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Satellite-based Estimates of Sea Ice Volume Flux: Applications to the Fram Strait Region

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Applications to the Fram Strait Region

Dissertation

Zur Erlangung des Doktorgrades der Naturwissenschaften
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Abstract

The sea ice export out of the Arctic Ocean through Fram Strait into the Greenland Sea is the single largest source of freshwater in the Nordic Seas and therefore of special importance for the hydrological cycle of the North Atlantic. On its way south, the exported sea ice melts and thereby modifies the stratification of the ocean surface mixed layer, which in turn influences oceanic deep convection and water mass transformation processes in the Nordic Seas and thus impact global ocean thermohaline circulation. The lack of spatial sea ice thickness information has been one of the weaknesses for previous existing methods to determine the sea ice export. In this study a new method to obtain the sea ice volume flux exclusively from satellite measurements is presented. Previous estimates of the sea ice volume flux relayed on ice draft measurements of a single Upward Looking Sonar (ULS) in the Greenland Sea. The GLAS laser altimeter onboard the ICESat satellite launched in 2003 offers for the first time the opportunity to obtain the spatial sea ice thickness distribution up to 86°N latitude. In this study a method to determine the sea ice freeboard from ICESat altimeter data is developed and applied to nine ICESat measurement periods between 2003 and 2007. Assuming hydrostatic balance and by utilization of further satellite, in situ and climatological data these sea ice freeboard measurements are converted to sea ice thickness maps of the Fram Strait region. The satellite-based ice thickness estimates are combined with sea ice area and sea ice drift, as retrieved from AMSR-E microwave radiometer measurements at 89 GHz, to obtain the sea ice volume flux. The errors of the input quantities and the final sea ice volume flux are assessed. Using this method the spatial sea ice volume flux distribution is obtained from satellite observations for the first time. The Fram Strait sea ice volume flux is further investigated by calculating a monthly sea ice volume flux time series between January 2003 and April 2007. Summer months have to be disregarded due to missing sea ice drift data. The sea ice volume flux shows large inter-annual and -seasonal variability. A mean monthly Fram Strait sea ice volume flux of $(248 \pm 90)\,\mathrm{km}^3/\mathrm{month}$ with respective minimum and maximum values of $112\,\mathrm{km}^3/\mathrm{month}$ (May 2003) and $484\,\mathrm{km}^3/\mathrm{month}$ (December 2004) was found. These satellite-based sea ice volume flux estimates from the years 2003 to 2007 are compared to previous sea ice volume flux estimates obtained for the period 1990 to 1999 and can be used as extension of these previous time series. Finally, a comparison of sea ice volume flux estimates from this study with oceanographic salinity measurements shows good coincidence of summer melting events. A comparison to model results reveals large differences in the lateral distribution of the sea ice volume flux. The presented method does not just allow, as previously, to determine the sea ice export through Fram Strait but has the potential to investigate and better understand the dynamics of sea ice volume changes north and south of Fram Strait.

