Small-scale dynamics of the under-ice boundary layer

Anders Sirevaag

Dissertation for the degree philosophiae doctor (PhD)
at the University of Bergen

31 October 2008

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Anders Sirevaag

Geophysical Institute
University of Bergen
Norway

UNIS
The University Centre in Svalbard

Bjerknes Centre
for Climate Research

Abstract

In ice covered polar regions, the interaction between ocean, ice and atmosphere is an important component in the complex climate system. Exchange of heat, mass and momentum occurs across the boundary layers, both in the ocean and in the atmosphere, hence understanding the involved processes are crucial in order to determine future climate.

In this thesis dynamics and thermodynamics of the under-ice boundary layer are investigated based on measurements of turbulent fluxes in close proximity to the ice/ocean interface and microstructure profiling of the upper ocean. The topic is addressed in four papers which focus on exchange processes at the ice/ocean interface as well as regional measurements of turbulence and turbulent fluxes in ice covered areas around Spitsbergen and in the Weddell Sea.

High rates of melting are often encountered as sea ice drifts into water with temperatures well above freezing, which may be typical of the marginal ice zones. It has been shown in previous studies that these melting rates are limited by double diffusive effects in a thin layer close the ice/ocean interface. In this study, turbulent fluxes from the under-ice boundary layer are used to show that double diffusive effects are important for the melting rates and show that the strength of this double diffusion is close to the range suggested by previous studies. It is also shown that by not considering double diffusive effects at the boundary, melting rates are overestimated by up to several cm per day.

By analyzing the conditional statistics of the Reynolds stress in the boundary layer it is found that the main fraction of the stress comes from high turbulence events, so called “sweeps” and “ejections”, which is consistent with boundary layer flows in other environments. Closest to the ice, the sweeps are found to be more intense than further away from the interface, which can be related to the observed increase in friction velocity with depth.

The West Spitsbergen Current transports Atlantic Water, which is the main source of salt and heat to the Arctic. This study presents measurements obtained during 6 drifting experiments northwest of Spitsbergen where the West Spitsbergen Current enters the Arctic and which also is an area of substantial air/sea/sea exchange. Heat fluxes within or in close proximity of the main branches of the West Spitsbergen Current are O(100) W m^{-2}, due to high mixed layer temperatures and large ice drift. Over the shelf areas high mixing and turbulent fluxes are observed due to tidal effects and interaction with topography. Heat fluxes averaged over the different water masses found in the area show that turbulent heat flux decreases with increasing distance from the surface. Hence it indicates that Atlantic Water is not the main source for vertical mixing of heat. A major contribution to mixed layer heat content is found to be horizontal advection and entrainment of water from below.

In the far Southern Atlantic, the Weddell Sea is another important site of ocean and atmosphere interaction. In the area of Maud Rise, a topographic feature in the eastern Weddell Sea, the water column is only weakly stable making it susceptible to deep convection. This study presents wintertime mixed layer turbulence measurements obtained during two ice drift over the Maud Rise. Heat fluxes were comparable to earlier studies in the same area and could be estimated from the mean properties of the mixed layer. The under-ice roughness was estimated to be very smooth and comparison with a one dimensional steady state model suggests that this is a local effect and not representative for the entire ice floe. The main source of turbulent kinetic energy is velocity shear from the ice, however in some periods horizontal heterogeneity in water masses, ice topography and open water fraction can affect the stability and introduce upstream sources of turbulent kinetic energy.

Acknowledgements

The point of submitting this thesis has always seemed far, far away. However, when the thesis now exists in its final form I would like to use this opportunity to thank all those that have helped along the way. First of all thanks to Ilker Fer for good discussions, invaluable help with writing and analyses, good company in the Arctic and for having such momentum in everything he does. I am also grateful to Miles McPhee who introduced me to the boundary layer in 2002 and whom I have had the pleasure of working with during several field campaigns since then. Thanks also to my main supervisor Tor Gammelsrød for being supportive in letting me do my own things.

