Water mass exchange in the sea west of Svalbard

A process study of flow instability and vortex generated heat fluxes in the West Spitsbergen Current

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Preface

This synthesis and a collection of papers are submitted for the degree of philosophiae doctor (PhD) in physical oceanography at the Geophysical Institute, University of Bergen. The thesis is divided into an introductory part and a part consisting of four papers.

Paper I	S. H. Teigen, F. Nilsen and B. Gjevik (2010). Barotropic instability in the West Spitsbergen Current. In *Journal of Geophysical Research - Oceans*, Vol. 115, C07016, doi:10.1029/2009JC005996.
Paper II	S. H. Teigen (2011). A two-layer model for linear stability analysis of shelf-slope currents. *Reports in Meteorology and Oceanography*, No. 1, Geophysical Institute, University of Bergen, Bergen, Norway.
Paper III	S. H. Teigen, F. Nilsen, R. Skogseth, B. Gjevik and A. Beszczynska-Möller (2011). Baroclinic instability in the West Spitsbergen Current. *Journal of Geophysical Research - Oceans*, in press, doi:10.1029/2011JC006974.
Paper IV	S. H. Teigen, F. Nilsen and R. Skogseth (2011). Heat exchange in the sea west of Svalbard. *Manuscript.*

I have also contributed to the following paper. It is not part part of the thesis.

Paper A C. Mauritzen, E. Hansen , M. Andersson , B. Berx , A. Beszczynska-Möller, I. Burud, K. H. Christensen, J. Debernard, L. de Steur, P. Dodd, S. Gerland, Ø. Godøy, B. Hansen, S. Hudson, F. Høydalsvik, R. Ingvaldsen, P. E. Isachsen, Y. Kasajima, I. Koszalka, K. M. Kovacs, M. Køltzow, J. LaCasce, C. M. Lee, T. Lavergne, C. Lydersen, M. Nicolaus, F. Nilsen, O. A. Nøst, K. A. Orvik, M. Reigstad, H. Schyberg, L. Seuthe, Ø. Skagseth, J. Skarðhamar, R. Skogseth, A. Sperrevik, C. Svensen, H. Søiland, S. H. Teigen, V. Tverberg and C. Wexels Riser (2011). Closing the Loop - Approaches to monitoring the state of the Arctic Mediterranean during the International Polar Year 2007-2008. In *Progress in Oceanography*, special volume "Arctic Marine Ecosystems in an Era of Rapid Climate Change", Vol. 90, Issues 1-4, Pages 62-89, doi:10.1016/j.pocean.2011.02.010

In accordance with the data policy of the International Polar Year (IPY), I have published eight datasets from the current meter mooring F0 in the Fram Strait (positioned at [8.864°E, 79.833°N]) in the IPY database - `http://www.dokipy.met.no`. The data can be browsed at (link accessed 2 Apr 2011):
`http://osisaf.met.no/thredds/catalog/data/UNIS/FS-iAOOS-mooring-F0/`.

This work is supported by the Norwegian Research Council through its IPY programme and the project iAOOS Norway - Closing the Loop (grant number 176096/S30) -
`http://www.iaoos.no/`.

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Finally, I am deeply grateful to my partner Julie, whom I first met in the magical land called Svalbard. Despite absence and departures, you always encouraged me and stood by my side.

St Jonsfjorden, April 2011 Sigurd Henrik Teigen

There is, one knows not what sweet mystery about this sea,
whose gently awful stirrings seem to speak of some hidden soul beneath.

- Herman Melville, ”Moby-Dick Or The Whale”

Chapter 1

Overview

1.1 Introduction

The first navigator to take advantage of the benign climatic influence of the West Spitsbergen Current (WSC) was probably the Dutch explorer Willem Barents (c. 1550-1597) [*Arlov*, 2005]. On his third voyage in search for the Northeast passage, he reached the eastern Fram Strait - the northernmost stretch of permanently ice-free sea in the world. On 19 June 1596, Barents and his crew sighted the north-west corner of Svalbard, making the first recorded discovery of the archipelago [*de Veer*, 1598]. The discovery did not bring much personal fortune for Barents, who in his tireless search for a navigable route to the Far East got ship-wrecked with his crew at the northern tip of Novaja Zemlya the following autumn. Beset by ice, they had little option but to suffer an arduous wintering. Next summer they struggled towards their rescue in open boats, but the already ill and weakened Willem Barents died shortly into their crossing [*Zeeberg et al.*, 2002]. Although unsuccessful in navigating the Northeast passage, Barents' journeys had led to the discovery of rich whaling and walrus hunting grounds, and just a few years later Dutch and English whalers [*Arlov*, 1994] were busy competing over the profitable exploitation of the bow-head whale in the waters around Svalbard. The common belief was then that Svalbard was somehow connected to Greenland by a northern extension of land, hence the ice-free whaling ground north of Svalbard was named "Whaler's bay". Advocating the idea of an ice-free interior of the Arctic Ocean (AO) caused by heating from sub-marine volcanoes, the Russian scientist and pioneer within research on atmosphere-ocean heat exchange, M. V. Lomonosov (1711-1765) persuaded Tsarina Catherine the Great to outfit an expedition to sail for the Pacific by following a route west of Svalbard. The expedition leader V. Chichagov (1726-1809), made two unsuccessful attempts to carry out the Tsarina's orders in 1765 and 1766, reaching a farthest north in heavy ice in Whaler's bay at 80°28'N [*Mills*, 2003]. Inspired by the Chichagov expedition, the Royal Navy embarked on a similar mission led by Commander C. Phipps in 1773. Although the prospect of finding a navigable sea route over the Pole may have acted as an underlying motive, the Phipps expedition is generally regarded as the first purely scientific enterprise to the area north of Svalbard. Among the scientific objectives were to "make experiments of the Saltness of the Sea & the degree of Cold by letting down the Thermometer to great depths as you have opportunity" [*Savours*, 1984]. Subsurface water sampling and temperature recording techniques were however still on an experimental stage. In retrospect, neither of the two techniques employed by the Phipps expedition could give reliable results. In Fig-

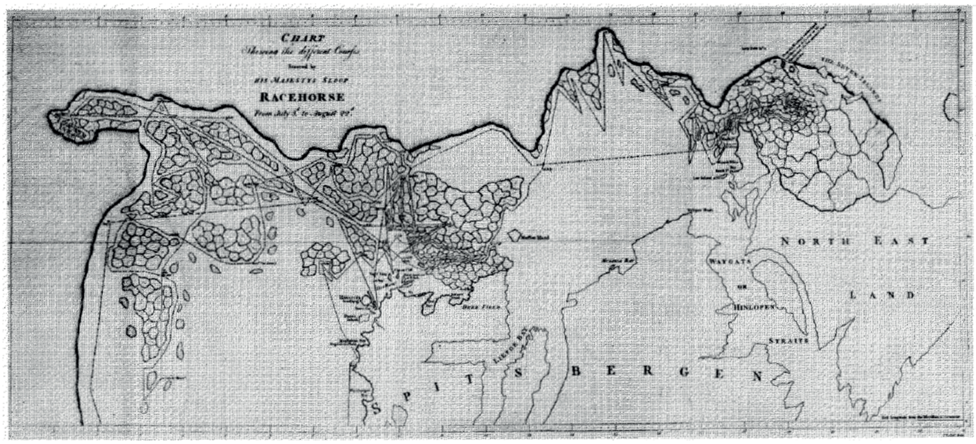

Figure 1.1. The ice-free area north of Svalbard called "Whaler's bay", depicted in an ice chart drawn by the 1773 Phipps expedition [*Savours*, 1984; *Phipps*, 1774]. Note the speculative outline of the North East Land.