Zusammenfassung

Der Export von Meereis aus dem Arktischen Ozean durch die Framstraße in die Grönlandsee stellt die größte Quelle von Süßwasser im Europäischen Nordmeer dar und ist daher von zentraler Bedeutung für den Süßwasserhaushalt des Nordatlantiks. Auf dem Weg nach Süden schmilzt das exportierte Meereis und bestimmt so maßgeblich die oberflächennahe Schichtung der Wassermassen, die wiederum die ozeanische Tiefenkonvektion im Europäischen Nordmeer und dadurch auch die globale thermohaline Zirkulation beeinflusst. Einer der bisherigen Schwachpunkte bei der Bestimmung dieses Eisexports ist das Fehlen flächendeckender Beobachtungen der Meereisdicke. In dieser Studie wird ein neues Verfahren vorgestellt, den Meereisvolumenfluss alleinig aus Satellitenbeobachtungen abzuleiten. Bisher beruhten Abschätzungen des Eisvolumenflusses in puncto Eisdicke auf den Eistiefgangsmessungen eines einzelnen Sonars in der Grönlandsee. Mit den seit 2003 gemessenen Daten des Laseraltimeters GLAS auf dem Satelliten ICESat ist es erstmalig möglich, die flächenhafte Eisdickenverteilung bis zu einer geographischen Breite von 86°N zu erfassen. In dieser Arbeit wurde ein Verfahren zur Bestimmung des Eisfreibords aus ICESat Laseraltimeterdaten entwickelt und auf neun ICESat-Messperioden zwischen 2003 und 2007 angewendet. Unter Annahme hydrostatischen Gleichgewichts und mit Hilfe von weiteren Satelliten-, vor Ort gemessenen und klimatologischen Daten werden aus diesen Eisfreibordmessungen Eisdickenkarten der Framstraßenregion erstellt. Diese Meereisdickendaten werden mit Satellitenmessungen der Eisbedeckung und Eisdrift zum Meereisvolumenfluss kombiniert. Für die Bestimmung der Eisbedeckung und Eisdrift werden jeweils AMSR-E Mikrowellenradiometermessungen bei 89 GHz verwendet. Die Fehler der Eingangsdaten und des Meereisvolumenflusses werden abgeschätzt. Mit dieser Methode kann erstmals die flächenhafte Verteilung des Meereisvolumenflusses aus Satellitendaten beobachtet werden. Der Meereistransport durch die Framstraße wird mit Hilfe einer monatlichen Zeitreihe zwischen Januar 2003 und April 2007 ausführlicher untersucht. Hierbei werden die Sommermonate aufgrund fehlender Eisdriftmessungen nicht berücksichtigt. Der Eisvolumenfluss unterliegt großer jährlicher und zwischenjährlicher Variabilität. Der mittlere monatliche Meereisvolumenfluss durch die Framstraße betrug $(248 \pm 90)\,\mathrm{km}^3$/Monat und erreichte minimale und maximale Werten von $112\,\mathrm{km}^3$/Monat (Mai 2003) und $484\,\mathrm{km}^3$/Monat (Dezember 2004). Der erhaltene Meereisvolumenfluss der Jahre 2003 bis 2007 wird mit früheren Meereisvolumenflussbeobachtungen verglichen und kann als Verlängerung dieser früheren Zeitserie verwendet werden.

Ein Vergleich der Volumenflussabschätzungen dieser Studie mit ozeanographischen Salzgehaltsmessungen zeigt eine gute Übereinstimmung der sommerlichen Eisschmelzperioden. Ein Vergleich mit Modellergebnissen läßt große Unterschiede in der räumlichen Verteilung des Volumenflusses erkennen. Die vorgestellte Methode erlaubt nicht nur, wie bisher, die Bestimmung des Meereisvolumenexports durch die Framstraße, sondern bietet auch die Möglichkeit, die Dynamik von Meereisvolumenänderungen nördlich und südlich der Framstraße zu untersuchen und besser zu verstehen.

Contents

Chapter 1

Introduction

Arctic sea ice: Where does it come from? Where does it go? The most fundamental answers to these questions were already given by Fridtjof Nansen in 1896. His vessel *Fram*, which entered the Arctic pack ice in the Laptev Sea near the New Siberian Islands in 1893, left the ice again in August 1896 in the Fram Strait after three years of ice drift (*Nansen*, 1897). Since then we know that the main transport of sea ice out of the Arctic Ocean is taking place via Fram Strait and that the source regions for this ice are as far away as the East Siberian Sea on the opposite side of the Arctic Ocean. Nansen also anticipated the importance of sea ice for the Earth's climate system when he described sea ice ocean interactions (*Nansen*, 1902). However, an accurate knowledge of sea ice dynamics and "where the ice goes" still remains an open question and is also the main topic of this work. Sea ice was realized to be one of the key components of the climate system and its interaction with the ocean and atmosphere has not only local but global relevance (*ACIA*, 2004, 2005). Thus here the variability of the Arctic sea ice mass exchange with the Greenland Sea and the possibilities of regularly monitoring it are in the focus. Anyhow, times have changed since Nansen's *Fram* drift. The 2007 *Tara* ice drift following Nansen's trace as part of the International Polar Year (IPY) about 110 years after the *Fram* drift, took only about 15 months for the same distance in a by extent significantly decreased sea ice cover (*Gascard et al.*, 2008). While the Arctic by exploitation of modern technique is not as hostile, dangerous and lonesome anymore as during Nansen's time, still the number of in situ measurements taken there is below the world average. Therefore, observations from space are of special importance.

In this study a technique to derive the sea ice volume transported out of the Arctic Ocean through Fram Strait entirely from satellite measurements is described. It is a multi-sensor study, where different data products from different satellites are combined. For the observation of the sea ice thickness a new method was developed. This is of special importance as before sea ice thickness could only be measured by in situ campaigns and moorings. Finally a time series of the ice volume transport through Fram Strait for 2003 to 2007 is presented. Monitoring anomalies in the Fram Strait sea ice volume flux is of special importance, as they can influence watermass transformation processes in the Greenland Sea and further downstream in the Atlantic Ocean. With the presented technique the lateral distribution of the sea ice volume flux can be directly observed, which was not possible with previous measurement techniques. The retrieval of sea ice volume is demonstrated for the Fram strait region but the used method can be easily adapted to other regions or applied globally.