I would also like to thank Frank Nilsen for always keeping the UNIS door open and being supportive to all sorts of fieldwork and projects. I will also thank all those that have made all the long days and weeks spent on ships or ice floes memorable and not only hard work. Thanks to Karolina for leading the way in getting a “turbulence-PhD” and to Elin for excellent office-company. Erik and Ivar are acknowledged for keeping the level of the compulsory soccer-discussions superior of any scientific discussion. Many thanks to all students and staff of the Geophysical Institute for good company, discussions, talks, coffee breaks, lunches, parties… over many years. Also thanks to the Bjerknes Centre for supporting my PhD project and for the good scientific community of climate science established over the last years.

Finally, my family – thanks to Endre and Oda for making it so easy to leave the office in the afternoon and distract my mind away from science. And last, but not least, I’m indebted to Carita for always being supportive and enthusiastic, I’m not sure I could have done this without you being the way you are.

Bergen, October 2008

Contents

1 Outline

The aim of this study is to investigate the dynamics of the under-ice boundary layer. This includes the general structure, driving forces, and exchange and interaction with ice and atmosphere. The study is based on measurements obtained mainly from drifting sea ice during various field projects both in the Arctic and Antarctic.

The thesis consists of this introduction and four manuscripts. The introduction provides a general scientific background (section 2), a more thorough description of this project and the measurements (section 3), a summary of the included manuscripts (section 4) and main results and suggestions for future work (section 5).

The four manuscripts included in this thesis are listed below and will in the following be referred to by their roman letters:

- **Paper I: Turbulent exchange coefficients for the ice/ocean interface in case of rapid melting.**
  Anders Sirevaag
  Submitted to Geophysical Research Letters

- **Paper II: Early spring oceanic heat fluxes and mixing observed from drift stations north of Svalbard.**
  Anders Sirevaag and Ilker Fer.
  Submitted to Journal of Physical Oceanography

- **Paper III: Wintertime mixed layer measurements at Maud Rise, Weddell Sea.**
  Anders Sirevaag, Miles G. McPhee, James H. Morison, William J. Shaw and Timothy P. Stanton.
  Submitted to Journal of Geophysical Research – Oceans

- **Paper IV: Conditional statistics of the Reynolds stress in the under-ice boundary layer.**
  Ilker Fer, Miles G. McPhee and Anders Sirevaag
  Geophysical Research Letters, Vol. 31, L15311 (2004).

Paper I uses heat and salt flux measurements obtained during rapid melting to estimate the role of double diffusion on the ice/ocean interface and estimate the effective melting rate compared to other parameterizations. **Paper II** presents measurements of heat fluxes and mixing in the area north and northwest of Svalbard where the main transport of heat and salt to the Arctic occur. In **Paper III** mixed layer measurements obtained during ice drifts over the Maud Rise topographic feature in the Weddell Sea are presented with focus on mixed layer dynamics and thermodynamics, while in **Paper IV**, turbulent fluctuations of velocity in the boundary layer are analyzed to describe the conditional statistics of the Reynolds stress.

2 Scientific background

2.1 Air/sea/ice interaction in polar oceans

For the global climate, interaction between ocean and atmosphere is important. The main exchange of heat, mass and momentum occurs across the boundary layers, hence boundary layer processes are of crucial importance for the efficiency of such an exchange.

In polar regions, there is a delicate balance between the ice covered ocean and the atmosphere. In the ocean, heat is normally stored below a colder mixed layer which again is insulated from the atmosphere by an ice cover. The ice cover is important for several reasons: (i) it insulates the warm ocean from the atmosphere (ii) it increases the surface albedo, hence reducing the amount of solar radiation input to the ocean (iii) it transfers momentum, an important source for ocean mixing, from the atmosphere to the ocean.