ure 1.1, the track of the Phipps expedition and the position of the ice edge they observed in Whaler's bay are depicted, making it the first "quasi-synoptic" ice chart from the area. In 1820, the English whaling captain and aspiring scientist William Scoresby the younger (1789-1857), published a book [*Scoresby*, 1820] on observations from his voyages to Greenland and Svalbard waters. Using a fir cask cast in brass with an opening in both ends, which would close when the descent of the bottle was halted, he attempted to sample water at depth. The bottle was allowed to stay at the desired depth for about half an hour to adjust to the ambient temperature. Then it was "hauled briskly up without stopping, and the temperature of the contained water immediately ascertained". Despite the observational difficulties, Scoresby was able to demonstrate that warm water underlying colder water is present down to 800 m in the ocean west of Svalbard. At other locations, Scoresby attempted to measure the temperature of water sampled from even greater depths (down to 1400 m), but these showed unrealistically high values (up to 3.3°C). In Figure 1.2 a temperature profile from the WSC taken by Scoresby on 16 May 1816 is shown. Based on these observations, Scoresby speculated "From the fact of the sea near Spitzbergen being usu-

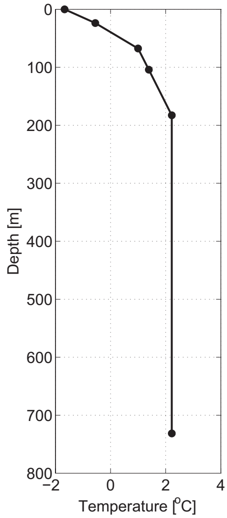

Figure 1.2. Temperature profile taken 16 May 1816, anchored to an ice floe at 79°00'N, 5°40'E [*Scoresby*, 1820].

ally six or seven degrees warmer at the depth of 100-200 fathoms, than it is at the surface, it seems not improbable that the water below is a still farther extension of the Gulf Stream, which, on meeting with water near the ice lighter than itself, sinks below the surface, and becomes a counter under-current."[1] At the time, experiments had recently been carried out which showed that the density of sea water increases steadily with decreasing temperature until it reaches the freezing point (unlike fresh water, which obtains a maximum density at 4°C). Scoresby dimissed that this could be the case, founding his argument in his practical experience of the submerging WSC. Overlooking the effect of the Atlantic Water (AW) being saltier, he found it unreasonable that the warmer water could descend below the colder polar water, unless the temperature dependence of sea water density resembled that of fresh water.

Despite Scoresby's early exposition of the sub-surface nature of the warm WSC, speculations of a polar heating source continued. *Wells* [1872] presented temperature measurements from the Whaler's bay area, speculating that the warm water was coming from the uncharted area around the Pole. With the Challenger expedition (1872-1876) and the advent of oceanography as a scientific discipline at the late half of the 19th century, scientific knowledge of the deep ocean advanced dramatically. The counter-part of the Challenger expedition in the Nordic Seas[2] and the Barents Sea was the Norwegian North Atlantic Expedition, which was launched in 1876, carrying out a pioneering interdisciplinary scientific program for three consecutive summers. In a brief news announcement to *Nature* from one of the cruises, *Mohn* [1878] notes, almost poetically: "It appears that here on the 80th parallel, the warm Atlantic current is still running north wards, backed up on the west coast of Spitzbergen. The polar ice, driven by northerly winds, is swimming on its back, and melted gradually off just like the end of the glaciers in the summer heat of the valleys." *Mohn* [1887] observed many interesting features from the waters around Svalbard, e.g. the patchy westward recirculating branches of the WSC, the northward cooling and gradual descent of AW contained in the WSC and the cold overflow water from Storfjorden.

The interior of the Polar Sea remained an object of speculation, and the German geographer August Petermann promoted the idea that the warm, poleward Atlantic current represented a thermal gateway to the Pole, where moderate ice conditions could be anticipated, once the ring of ice around the Pole was breached [*Tammiksaar et al.*, 1999; *Mills*, 2003]. Petermann also suggested that a peninsula or series of islands extended all the way from the northern coast of Greenland to the Bering Strait, naming the undiscovered land mass "Petermann land". As the German Koldewey and Austro/Hungarian Payer/Weyprecht expeditions failed to reach the Pole via the Fram Strait and the Barents Sea, Petermann adviced the American explorer and navy officer George W. De Long to take the route through the Bering Strait and follow the coast of the hypothetical Petermann land to the Pole [*Wright*, 1953]. De Long's vessel Jeanette froze in east of Wrangell Island in 1879 and was crushed by the ice north of the New Siberian Islands two years later. A few survivors managed to reach inhabited settlements in the Siberian mainland. In 1884, objects from the Jeanette were discovered on an ice floe southwest of Greenland. In a newspaper article, Professor H. Mohn proposed that currents had

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[1] 6-7°F temperature difference corresponds to 3.3-3.9°C, while 100-200 fathoms is 180-360 m (one fathom is six feet).

[2] Here the Nordic Seas is defined as the Iceland, Greenland and Norwegian Sea, following *Furevik et al.* [2007].

transported the objects across the North Pole. Fridtjof Nansen picked up the idea, and launched a daring plan of freezing in a vessel close to the location where the Jeanette was shipwrecked and letting it drift across the Polar Sea [*Sverdrup*, 1950]. The hull of Nansen's vessel Fram was designed to make the pressure of the ice lift the vessel, rather than crushing it down. Freezing in a little further west than intended, Fram drifted as close to the Pole as 85°57'N, ending up in the Fram Strait after a little more than 3 years of drift. During the drift of the Fram, several deep soundings were taken, finally proving that the AO consisted of at least one deep basin. Temperature profiles documented the influence of AW all the way east to the New Siberian Islands [*Nansen*, 1902]. The efforts of the Norwegian oceanographic surveys in the early 20th century culminated in the report by *Helland-Hansen and Nansen* [1909]. In Figure 1.3, the circulation in the Nordic Seas according to *Helland-Hansen and Nansen* [1909] is depicted, a picture which is still largely correct [*Blindheim and Østerhus*, 2005]. One of the differences from [*Mohn*, 1878], is that the pathway of the WSC is more accurate, the Norwegian Atlantic Slope Current (NwASC) splitting into the Barents Sea Branch (BSB) and the slope confined WSC south of Bear Island. The westward recirculating branches and the fact that the WSC enters the AO are also emphasized. The South Cape AW branch circulating Storfjordrenna south of Svalbard is also indicated. In [*Helland-Hansen and Nansen*, 1912] the picture around Svalbard was supplemented by the first determination of both temperature and salinity in the WSC with reliable methods, which revealed the northward freshening of the WSC due to lateral exchange with fresher polar water masses. By comparison with earlier observations, a substantial interannual variability in temperature was also documented. The seminal paper by *Helland-Hansen and Nansen* [1909] provided the first large scale description of the circulation in the Nordic Seas and according to *Dickson and Østerhus* [2007], the focus of later contributions has been to quantitatively ascertain the transports and fluxes and determining variability by long-term monitoring. Covering such a vast area requires coordinated effort, and the 4th International Polar Year (IPY) 2007-2009 provided one such unique opportunity [*Krupnik et al.*, 2011]. iAOOS (integrated Arctic Ocean Observing System) was one of the initiatives for the 4th IPY, focusing on development of a long-term monitoring system for the Arctic. The present thesis is part of the Norwegian contribution to the initiative, "iAOOS-Norway: Closing the loop" [*Mauritzen et al.*, 2011]. "The loop" is the northward flow of warm and saline AW in the eastern portion of the the Nordic Seas and the returning cold, dense water from the Arctic in the west. The 4th IPY coincided with a dramatic reduction in summer sea ice extent, reaching a minimum of 4.1×10^6 km^2 on 14 September 2007 (37% less than the climatological average), unprecedented in the era of satellite record [*Comiso et al.*, 2008]. Even prior to the record in 2007, summer sea ice decline was faster than forecast by global climate models [*Stroeve et al.*, 2007]. In Figure 1.4, the record low mean September ice extent in 2007 and the median September ice extent (1979-2000) are shown [*Fetterer et al.*, 2002, updated 2009]. In 2007, open water existed for almost the entire distance between Eastern Siberia and the North Pole, evoking associations with Lomonosov and Petermann's discredited vision of an ice-free polar sea. One component in the iAOOS project was participation in the scientific observations made from the Arctic schooner Tara [*Gascard et al.*, 2008], which set out in 2006 to repeat the drift of the Fram. Reduction in perennial and multi-year ice extent [*Nghiem et al.*, 2007], combined with a general thinning [*Rothrock et al.*, 1999] of the Arctic sea ice has led to a more mobile ice cover, speeding up the transpolar drift. The drift tracks of Tara and Fram