1.1 Aims

The main aims and questions addressed in this study can be described as follows:

- Development of an exclusively satellite based method to monitor the sea ice volume flux.

- What is the amount and variability of the Fram Strait sea ice volume flux between 2003 and 2007? How does the Fram Strait ice volume transport change inter-annually and inter-seasonally?

- Calculation of a monthly Fram Strait sea ice volume flux time series between January 2003 and April 2007. How large is the amount and variability of the sea ice volume flux during these years in comparison to measurements during the 1990s? Can our estimates be used as an extension of the former time series?

- Combination of different satellite datasets to monitor the spatial distribution of the sea ice volume flux. For this purpose sea ice thickness estimates obtained from ICESat laser altimetry are combined with sea ice area and drift measurements obtained from satellite microwave radiometry (AMSR-E) to retrieve the spatial distribution of the sea ice volume flux.

- Validation of the used sea ice concentration, drift, and thickness datasets to assure their quality for the sea ice volume flux retrieval. Error assessment of these quantities and the sea ice volume flux.

- How does the satellite based sea ice volume flux compare to oceanographic measurements? To get further insight in the sea ice – ocean interactions the sea ice volume flux observations will be compared with in situ ocean salinities measurements obtained from a mooring in the Greenland Sea.

- How does satellite based and modeled sea ice volume fluxes compare? Our sea ice volume flux observations will be compared with results from two coupled sea ice – ocean models.

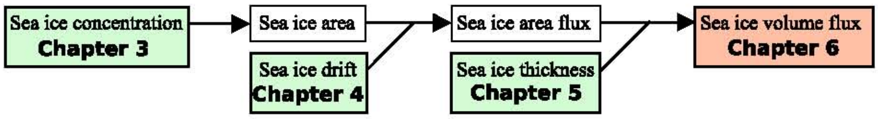

Figure 1.1: Schematic flow diagram of how the quantities involved (green boxes) have to be combined to get the sea ice volume flux. In the lower part of each box the belonging chapter is listed.

How long ICESat will continue to operate is unsure, as its designed lifetime of three years with a five-year goal is already exceeded. But plans for ICESat-II are underway and the radar altimeter satellite CryoSat-2 is scheduled for launch in 2009. It is anticipated that the presented sea ice volume flux retrieval method can be easily adapted to CryoSat-2 measurements. Thus, there is good hope that the time series can be continued in future and will help to understand climate relevant processes.

1.2 Structure

This work is organized as follows:
First, in Chapter 2 an introduction to the Arctic climate system and the main processes relevant for this study are given. In the second part of Chapter 2 the used data and sensors are described. The main quantities to retrieve the sea ice volume flux are the sea ice concentration (area), sea ice drift, and sea ice thickness. These quantities are described one after the other in Chapters 3, 4, and 5. The volume flux finally is described in Chapter 6. Figure 1.1 shows a flow diagram how the quantities have to be combined and in which chapter they are described.

The sea ice concentration and drift are derived from passive microwave AMSR-E data using existing methods. The focus for these two quantities therefore lies on the evaluation of the quality of the datasets by comparing them with reference data. This is a prerequisite to estimate the uncertainty of the final ice volume flux data. For the ice thickness a new method was developed to obtain the ice freeboard from ICESat laser altimeter measurements and afterwards convert them to ice thicknesses using additionally QuikSCAT radar backscatter data for sea ice type discrimination. Finally, all three datasets have to be combined to derive the sea ice volume flux. The meridional Fram Strait sea ice volume transport is calculated and compared with model data and oceanographic salinity measurements in the Greenland Sea. *Holfort and Meincke* (2005) state that "the measurements of liquid freshwater flux are of minor value if not the information on freshwater fluxes with the ice are available in parallel". Here a first step in that direction is made. Finally, a conclusion and outlook is given in Chapter 7.

1.3 Publications

Parts of this thesis were published in the following journals and book:

- A first version of sea ice volume flux retrieval method presented in Chapters 5 and 6 and first results were published in:

  Spreen, G., S. Kern, D. Stammer, R. Forsberg, and J. Haarpaintner (2006), Satellite-based Estimates of Sea Ice Volume Flux through Fram Strait, *Ann. Glaciol.*, *44*, 321–328.

  Spreen, G., S. Kern, and D. Stammer (2006), Utilization of Multiple Satellite Sensors to Estimate Sea Ice Volume Flux through Fram Strait, in *Arctic sea ice thickness: past, present & future, Climate Change and Natural Hazards Series 10*, vol. EUR 22416, edited by P. Wadhams and G. Amanatidis, chap. 16, pp. 176–192, European Commission, Brussels.