Over the last decades, there has been a significant change in the Arctic ice cover with a reduced ice extent and a transition towards thinner and younger sea ice [e.g. *Maslanik et al.*, 2007; *Nghiem et al.*, 2007]. There has also been observed an increased heat transport into the Arctic through the Fram Strait [*Schauer et al.*, 2004] and through the Berings Strait [*Woodgate et al.*, 2006]. This change in water mass properties with more heat available below the mixed layer and the change in ice cover which changes the dynamic and thermodynamic properties of the sea ice, modifies the balance at the ice/ocean interface. Although the ice cover is predicted to further decrease [e.g. *Holland et al.*, 2006; *Serreze et al.*, 2007], it is still not clear how a change in the composition of the components within the ice/ocean interaction will impose on a future climate.

Making measurements of small scale processes in the ice covered areas of the world oceans is logistically challenging, expensive and hard to maintain on a regular basis due to the inaccessibility of the study areas. A goal of making such measurements is to establish and test parameterizations and representations of the turbulent properties and fluxes based on the main properties of a flow or boundary layer. This makes it possible to estimate key parameters of the air/sea/ice exchange from automated measurements such as drifting buoys or satellite measurements or from more standard oceanographic measurements such as hydrography. Well working parameterizations are also crucial for modelling at all levels from complex earth system models to high resolution turbulence models, where the choice of parameterization scheme has large impact on the resulting air/sea/ice interaction [e.g. *Holland and Jenkins*, 1999; *Schmidt et al.*, 2004].

In this study, two geographical regions, which are important with respect to air/sea/ice interaction, are considered. These are the area north of Spitsbergen, where the main inflow of warm and saline water to the Arctic occurs (Figure 1) and the eastern Weddell Sea (Figure 2).

2.1.1 Inflow to the Arctic

The Norwegian Atlantic Current transports warm and saline Atlantic Water (AW) along the western coast of Norway, being the main reason for the mild climate in this region.