Figure 1.3. The circulation in the Nordic seas, according to *Helland-Hansen and Nansen* [1909]. Here, the WSC and its recirculating branches have been emphasized with red color.

are shown in Figure 1.4, revealing the much faster drift of Tara, completing its drift in 506 days (less than half of that of the Fram) and missing the North Pole by merely 90 nautical miles.

To monitor and be able to interpret changes in poleward ocean heat flux are essential for understanding the present and future states of the Arctic sea ice cover [*Dickson et al.*, 2008]. The WSC is the major source of oceanic heat to the Arctic, and fills the 150-900 m layer of the Eurasian and Canadian basins with water that has a temperature warmer than 0°C [*Polyakov et al.*, 2005], well above the freezing point of sea water. Above the Atlantic layer is the thin (100-150 m thick) cold halocline layer, which acts as a buffer protecting the surface water and the polar pack ice against the warmer water beneath. The changes seen in the Arctic creates a backdrop and motivation for the present thesis, which is a process study of the final transformation of the WSC occuring in the Fram Strait. In the introduction to his thesis on the hydrography of the WSC, *Saloranta* [2001] commented that "The major shortcomings connected with the oceanography of the WSC have been the sparseness of observations as well as the lack of physical explanations for the phenomena observed". A relatively densely spaced mooring section has now been in operation across the WSC at 78°50'N since 1997, maintained by the Alfred Wegener Institute (AWI). In the present thesis, the fundamental concepts of unstable barotropic (**Paper I**) and baroclinic shelf waves (**Paper II** and **III**) are applied in order to explain long-periodic transient oscillations observed in the mooring data from the WSC. The isopycnal heat loss associated with the vorticity fields generated by the flow instability is estimated by signal analysis of the mooring data. In **Paper IV**, the oceanic surface heat exchange in the eastern Fram Strait is estimated from bulk formulas and compared with the results of the lateral heat exchange due to eddy activity.

1.2 Description of the West Spitsbergen Current

The North Atlantic Current, which is the northward extension of the Gulf Stream, flows into the Norwegian Sea through the Faeroe–Shetland Channel and over the Iceland–Faeroe Ridge [*Orvik and Niiler*, 2002; *Hansen et al.*, 2008]. The warm and saline Atlantic water masses continue in two branches, the Norwegian Atlantic Slope Current (NwASC) following the shelf edge offshore of Norway and the western Norwegian Atlantic Current (NwAC) manifesting itself as a frontal jet along the Arctic frontal zone [*van Aken et al.*, 1998] (Figure 1.4). South of Bear Island, about 60% [*Walczowski and Piechura*, 2007] of the AW carried by the NwASC continues northward as the slope confined WSC branch, the rest flowing east into the Barents Sea with the BSB. Observations and numerical model experiments indicate [*Gammelsrød et al.*, 2009] that the BSB may experience enough cooling while crossing the shallow Barents Sea to represent a net heat sink for the AO as the modified AW finally spills down the St Anna trough between Franz Josef Land and Novaja Zemlja and into the Eurasian Basin. The rather barotropic [*Fahrbach et al.*, 2003] slope branch of the WSC is topographically steered [*Saloranta*, 2001] towards the north, and extends all the way to the bottom between the 300 and 800 m isobaths [*Haugan*, 1999]. The surface layer over the shelf is typically much fresher than the AW of the WSC, making the Arctic front appear as a density front at the shelf break. Below the 0-50 m surface layer, the warm and saline AW and cold and fresh Arctic water masses on the shelf are merely delineated by a Temperature-Salinity (TS) front, without any sharp horizontal gradient in density [*Saloranta and Svendsen*, 2001]. This subsurface Arctic

