to reach the bottom of the ocean in order to locate and observe seafloor hydrothermal vents under the Arctic sea ice cover. Since active hydrothermal vents are believed to exist also on Jupiter's moon Europa, NASA also co-founded the project as it can be seen as a pilot study towards developing techniques for exploration of the sea floor under the thick ice covering the surface of Europa. According to NASA scientists, Europa's seafloor may well be capable of supporting life (Wall, 2012).

Figure 22. Swedish ice breaker Oden during the AGAVE 2007 Expedition. Photo: Chris Linder.

4.3 Thermal vent power estimates through hydrothermal plume observations

When warm hydrothermal fluid is injected back into the ocean it rises up through the water column due the lower density of the fluid compared to the surrounding sea water, creating a so called *buoyant plume* much like smoke emanating from a factory chimney (Figs. 19-20). The vertical velocity of the fluid creates turbulence which causes mixing of the vent fluid with the surrounding sea water. This leads to increased dilution of the vent fluid with increasing distance from the vent orifice. The plume will keep rising and diluting (increasing its radius) until the point where it reaches neutral buoyancy meaning that the density of the plume water is equal to the ambient sea water. At this point the plume spreads out horizontally forming the Neutrally Buoyant part of the hydrothermal Plume (NBP), Fig. 19. In the Arctic deep water the salinity increases slightly with increasing depth. For this reason the plume water (constantly entraining saltier water from below) will be slightly saltier than the ambient water which in turn means that when the level of neutral buoyancy is reached the plume temperature exactly compensates for the salinity difference between the plume and the ambient sea water. This gives the NBP a "signature" in terms of salinity and temperature. Since the horizontal length scale of the NBP can be on the order of up to 10 000 m (or perhaps more) compared to the buoyant part of the plume which can be on the order of tens of meters, this NBP signature is commonly exploited when searching for hydrothermal vents; when lowering a CTD (an instrument measuring salinity, temperature and pressure) through the water column the temperature profile will show a positive anomaly from the "background" profile when passing through a NBP (Fig. 23). Thus by making many CTD profiles the approximate location of an individual vent can be determined. This is what the first part of *paper IV* is dealing with. This documentation of the AGAVE plume mapping campaign constitutes an important reference for future expeditions to the Gakkel vents. The second part of the paper is dealing with thermal power (i.e. total heat flux) estimates of the individual vents through numerical plume modeling. For details regarding the method and the results the reader is referred to *paper IV*. Here we will discuss some aspects of the method since it is unique for this paper.

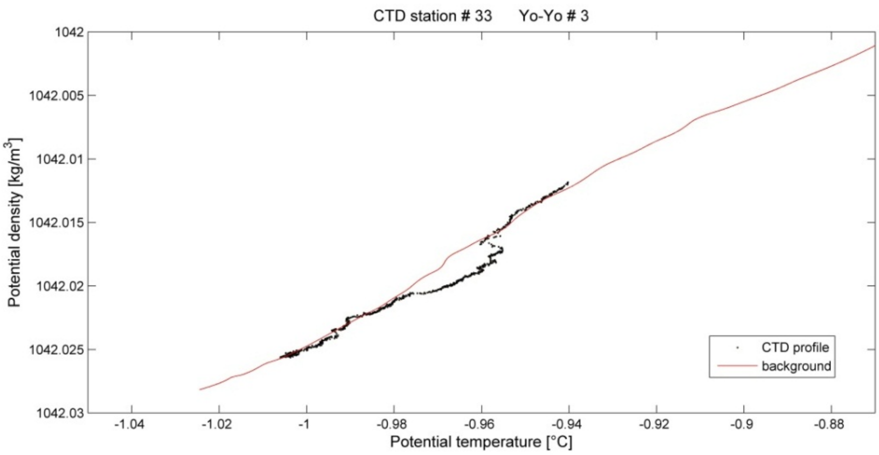


Figure 23. An example of a CTD profile with a NBP temperature anomaly compared to the background density profile. The figure is taken from *Paper IV*.

In order to calculate the thermal power of a vent we need to know three boundary conditions at the vent outlet: the nozzle area, and the velocity and temperature of the emanating water. None of these parameters are known since the only thing we actually observe is the temperature anomaly of the NBP. We do not even know the depth of the vents since the bathymetry in this region is extremely steep meaning that we cannot assume that the vent depth equals the depth right beneath the NBP observation.