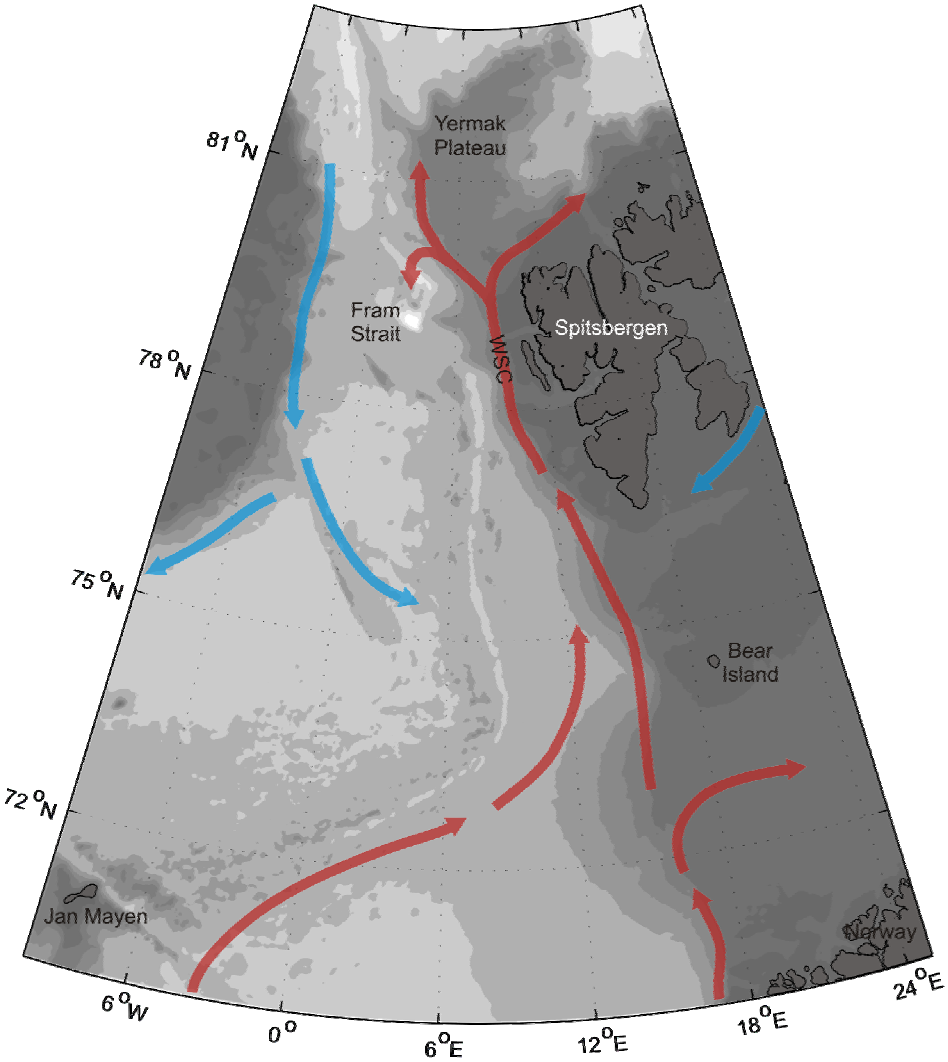

Figure 1 General pathways of inflow and outflow to the Arctic through the Fram Strait. Red arrows indicate flow of Atlantic Water whereas blue arrows indicate outflow of Polar Water or Arctic Water. Dark topography is shallow, light is deeper. Map is based on *Blindheim and Østerhus* [2005], *Bourke et al.* [1988] and *Skagseth* [2008].

Further north, a branch continues into and partially recirculates within the Barents Sea [*Skagseth*, 2008], while a major fraction continues along the western coast of Spitsbergen, called the West Spitsbergen Current (WSC, Figure 1). The Fram Strait is the main connection between the Arctic Ocean and the Nordic Seas and the main contribution of heat and salt to the Arctic is transported by the WSC through this passage [*Aagaard et al.*, 1987]. Northwest of Spitsbergen, the WSC continues as two branches; one northwards along the isobaths of the Yermak Plateau (the Yermak Branch), while the other continues eastward across the shallow shelf area north of Spitsbergen (the Svalbard Branch). Roughly 2/3 of the water within the core of the WSC is recirculated within the Fram Strait whereas 1/3 of the water continues directly into the Arctic, mainly from the Svalbard Branch [*Manley*, 1995]. Along its path, the original AW of the WSC is modified by interaction with the ice and the atmosphere to form intermediate waters within the Arctic. Although being the main source of heat to the Arctic, the WSC looses a significant amount of heat on its way. Changes in heat content estimated from hydrographic sections across the main branch of WSC results in an estimated heat loss from the core of AW of O(100) W m^{-2} [*Boyd and D'Asaro*, 1994; *Cokelet et al.*, 2008; *Saloranta and Haugan*, 2004; *Aagaard et al.*, 1987]. A significant part of the heat loss is most likely attributed to horizontal advection and diffusion of heat and by isopycnal mixing offshore or onshore of the core of the WSC [*Boyd and D'Asaro*, 1994; *Cokelet et al.*, 2008; *Steele and Morison*, 1993].

2.1.2 The Weddell Sea

In the southern hemisphere, the Weddell Sea stands out as an important region for producing the deep water masses of the world oceans. Situated in the southern Atlantic Ocean, the general circulation is dominated by the cyclonic Weddell Gyre which mainly consists of Weddell Deep Water which is modified water from the Antarctic Circumpolar Current (ACC, Figure 2). The large shelf areas with persistent offshore winds, keep the coastal polynyas open during the winter, maintaining a high production of sea ice. Brine release from the forming ice produces the high salinity shelf water which cools under the floating ice shelves before it descends down the continental slope. A modified version of the shelf water exits the Weddell Sea as Antarctic Bottom Water [*Foster and Carmack*, 1976]. The Weddell Sea also has a large potential for open ocean convection due to the often encountered thin and weak pycnocline that separates the mixed layer from the warmer waters below [*Gordon*, 1991]. An example of this is the Weddell Polynya which persisted for about