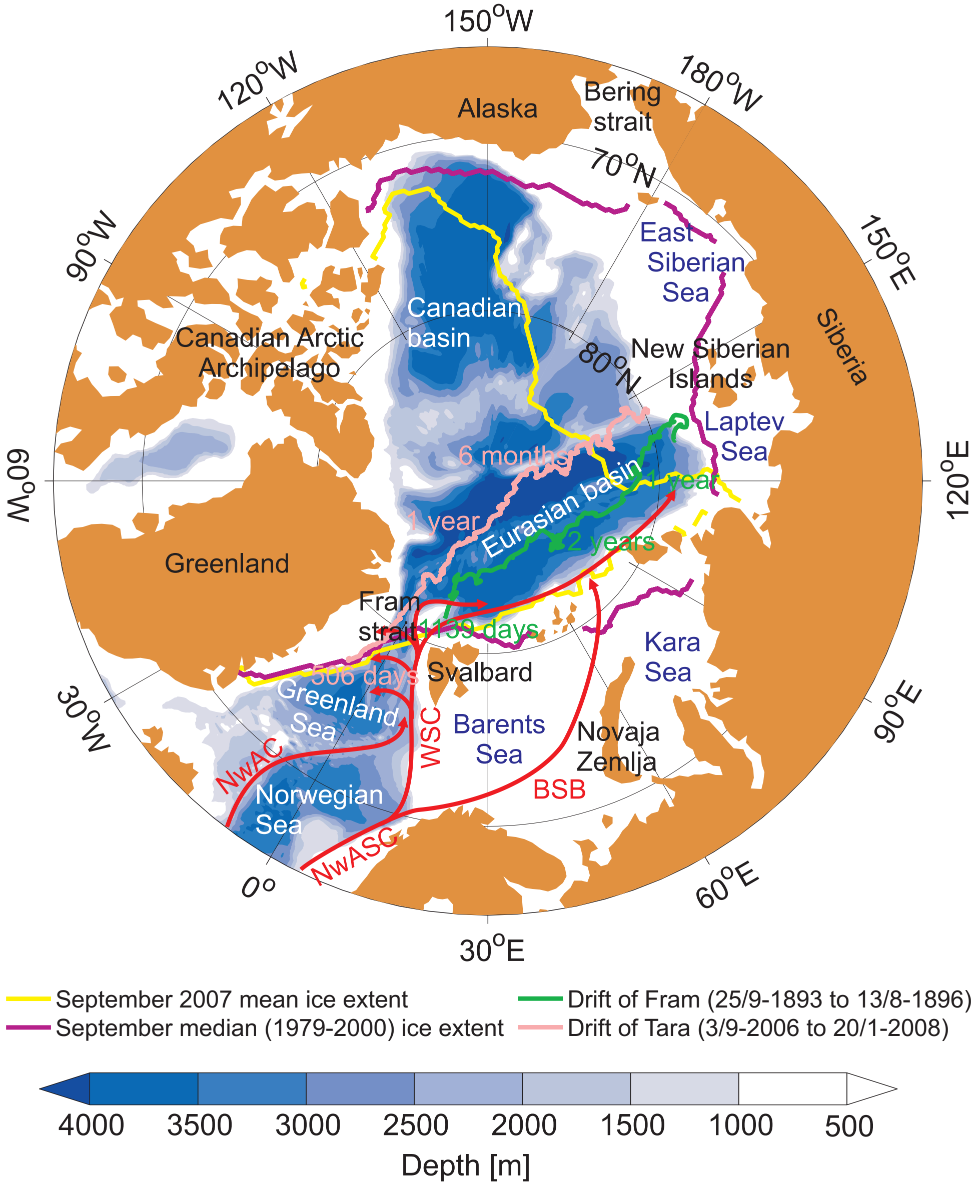


Figure 1.4. Bathymetry of the Arctic Ocean and surrounding seas. Atlantic water pathways [*Orvik and Niiler*, 2002; *Walczowski and Piechura*, 2007] towards the Arctic Ocean are illustrated (red arrows). The contour of the mean ice extent in September 2007 and the median September ice extent (1979-2000) are also shown [*Fetterer et al.*, 2002, updated 2009]. The drift tracks of the Fram [*Colony and Thorndike*, 1984] and Tara [*Pedersen*, 2011] are indicated.

TS front seems to be confined near the shelf break and extends down to the bottom. Occasionally, upwelling winds may cause extensive flooding of AW onto the shelf [*Cottier et al.*, 2007]. According to *Polyakov et al.* [2005], the advection time from Svinøy at 63°N to the Fram Strait (79°N) is about 1.5 years. The NwASC and its continuation, the slope branch of the WSC, is the main pathway between the North Atlantic and the AO, but recent studies [*Walczowski et al.*, 2005; *Walczowski and Piechura*, 2007] indicate that a highly variable [*Beszczynska-Möller et al.*, 2007] part of the offshore NwAC branch also reaches Fram Strait, converging with the eastern WSC branch at about 78°N. It contributes to the westward recirculation branches of AW from the WSC, which shoot off along the Fracture Zones (FZ) in Fram Strait between 76°N to 81°N [*Bourke and Paquette*, 1988]. The tendency of the WSC to form eddies is well documented [*Johannessen et al.*, 1987; *Gascard et al.*, 1988, 1995], and the recirculating branches are believed to be composed mainly by eddies. At about 80°N, two paths of the eastern WSC branch emerge, the Yermak branch following the outer rim of the Yermak Plateau (YP) centered around the 1500 m isobath [*Gascard et al.*, 1995] and the Svalbard branch crossing the 600 m deep YP close to the northern coast of Svalbard. The Svalbard branch is responsible for the recurrent (at least since 1773, see Figure 1.1) sensible heat polynya called Whaler's bay [*Cottier et al.*, 2010] and the bulk of AW that penetrates far into the AO [*Aagaard et al.*, 1987]. According to *Bourke and Paquette* [1988] the Yermak branch and the westward turning branches constitute 80% of the flow of the WSC, while the rest is brought into the AO by the Svalbard branch. The observations by *Perkin and Lewis* [1984] indicated that the Yermak branch partly reunites with the Svalbard branch after passing around the plateau. *Manley* [1995] estimated that 45% of the AW carried by the WSC is recirculating within Fram Strait, while 25% enters the AO with the Yermak branch, and the remaining 30% with the Svalbard branch.

A high degree of variability in the heat and volume tranport of the WSC was already documented with direct current measurements by *Aagaard and Greisman* [1975] and *Hanzlick* [1983]. The heat and mass flow through Fram Strait has now been monitored continuously since 1997 [*Fahrbach et al.*, 2003; *Schauer et al.*, 2004] and recent estimates [*Schauer et al.*, 2008] show that the mean northward transport of AW across a mooring section along the 78°50'N parallel constitutes 5-7 Sv (1 Sv$= 1\times10^6$ m^3/s). The associated heat transport of the AW displayed a two-step increase from 26 TW (1 TW $= 1 \times 10^{12}$ W) in 1997 to its decadal maximum of 50 TW in 2004, but then decreased to less than 35 TW in 2007 [*Schauer and Beszczynska-Möller*, 2009]. The volume transport experienced a similar increase, but this was mostly due to the temperature increase, putting more water into the AW inflow category.

Many of the ideas and concepts which are explored in this thesis are inspired by the works of earlier investigators. In his detailed analysis of current meter data from the WSC, *Hanzlick* [1983] briefly investigated the possibility that barotropic or baroclinic instability were sources of sub-inertial oscillations, utilizing simplified, analytical models. In Figure 1.5, the different stages of WSC cooling depicted by *Boyd and D'Asaro* [1994] are illustrated. Initially, direct heat loss to the atmosphere dominates the cooling process (Figure 1.5a). As sea ice from the Barents Sea is being advected over the warm core of the WSC (Figure 1.5b), melting of ice contributes to cool and freshen the current. A fresher layer is being established over the core, inhibiting deep convection. Despite the fresher surface layer, isopycnal diffusion by mesoscale eddies connects the core of the WSC with the surface (Figure 1.5c), maintaining the cooling process. *Saloranta and*

Table 1.1. The along-shelf (in the y-direction) summer and winter gradients in temperature (T) and salinity (S) presented by *Saloranta and Haugan* [2004] for the eastern WSC branch between the 500 m and 1200 m isobaths. Mean heat loss rates (Q_a) are also tabulated.

Season	Layer interval [m]	$\mathrm{d}T/\mathrm{d}y$ [°C/100 km]	$\mathrm{d}S/\mathrm{d}y$ [psu/100 km]	Q_a [W/m^2]
Summer	0-100	-0.32	-0.028	-130
	100-500	-0.20	-0.010	-330
	0-500	-0.22	-0.013	-460
Winter	0-100	-0.42	-0.025	-350
	0-250	-0.40	-0.016	-830
	100-500	-0.31	-0.004	-1050
	0-500	-0.34	-0.008	-1400

Svendsen [2001] found that barotropic instability is probably an important mechanism for accentuating cross-front exchange at the shelf-edge Arctic front. *Saloranta and Haugan* [2004] noted that the observed combination of cooling and freshening is not consistent with a hypothesis of pure isopycnal offshore mixing, and suggested influence from diapycnal mixing connected to exchanges with shelf waters. In Table 1.1, the climatological values of northward cooling and freshening of the WSC found by *Saloranta and Haugan* [2004] are tabulated. Wintertime heat loss is 50% larger than in summer, and the sub-surface cooling of the WSC is 2.5-3 times higher than in the surface layer. *Nilsen et al.* [2006] investigated how the influence of stable topographic wave modes around the diurnal tidal frequency (K_1) contributes to water mass exchange at the shelf break. *Cottier and Venables* [2007] showed how double diffusive interleaving across the Arctic front between the WSC and the cooler, fresher shelf water could lead to a denser end-product, promoting isopycnal mixing and subsequent convection. The huge sub-surface heat loss (Table 1.1) documented by *Saloranta and Haugan* [2004] provides motivation for conducting a detailed study of the processes in the ocean that promote isopycnal mixing and lateral water mass exchange in the WSC. Barotropic and baroclinic instabilities are likely process candidates, which have been pointed to by numerous earlier investigators [*Hanzlick*, 1983; *Boyd and D'Asaro*, 1994; *Saloranta and Svendsen*, 2001; *Nilsen et al.*, 2006]. A vast literature exists within research on geophysical flow instability, but the studies are often too generic or too specific to be directly applied to the WSC. In the papers presented in the present thesis, our philosophy has been to establish a methodology which enables us to apply a linear stability analysis directly on the time series of current meter measurements in the WSC. This reveals a time record of unstable barotropic (**Paper I**) and baroclinic (**Paper III**) events and the dispersion characteristics of the unstable vorticity waves, which again can be used to extract information about the vortex generated fluxes. By considering also the surface heat fluxes (**Paper IV**), we address some of the basic problems presented by *Mosby* [1972], connecting lateral eddy fluxes with surface heat exchange.