- Sea ice volume flux estimates using sea ice drift data retrieved from QuikSCAT instead of AMSR-E measurements (Chapter 6, Section 6.5.1) were presented in:

  Haarpaintner, J. and G. Spreen (2007), Use of Enhanced-Resolution QuikSCAT/SeaWinds Data for Operational Ice Services and Climate Research: Sea Ice Edge, Type, Concentration, and Drift, *IEEE Trans. Geosci. Remote Sens.*, *45*(10), 3131–3137.

- Parts of the AMSR-E 89 GHz sea ice concentration retrieval and validation (Chapter 3) were published in:

  Spreen, G., L. Kaleschke, and G. Heygster (2008), Sea ice remote sensing using AMSR-E 89-GHz channels, *J. Geophys. Res.*, *113*, C02S03, doi:10.1029/ 2005JC003384.

Chapter 2

Fundamentals: The Arctic Climate System, Instruments and Data

In the first part (Section 2.1) of this chapter an introduction to the main climate components of the Arctic climate system important for this study are given. In the second part (Section 2.2) the used satellite sensors and datasets will be introduced.

2.1 The Arctic Climate System

2.1.1 The Arctic

Different definitions for the Arctic geographical coverage exist. The Arctic region can be defined by the July 10°C isotherm of the air temperature at the surface. The thereby defined area covers the complete Arctic Ocean including all marginal seas and the Greenland, Bering and Labrador Sea. On land Greenland and parts of Iceland, Canada, Alaska, and Russia are covered. The 10°C isotherm in large parts lies near the Arctic Circle at 66°33′N latitude, which can be taken as an alternative border definition for the Arctic. Figure 2.1 on the following page shows a geographical overview including topography and bathymetry of the Arctic and surrounding areas including geographical names used throughout this study. The inset shows in detail the concrete study region around Fram Strait and the Greenland Sea. The majority of the northern hemisphere cryosphere is located in the Arctic with its most prominent features, the Greenland Ice Sheet and the Arctic sea ice cover.

The Arctic is a "hot-spot" of the global climate change occurred during the last hundred years, which means the Arctic is one of the most responsive regions to climate change. The Intergovernmental Panel on Climate Change (IPCC) reported in its 4th assessment (*IPCC*, 2007) that the Arctic surface temperature increase of about 1.5°C was twice as high during the last century (1906 to 2005) as the global surface temperature increase (*Trenberth et al.*, 2007). For western Canada, Alaska, and Siberia an even higher warming of 2–3°C during the last