3 years in the 70's [*Carsey*, 1980] and which led to a massive exchange of heat between the ocean and the atmosphere. The formation of the Weddell Polynya occurred close to Maud Rise, a topographic feature in the eastern Weddell Sea (Figure 2). At this location, Warm Deep Water flows along the northwestern flank of the Maud Rise and mixing with the topography in the area aids modifying the local water masses. The water column is only marginal stable with a weak pycnocline. If warmer water masses are mixed upwards, non-linearity in the equation of state of sea water (thermobaricity) will make this water lighter than water above and the convection will continue. As the heat melts the ice, the mixed layer will again be stratified and convection will come to a halt. However, if the density difference between the mixed layer and the underlying water masses is small enough, input of fresh water on top is not enough to stop the deep convection.

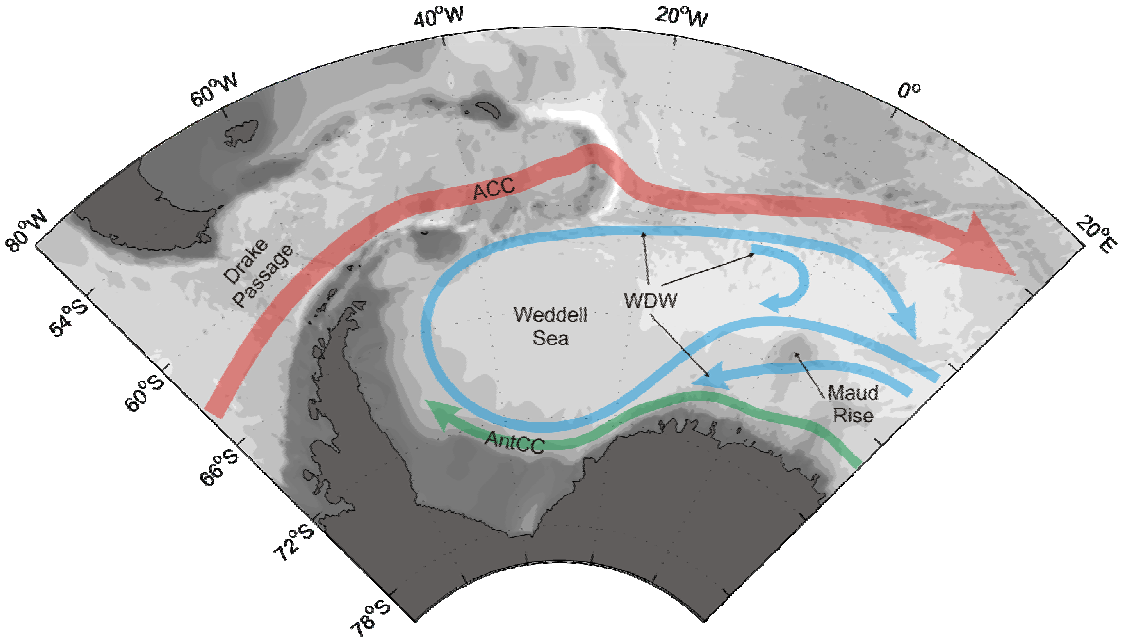

Figure 2. Map showing the bathymetry and main circulation features of the Weddell Sea. Red arrow (ACC) is the Atlantic Circumpolar Current, blue arrows are circulation of Warm Deep Water (WDW) within the Weddell Sea and green arrow indicates the Antarctic Coastal Current (AntCC). Dark topography is shallow, light is deeper. Map is based on *Orsi et al.* [1999], *Schröder and Fahrbach* [1999] and *Smedsrud* [2005].

The Maud Rise region has shown to have water masses that are only marginally stable to this type of deep convection [*McPhee*, 2000] and for some areas only a slight additional freezing at the surface and mixing at the pycnocline would make the water column susceptible for deep convection, as in the Weddell Polynya event [*Akitomo*, 2006; *McPhee*, 2003].