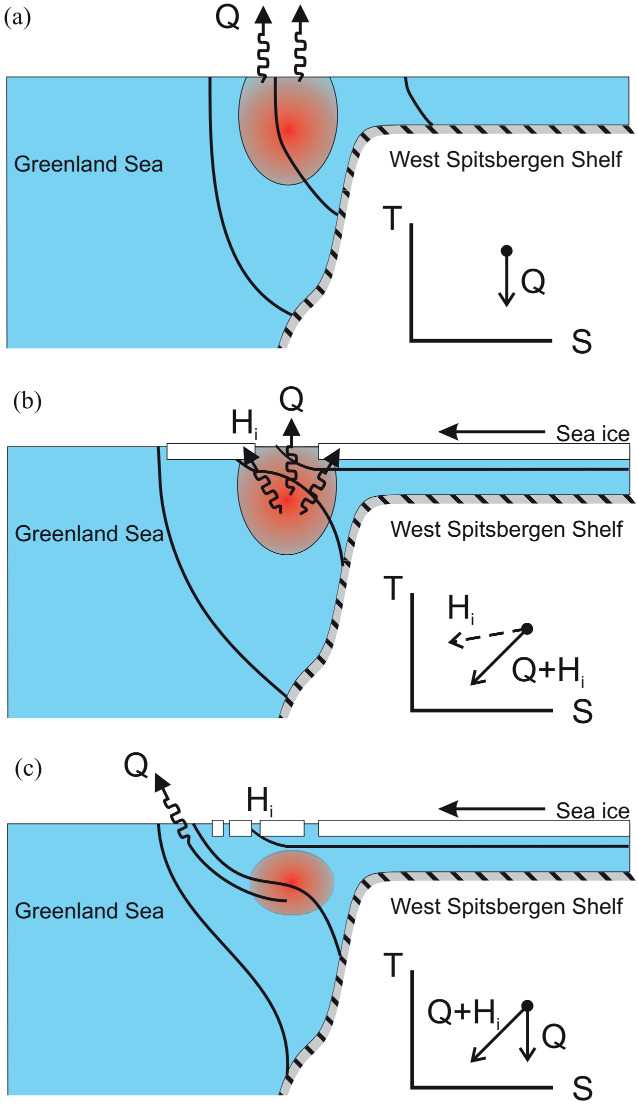


Figure 1.5. Conceptual stages in WSC heat loss, after *Boyd and D'Asaro* [1994]. In stage (a), corresponding to an ice-free situation, direct heat loss to the atmosphere (Q) is dominating, manifesting itself as a vertical line in the TS-diagram. Later (b), sea ice is advected in from the Barents Sea, both cooling and freshening the current (H_i). Finally, after the WSC has been capped by a fresher, cooler surface layer (c), cooling is still taking place by isopycnal diffusion along the density lines outcropping on the offshore flank of the current.

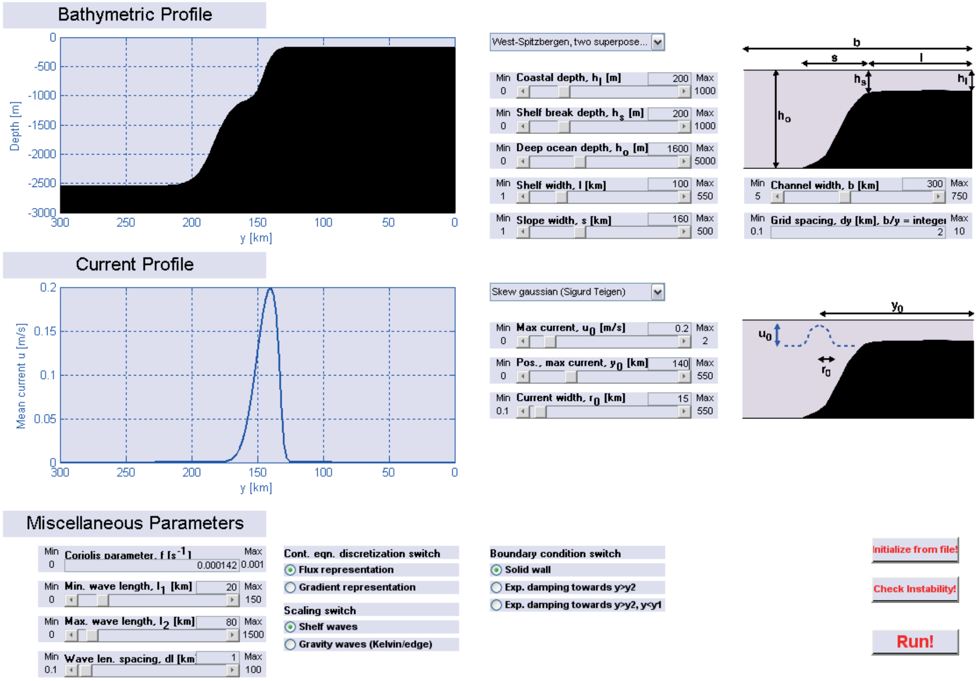
1.3 Global and regional influence of the West Spitsbergen Current

It is now well documented that the Arctic climate is going through a dramatic change [*ACIA*, 2004; *Kaufman et al.*, 2009] with rising air temperatures, thawing permafrost, declining snow cover, glacial retreat and diminishing sea ice cover, with the reduction in summer sea ice extent being one of its most expressive manifestations (Figure 1.4). The Fram Strait is a key region for understanding the variability in the oceanic component of the system, both the input of oceanic heat and salt with the WSC [*Schauer et al.*, 2008], but also the export of sea ice and freshwater from the AO [*de Steur et al.*, 2009]. Warm anomalies formed in the eastern subpolar gyre [*Holliday et al.*, 2007], have been tracked through the Nordic Seas [*Orvik and Niiler*, 2002] into Fram Strait [*Walczowski and Piechura*, 2007], spreading further into the Eurasian basin [*Dmitrenko et al.*, 2008; *Ivanov et al.*, 2009]. *Holliday et al.* [2008] found a 3-4 years time lag between the subpolar gyre and the Fram Strait, and predicted that the AW temperature in Fram Strait would start to decrease in 2007 or 2008. Results from the DAMOCLES mooring section [*Schauer and Beszczynska-Möller*, 2009] support the prediction, showing that the temperature has in fact decreased the last couple of years. An increased upward oceanic heat flux from the intruding AW in the AO could lead to a rapid loss of the remaining sea ice cover [*Turner*, 2010]. The study by *Polyakov et al.* [2010] shows that Atlantic layer warming did contribute to pre-conditioning the perennial ice cap for the extreme ice loss seen in the past years. Recent studies show that the overflow across the Greenland-Scotland ridge has been fairly stable the last 50 years [*Olsen et al.*, 2008]. However, *Karcher et al.* [2011] showed with model experiments that the warm, low-density AW anomalies in the AO may reduce the Denmark Strait overflow when they eventually spill out in the Nordic Seas 15-25 years after their entry to the AO. The potential sensitivity of the Atlantic Meridional Overturning Circulation (AMOC) to greenhouse-gas and other climate forcing has been known for a while, and also that state switches in the AMOC may be capable of causing rapid changes in the Earth's climate [*Dickson et al.*, 2003]. As shown by *Rhines et al.* [2008], the eastern Fram Strait stands out as one of the regions where the seasonal heat storage is most efficiently depleted from the upper ocean, leaving winter time cooling to inflict a substantial net buoyancy loss. Traditionally, deep convection in the Greenland Sea was considered as the main source of overflow water from the Nordic Seas [*Aagaard et al.*, 1985; *Rudels*, 1995]. *Mauritzen* [1996a,b] revised this notion by stressing the importance of the gradual densification of AW as it is being cooled along its pathway through the Nordic Seas. *Walin et al.* [2004] considered the dynamical consequences of the along-shelf buoyancy loss, finding that an initially baroclinic boundary current will develop two branches, one baroclinic seaward jetstream and one barotropic slope current. As buoyancy is lost by surface cooling, the transport of the jetstream will decrease, while the transport of the barotropic slope current increases accordingly. *Eldevik et al.* [2009] studied the properties of the deep overflow, finding that it consists of at least 64% recirculating AW, supporting the hypothesis of *Mauritzen* [1996a,b]. Owing to the importance of the Fram Strait for the AMOC, it is critical to establish what processes control the buoyancy loss and the westward transport of heat and salt from the eastern boundary currents in Fram Strait to the southward overflow water.