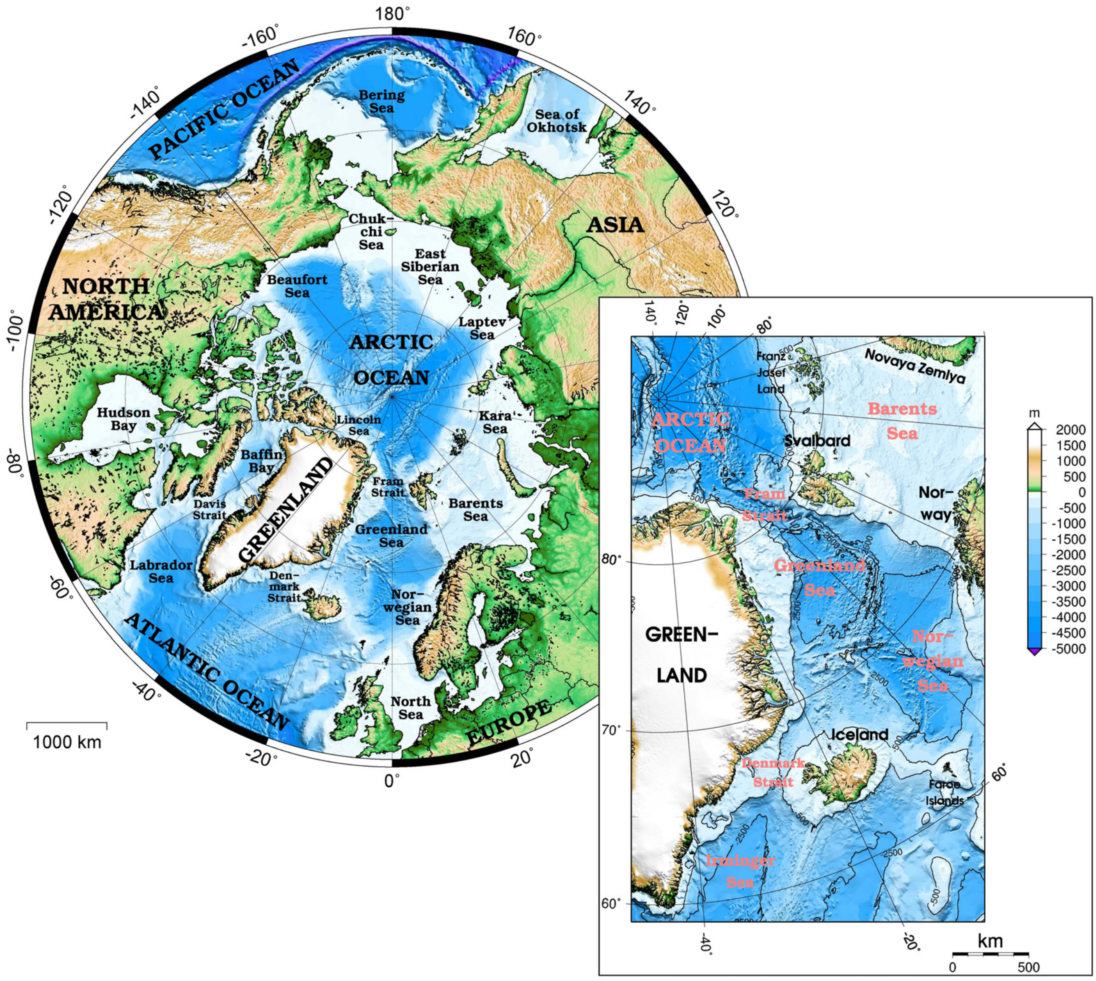

Figure 2.1: Overview of the Arctic (left) and the study region around Fram Strait (right) including topography, bathymetry and names of geographical places used. In the Fram Strait map the 500 and 2500 m depth isolines are marked in black.

50 years (1954–2003) was reported (*ACIA*, 2004, 2005). The Arctic sea ice cover decreased by about 3% per decade since 1978. The Greenland Ice Sheet has been shrinking with a rate of about 50 to 100 Gt/yr (equivalent to about 0.2 ± 0.1 mm/yr sea level rise) at least for 1993 to 2003. Before that date estimates are uncertain (all from *Lemke et al.*, 2007). The land to sea distribution in the Arctic is completely different from the Antarctic. The mediterranean Arctic Ocean is completely surrounded by land masses. The ground is frozen all year around (permafrost) down to depths of several hundred meters to kilometers, but the surface is not permanently covered by ice or snow and thus exhibits the darker soil with larger absorption to the sun light during summer. Therefore, the winter to summer temperature differences on land are large. All this leads to the larger temperature increase on land compared to the ocean during the last decades.

2.1.2 The Arctic Ocean

The Arctic Ocean is a mediterranean sea with a depth of more than 4000 m over large parts of the Amundsen basin. Enclosed are several shallow marginal seas with depths below 500 m. These are the Barents, Kara, Laptev, East Siberian, Chukchi, Beaufort, and Lincoln Sea (see Figure 2.1). The Arctic Ocean has only one deep passage, the Fram Strait, where the majority of water mass exchange with the world oceans takes place. The Fram Strait is approximately 440 km wide and 3000 m deep. Other connections are the Bering Strait, the Barents Sea and the Canadian Archipelago.

The circulation in the Arctic Ocean is dominated by thermohaline forcing. This is in contrast to the major ocean basins Pacific, Atlantic, and Indian Ocean, where most currents are wind driven and only modified by thermohaline effects. The input of brine and fresh water due to freezing and melting of sea ice, respectively, is one of the major components of the thermohaline forcing. The influence of melting and freezing of sea ice on the ocean is enhanced by the fact that in the cold arctic regions changes of the salinity of seawater have a larger effect on the seawater density than they would have in warmer regions. Figure 2.2 on the following page shows the seawater density in dependence of its temperature and salinity. For example at -1°C a change of salinity from 32 to 34 psu causes a density change of 1.6 kg/m^3, while at 20°C for the same salinity change the density would only change by 1.5 kg/m^3. This is only a slight difference but nevertheless important for the role of sea ice in enhancing or hampering ocean convection due to ice formation or melting, respectively. As can be seen from Figure 2.2 on the next page for low temperatures the water density is getting almost independent of the temperature. Further cooling is not increasing the density anymore. Therefore, changes in salinity are the main driver for density changes at low temperatures. Figure 2.2 on the following page also shows the freezing temperature and line of maximum water density in dependence of temperature