The method used in *paper IV* for estimating vent thermal power from NBP observations is novel but very straightforward and natural in these days where significant computing power is easily accessed; we run the plume model with all plausible boundary condition combinations. In this way we can investigate the range of vent conditions that produce a modeled NBP temperature anomaly that matches our observations. In a uniformly stratified ocean there are three boundary conditions (as mentioned above) since the rise height then is independent of depth. In this region however the background salinity and temperature gradients varies with depth meaning that the source depth also becomes a boundary condition. This was the first lesson learned; we need to consider the actual background profiles of temperature and salinity, something that is usually not considered in this type of hydrothermal plume modeling. The model was run about 1.1 million times, each time with a different boundary condition combination. It might sound like a large number but if considering that the fourth root of 1.1 million equals about 32 we realize that this is in fact a quite sparsely spaced grid of input values in each parameter (although it is not evenly distributed between the four model input parameters).

The plume model used in *paper IV* was developed by the present author. It is based on the physics discussed by Morton et al. (1956) and is very similar to the model presented by Speer & Rona (1989). We made however three significant improvements to the model: we use variable observed background salinity and temperature gradients (as mentioned above); we apply a non-linear equation of state dependent on pressure, temperature and salinity as presented in Sun et al. (2008); we conserve internal energy rather than temperature meaning that we apply a variable *specific heat* dependent on pressure, salinity and temperature (also presented in Sun et al. (2008)) rather than a constant one.

One intriguing model result that follows from conserving energy is that the plume rise height becomes a function of the buoyancy frequency (i.e. the density stratification) and thermal power alone. Consequently, if the buoyancy frequency is fairly constant with depth, all the information needed in order to estimate the thermal power is the *rise height* and the *buoyancy frequency*, two fairly easily observed parameters. This result contradicts the conclusion of Speer & Rona (1989) arguing that observations of the NBL layer are not useful for estimating the thermal power of hydrothermal vents. As a future outlook it would be fairly simple to fit an analytical expression to the numerical model results where the thermal power is expressed as a function of buoyancy frequency and rise height.

5. Future outlook

Usually when doing research you end up with more questions than you started off with. This is also the case in the present thesis and there are a number of potential spin-off projects that could be interesting to continue working with.

To begin at the end of the thesis, with *paper IV*, an improved analytical plume model based on the numerical model results (as described in section 4.3) can be useful for many applications. Such model needs however to be tested against e.g. detailed observations from existing well controlled artificially generated plumes. There is a very interesting ongoing study on fjord ventilation and sediment phosphorus dynamics in a fjord on the Swedish west coast (Stigebrandt & Liljebladh, 2011). Here fresh surface water is being pumped down into the deep water in order to oxygenize the normally anoxic conditions. The project has collected a wealth of data on plume initial conditions and rise height as well as background stratification. A future outlook would be to verify both the numerical and a fitted analytical model with these observations.

When working on the long term variations in insolation in the Arctic I noticed a skewness of the insolation intensity around midsummer which varies on inter-millennial time scales (it is hardly noticeable at the present time). This skewness has an effect on the annual ice melt such that the average ice thickness becomes a function of the insolation distribution over the year, rather than on annual mean insolation alone. Put in other words, for the same annual mean insolation we get more ice melt when the insolation is skewed towards autumn and less when it is skewed towards spring. There are also variations in the peakedness (or kurtosis) of the insolation distribution over the Arctic summer meaning that the insolation can be more/less intense but distributed over a shorter/longer period of time. As a future investigation one could study the mechanisms controlling the effect of the annual insolation distribution on the ice cover. The effect is likely linked with the annual cycle of the atmospheric conditions, the albedo formulation and the snow precipitation.

In *paper II* we show that the snow precipitation influences the Arctic sea ice cover sensitivity and that it is intimately coupled to the surface albedo parameterization. A future outlook in this context could be to apply a more realistic sporadic rather than constant snow precipitation. Precipitation could also be integrated into the model as an internal quantity.

As of *paper I*, the natural way forward would be to further investigate the role of ice divergence with a 2D ice model where also ice advection and regional variations in other forcing parameters can be taken into account.

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