The extraordinary reduction in sea ice extent and volume seen in the past years has received considerable attention, but only recently are we starting to grasp the regional significance of this development. In Svalbard, warm Atlantic water masses are always available for melting sea ice by winter-time flooding of the shelf, caused by coastal upwelling due to continuous winds from the north [*Cottier et al.*, 2007]. AW from the WSC is to a variable degree topographically steered along the troughs at the mouths of the westward facing fjords of Svalbard, having a profound impact on the physical environment inside the fjords. AW pulses are well documented in Isfjorden [*Nilsen et al.*, 2008] and Kongsfjorden [*Svendsen et al.*, 2002; *Cottier et al.*, 2005]. Eddy overturning caused by barotropic instability at the shelf edge front may also lead to on-shelf advection of heat [*Saloranta and Svendsen*, 2001; *Tverberg and Nøst*, 2009], inhibiting sea ice growth. Reduction in sea ice extent and thickness may change the timing of the phytoplankton bloom due to earlier spring break-up. Arctic marine ecosystems may suffer from a potential mismatch between the peaks in high-quality food supply and the reproductive cycle of key Arctic grazers [*Søreide et al.*, 2010]. Recent analyses of satellite-derived chlorophyll-a concentrations show that there has indeed been a trend towards earlier phytoplankton blooms in the areas where the reduction in summer ice extent has been most dramatic, e.g. in the Hudson Bay, Baffin Sea, Greenland coastal areas, Kara Sea and around Novaya Zemlya [*Kahru et al.*, 2011]. A switch to warmer ocean temperatures may also cause a northward shift of ecosystems [*Falk-Petersen et al.*, 2007]. The reappearance of blue mussels at Sagaskjæret in Isfjorden in Svalbard after 1000 years of absence was most likely associated with AW inflow and warming [*Berge et al.*, 2005], and may serve as an example. As a consequence, it is of great interest, not only for the global issues of the future of the perennial ice cover in the AO or the AMOC, but also for the local climate in Svalbard to investigate the mechanisms behind AW modification and exchange as it is being transported around the archipelago.

1.4 Instability of slope currents

Topographic shelf waves are sources of sub-inertial oscillations, which are able to travel long distances along continental margins [*Mysak*, 1980a,b]. In the presence of a sheared mean current, a typical feature of continental slopes [*Huthnance*, 1981, 1992], the waves may become unstable [*Collings and Grimshaw*, 1984]. The stability analysis of homogeneous shear flows has a long history in hydrodynamic theory [*Drazin*, 2002], and echoes the names of some of the founding fathers of the discipline (e.g. Helmholtz, Kelvin, Rayleigh and Reynolds). For geophysical applications it is of course interesting to include the effects of rotation and stratification [*Cushman-Roisin and Beckers*, 2011]. Essentially, there are two possible energy sources for the instabilities, either the kinetic energy in the horizontal current shear (barotropic instability) or the potential energy in horizontal density gradients (baroclinic instability) [*Pedlosky*, 1964a,b]. Accordingly, the studies of shelf waves in the presence of a mean current is usually divided into two categories, depending on whether the flows are classified as barotropic or baroclinic [*Mysak*, 1980a]. A necessary condition for barotropic instability including the Coriolis force was first derived by *Kuo* [1949]. The corresponding condition for barotropic instability of an along-slope current was elaborated by *Niiler and Mysak* [1971]. For barotropic instability, a necessary condition is that the background potential vorticity must attain at least one extremum within the domain. In the present thesis, the approach formulated by *Gjevik* [2002] was used to study the stability of barotropic shelf waves in the WSC (**Paper I**). In order to ease the examination of generic shelf and current profiles, the original `Fortran` code developed by



West-Spitzbergen, two superpose...

Coastal depth, h_l [m]: 200 (Min 0, Max 1000)

Shelf break depth, h_s [m]: 200 (Min 0, Max 1000)

Deep ocean depth, h_o [m]: 1600 (Min 0, Max 5000)

Shelf width, l [km]: 100 (Min 1, Max 550)

Slope width, s [km]: 160 (Min 1, Max 500)

Channel width, b [km]: 300 (Min 5, Max 750)

Grid spacing, dy [km], b/y = integer: 2 (Min 0.1, Max 10)

Skew gaussian (Sigurd Teigen)

Max current, u_0 [m/s]: 0.2 (Min 0, Max 2)

Pos., max current, y_0 [km]: 140 (Min 0, Max 550)

Current width, r_0 [km]: 15 (Min 0.1, Max 550)

Coriolis parameter, f [s^{-1}]: 0.000142 (Min 0, Max 0.001)

Min. wave length, l_1 [km]: 20 (Min 0, Max 150)

Max. wave length, l_2 [km]: 80 (Min 0, Max 1500)

Wave len. spacing, dl [km]: 1 (Min 0.1, Max 100)

Cont. eqn. discretization switch
● Flux representation
○ Gradient representation

Scaling switch
● Shelf waves
○ Gravity waves (Kelvin/edge)

Boundary condition switch
● Solid wall
○ Exp. damping towards y>y2
○ Exp. damping towards y>y2, y<y1

Figure 1.6. Screen capture of graphical user interface in `Matlab` for analysis of stable and unstable barotropic shelf waves.

Gjevik [2002] was translated to `Matlab` and a graphical user interface was implemented. The layout of the user interface is shown in Figure 1.6. The study of baroclinic instability traces its origin back to V. Bjerknes, and the first attempts to understand the generation mechanisms behind mid-latitude cyclones [*Friedman*, 1989]. The Bergen school assumed that the instability was due to the sharp polar front, but the mathematical treatments by *Charney* [1947] and *Eady* [1949] showed that exponential disturbances in the atmosphere is an intrinsic property of stratified flow on a rotating planet [*Eliassen*, 1983]. Baroclinic instability is now recognized as an explanation model for the synoptic transients responsible for the ordinary "weather" on Earth [*Pierrehumbert and Swanson*, 1995], but is also most likely responsible for synoptic eddy fields in the ocean [*Gill et al.*, 1974] as well. The ocean's reservoir of potential energy is maintained by large-scale wind and surface fluxes. Baroclinic instability is able to transfer energy from the potential energy stored in the horizontal density gradients to the first baroclinic mode and from there to the barotropic mode, in which an inverse cascade of barotropic kinetic energy to larger horizontal scales happens until the eddy motions are finally dissipated [*Ferrari and Wunsch*, 2009]. In this sense, baroclinic instability plays an important role in the energy transfer occurring in the global ocean, and parameterization of the eddy fluxes associated with the process is necessary in climate model runs [*Isachsen*, 2010]. The "puzzling waves" in the density field in the Norwegian Sea described by *Helland-Hansen and Nansen* [1909] are often cited as early observational evidence of meso-scale eddy activity in the area. Starting with

Orlanski [1969], layered models have been used extensively to study baroclinic instability in current jets over sloping topography. *Mysak and Schott* [1977] used a simple two-layer model to study baroclinic instability in the NwASC. The model formulation of *Mysak and Schott* [1977] was later applied to the WSC by *Hanzlick* [1983], who investigated possible explanations for spectral peaks of sub-tidal frequency in current measurements from the WSC. Although more general approaches exist, including continuous stratification, vertical and horizontal shear in the same formulation [*Pedlosky*, 1987], for the present study we choose follow in the path of numerous earlier investigators and treat the baroclinic instability problem in a layered formulation [*Mysak*, 1980a]. By employing an idealized, two-layer linear stability analysis (**Paper II** and **Paper III**), our desired goal has been to provide a useful interpretation of the observed long-periodic transient oscillations in the WSC, avoiding unnecessary topographical details and secondary dynamical processes.

Chapter 2

Summary of papers

Paper I

In this paper we investigate the characteristics of unstable barotropic shelf waves in the shelf-break branch of the WSC. We find that the current close to the slope is best described as an asymmetrical jet, as the along-shelf current is decaying faster onshore (towards the quiescent shelf) than offshore. The sharper cross-shelf shear on the shelf-side increases the likelihood of barotropic instability. The background current is modeled by fitting the current meter data to an analytical skew Gaussian profile, which is used as input to a numerical linear stability analysis. Assuming periodic, small amplitude perturbations in the along shelf direction, the stability problem is reduced to an eigenvalue problem by discretization in the across shelf direction. The eigenvalue problem for the wave frequency, when along shelf wave number is specified, is solved numerically. The dispersion characteristics of the unstable waves are compared with wavelet and rotary spectrum analysis of the current meter data, showing good agreement. By complex demodulation, the signal associated with the oscillations of the most unstable wave mode is extracted, allowing a computation of the lateral isopycnal eddy heat fluxes.

Paper II

This paper is structured as a technical report, expanding the numerical model used in **Paper I** to a two-layer formulation for investigating stable and unstable baroclinic shelf waves. Details on the derivation of the model, the numerical grid and solution are presented. Model results are compared with analytical results for a step-shelf, showing almost exact agreement. The model is also compared with the results of *Mysak and Schott* [1977], i.e. a linear slope with uniform current in both layers. Applications to the WSC and shelf topography are presented, along with an evaluation of calculation domains.

Paper III

Paper III extends the analysis in **Paper I** by investigating the possibility for baroclinic instability in the WSC over the deeper section (1000-2500 m) of the slope. The two-layer model described in **Paper II** was utilized, modelling the situation of a warm Atlantic layer capping the colder deep water in the Fram Strait. The slowly evolving background current profile and stratification were estimated from the mooring data and given as input to the linear stability analysis, revealing the dispersion characteristics of the unstable baroclinic shelf waves. Wavelet and rotary spectrum analysis of the current meter data from September 2007 to July 2009 detect transient signals with significant energy at similar oscillation periods as indicated by the linear stability analysis. By complex demodulation of the temperature and current data, the signal associated with the most unstable mode was studied in detail, finding several episodes of intense offshore heat loss from the WSC.

Paper IV

In **Paper IV**, the analyses in **Paper I** and **Paper III** are put into a broader context by also considering the influence of atmospheric heat exchange and sea ice melting. The oceanic surface fluxes in the Fram Strait are estimated for the time period September 2007 to September 2009, based on bulk parameterizations with input from satellite observations and reanalysis fields. Interannual variability in the impact of sea ice melt on the heat budget of the WSC is reviewed by analysing the satellite record (1979-2009) of sea ice coverage. Comparisons are made between the surface fluxes and lateral heat exchange due to eddy fields found in **Paper I** and **Paper III**. The Garrett-Munk spectrum at the shelf-break mooring is determined, revealing insight into the diapycnal mixing occurring there. The influence of the stable shelf mode being amplified by the diurnal (K1) tide is also reviewed. Finally, the estimates from the different heat loss processes are compared, revealing the decisive heat loss associated with unstable (barotropic and baroclinic) vorticity waves occuring around the turn of the year (November to January) for both the two analysed winters.

2.1 Conclusions

The main findings in this thesis are:

- Analysis the current meter records over the upper slope domain (between the 1000 m isobath and the shelf-break) and the additional shelf-break mooring revealed the asymmetric nature of the current profile of the barotropic WSC branch. The stronger horizontal shear on the shelfward side makes the current disposed for barotropic instability (**Paper I**).

- Barotropically unstable conditions prevail in the upper slope domain during $\sim 40\%$ of the analysed time record between September 2007 and June 2008, with typical wave lengths ranging 20-40 km and wave periods between 40-70 h. Wavelet and rotary spectrum analysis detected elevated levels of energy at the same oscillation periods as predicted by the linear analysis (**Paper I**).

- For the asymmetric barotropic jet, the vorticity centre of the unstable shelf waves is typically positioned at the shelf edge, in an ideal position to promote isopycnal exchange across the Arctic TS-front. The along-shelf cooling caused by the barotropic instability process was estimated to reach -0.08°C/100 km (**Paper I**).

- A shallow-water two layer linear model for stability analysis of baroclinic slope jets was developed and verified, revealing new insight into the prevalence and structure of unstable baroclinic shelf waves in the WSC (**Paper II**).
- The two-layer model was successfully applied to the WSC over the deeper section of the slope (between the 1000 and 2400 m isobaths), where the Atlantic layer is shoaling over the deep water of the interior of the Greenland Sea. The baroclinic slope current was modelled as a Gaussian jet in both layers. A sensitivity analysis showed that the solution was not very sensitive to small variations in the half-width and across-shelf position of the jet (**Paper III**).
- The dispersion characteristics of the unstable baroclinic shelf waves were revealed, with typical wave periods of 35-75 h and wave lengths 15-30 km. The analysis indicated that the baroclinic instability process was active for $\sim 30\%$ of the analysed period (September 2007 to July 2009). Assuming offshore outcropping isopycnals, the heat loss inflicted on the core of the WSC by the most unstable baroclinic shelf wave was estimated to reach 240 $\mathrm{W/m^2}$. The modal structure of the most unstable baroclinic shelf wave is focused close to the position of the maximum current over the deeper slope (**Paper III**).
- Barotropic and baroclinic instability processes are most active during winter time, due to sharper horizontal and vertical current shears. Earlier studies point to the wind field being responsible for intensifying the current during wintertime (**Papers I** and **III**).
- Extensive surface heat loss during winter is episodical, most intense over the warm core of the WSC and may reach 500 $\mathrm{W/m^2}$ (averaged over a 8 day period) (**Paper IV**). Wave characteristics found by linear stability analysis of the WSC have been used to extract the signal of the isopycnal eddy heat fluxes associated with them. The heat loss may reach the same order of magnitude as the atmospheric heat loss directly over the core (**Papers I**, **III** and **IV**).
- The amount of sea ice being advected directly over the warm core of the WSC (south of 79°N) has been greatly reduced in the recent years. In 2006-2009 the ice concentration was only 10-17% of the climatological mean (1979-2000), and may not have been so essential for cooling and freshening the current (**Paper IV**).
- Lateral exchange by isopycnal diffusion may play an important role in preconditioning the WSC for excessive winter heat loss to the atmosphere by reducing the vertical stability, which may enhance convection (**Paper IV**).

To summarize, the present thesis represents another step towards understanding the dynamical processes that affect the AW transformation occurring in the sea west of Svalbard. The stability properties of the WSC have been thoroughly examined, based on a slowly varying background current profile determined from mooring data. Our findings support and extend the results of *Boyd and D'Asaro* [1994] and *Saloranta and Haugan* [2004], demonstrating that the processes of offshore isopycnal diffusion of heat and lateral water mass exchange across the Arctic front are intensified by flow instability in the WSC during winter. Quantitative estimates of the amount of cooling being inflicted on the core of the WSC by these processes are also presented. The vorticity wave structures emerging from the modelled barotropic and baroclinic instability processes serve different roles in the cooling of the WSC. The unstable barotropic wave associated with the asymmetric slope-break jet is eroding the density front between the core and the shelf, both reducing the resistance against vertical convection and opening the shelf for lateral water mass exchange. Over the deeper section of the slope, the unstable baroclinic waves are acting to diffuse heat offshore, at the same time unlocking the geostrophic control on across-shelf transport. They also represent a generation mechanism for the energetic eddies that are frequently observed in the Fram Strait, being potentially important for the westward recirculation.

2.2 Future work

As a part of iAOOS-Norway, a mooring was deployed at the shelf-break, in continuation of the AWI mooring section. In addition, another mooring was deployed 10 km upstream of the shallowest AWI mooring. Unfortunately, this mooring was lost, possibly due to trawling. Access to upstream moorings would have been valuable in order to track the along-shelf propagation of vorticity wave signals, and is a subject that could be looked into by future investigations. The shelf wave models employed in the present work are assuming uniform topography in the along-shelf direction. However, topographic anomalies may lead to wave scattering [*Huthnance*, 1987] and also destabilize baroclinic flows [*Bracco and Pedlosky*, 2003]. Along the WSS, there are deep troughs running all the way from Isfjorden and Kongsfjorden to the shelf break, which may act to destabilize the current and promote eddy formation [*Bracco et al.*, 2008]. In Figure 2.1 the standard deviation of a one year record of satellite measurements of Sea Level Anomaly (SLA) in the eastern Fram Strait is plotted. The slope region between 79°N and 80°N stands out as an area with high variability in SLA, an indicator of enhanced eddy activity [*Pujol and Larnicol*, 2005]. Just upstream of this region there is a 800-1000 m deep plateau area named the Vestnesa Ridge. This is close to the spot where the eastern WSC branch bifurcates into the Yermak and Svalbard branches. Eddies generated in this area may translate both in a cross-slope direction towards deeper areas [*Johannessen et al.*, 1987] and climb the slope of the Yermak plateau [*Gascard et al.*, 1995]. The westward eddy path is part of the recirculation pattern in the Molloy topographic structure as reported in literature, and would be an interesting area to study eddy activity through mooring observations, high resolution numeric models, and idealized modeling of the abrupt change or constriction in the Vestnesa Ridge topography. Detection of individual eddies from satellite altimetry data may also be a viable course of action [*Lilly et al.*, 2003]. In our model of wavelike perturbations to the WSC, we assume a complex wave frequency - opening the possibility for instabilities that will grow exponentially in time. Another approach is to allow for complex wave numbers [*Gaster*, 1965; *Cushman-Roisin*, 2009], which may lead to spatially exponential disturbances. This could be an interesting path to follow, and would complement the present analysis. Wind forcing is a possible source of energy for exciting shelf waves [*Gjevik*, 1991; *Nilsen*, 2004]. Apart from being a source of perturbation, the wind field may well be the driving mechanism behind the winter time sharpening of the horizontal and vertical current shear in the WSC [*Jónsson et al.*, 1992]. *Jakobsen et al.* [2003] showed from drifter data that there was a 20% increase in flow speed in the Nordic Seas during winter time, and even more close to the continental slopes. They attributed the intensification to the wind stress forcing being up to four

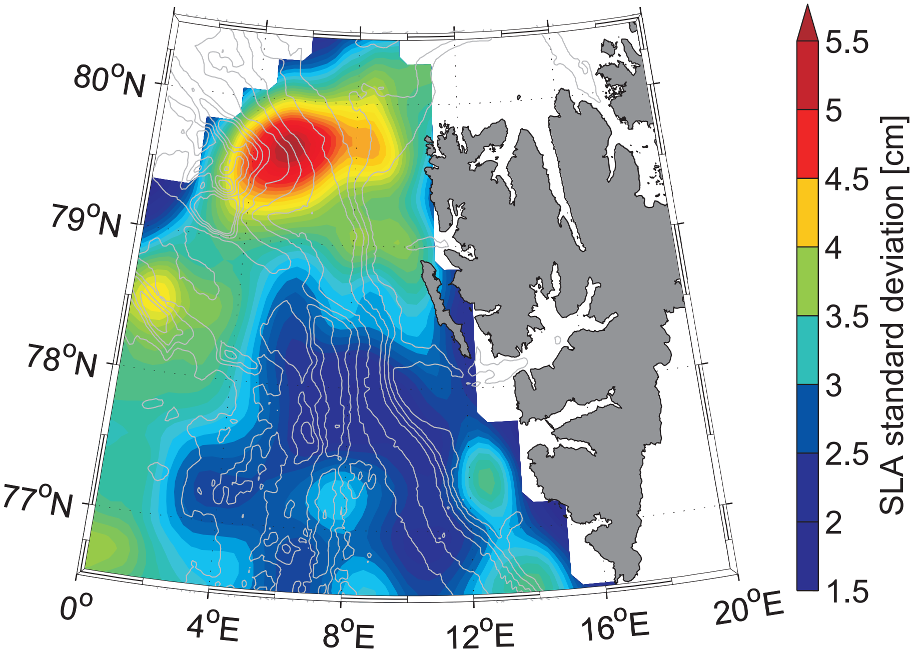


Figure 2.1. Standard deviation (for the entire year of 2004) of Sea Level Anomaly. Sea bed bathymetry is also indicated (gray contour lines).

times larger during wintertime. Interannual variability is linked with the North Atlantic Oscillation (NAO), with currents being stronger during phases of high NAO index. The barotropic and baroclinic instability processes studied in the present thesis depend on the seasonal changes in current shear, hence it would be of great interest to look into the forcing mechanisms for the ambient flow. Access to data collected by sea gliders would provide a much better spatial and temporal picture of the hydrography in Fram Strait, thereby providing a better basis for estimating the position of the fronts and the slopes of the isopycnals.

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Appendix A

Abbreviations and Acronyms

Below is a list of abbreviations and acronyms used in the introduction and elsewhere throughout the thesis.

ADCP	Acoustic Doppler Current Profiler
AMOC	Atlantic Meridional Overturning Circulation
AO	Arctic Ocean
ASW	Arctic Surface Water
AW	Atlantic Water
BSB	Barents Sea Branch
CTD	Conductivity Temperature Depth
DAMOCLES	Developing Arctic Modeling and Observing Capabilities for Long-term Environmental Studies
ECMWF	European Centre for Medium-Range Weather Forecasts
EGC	East Greenland Current
ERA	ECMWF Re-Analysis
FZ	Fracture Zone
GM	Garrett-Munk
iAOOS	integrated Arctic Ocean Observing System
IPY	International Polar Year
LAIW	Lower Arctic Intermediate Water
NAO	North Atlantic Oscillation
NwAC	Norwegian Atlantic Current
NwASC	Norwegian Atlantic Slope Current
O&SI SAF	Ocean & Sea Ice Satellite Application Facility
PV	Potential Vorticity
PW	Polar Water
RAW	Return Atlantic Water
SLA	Sea Level Anomaly
SMMR	Scanning Multichannel Microwave Radiometer
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SVD	Singular Value Decomposition
TS	Temperature-Salinity

UAIW	Upper Arctic Intermediate Water
WSC	West Spitsbergen Current
WSS	West Spitsbergen Shelf
WSSl	West Spitsbergen Slope
YP	Yermak Plateau