2.2 Sea Ice

In a simplified way, sea ice forms a closed lid between the ocean and the atmosphere which excludes heat from being transferred either way and alters the way momentum is transferred into the ocean. However, sea ice contains salt which influences the thermodynamical properties of the ice itself and presents an extra source of buoyancy at the ice/ocean interface.

When formed from sea water, a fractional amount of the salt initially contained in the water is contained within the ice structure. Within the ice, salt is concentrated in a high salinity liquid component, called brine, in so called brine pockets. The salinity of the brine and the fractional volume of brine pockets, depends on the ice temperature and distance from the ice/ocean interface. The salinity of sea ice is considered as the bulk salinity, which is the determined as the salinity of the brine times the fraction of brine pockets within a unit volume of sea ice. The main mechanism for desalination of sea ice is gravity drainage [*Notz et al.*, 2005], which is a function of the permeability of the ice, the brine density relative to the seawater density and the height above the ice/ocean interface. Basically, above a certain height, buoyancy forces are stronger than viscous forces and brine drains through an interconnected network of brine channels. During summer, draining of melt ponds which is formed by melting at the ice surface, will flush the brine within the ice structure as well. This way multiyear ice has a lower bulk salinity than first year ice. Release of salty brine from the ice can be a direct source of turbulence in the ocean boundary layer [*Widell et al.*, 2006], however the most pronounced effect of brine is changing the ice’s thermodynamic and optical properties. The thermal conductivity, the latent heat of fusion and extinction of short wave radiation are all affected by the salinity of sea ice, hence it is important for the transport of heat, melting/freezing and the transfer of short wave radiation through the ice.

The under-ice surface of the sea ice is an important driving force for turbulence in the under-ice boundary layer. The roughness of the sea ice covers a range from very smooth newly formed ice to heavily ridged multiyear ice with keels extending tens of meters into the ocean. Keels of this size cover a considerable fraction of the boundary layer, hence being an important source of turbulence. The under-ice roughness length, z_0, which is considered to be about 1/30 of the under-ice surface roughness elements, range from several centimetres for Arctic pack ice [e.g. *McPhee et al.*, 1987] to a fraction of a millimetre for landfast first year ice [e.g. *Crawford et al.*, 1999].

2.3 The under-ice boundary layer

The under-ice boundary layer is, as most natural flows, fully turbulent and the properties of the turbulence are to a large extent determined by the stratification of the boundary layer. Changes in stratification are normally determined by a changing background salinity gradient or a negative or positive buoyancy flux at the surface from melting or freezing. A neutral boundary layer include a surface layer covering the upper meters in which the variation in Reynolds stress is negligible (Figure 3A). This layer is called the constant-stress layer and it has a logarithmic profile of horizontal velocity following the "Law of the Wall"

$$U(z) = \frac{u_{*0}}{k} ln(\frac{|z|}{z_0}) \qquad (1)$$

where u_{*0} is the interface friction velocity, k = 0.4 is Von Karman's constant and z_0 is the under-ice roughness. The interface stress, or Reynolds stress, $\tau_0 = u_{*0}^2$ is related to the vertical velocity gradient by the eddy diffusivity, K_ρ which is the product of interface friction velocity and a characteristic length scale, the mixing length λ. The mixing length is assumed to be the distance over which the energy-containing eddies diffuse momentum and for the neutral case, mixing length increases linearly from the ice/ocean interface, $\lambda = k|z|$ within the surface layer (Figure 3A). Outside the surface layer, the mixing length increases but tend to be limited by the planetary length scale, as depicted in Figure 3.

In case of a stable stratification, layering limits the mixing length which will be smaller than the case for neutral stability (Figure 3B). For the unstable case, the only limiting scale on the mixing length will be the depth of the mixed layer (Figure 3C).

For a steady, horizontally homogeneous boundary layer, the balance of turbulent kinetic energy (TKE) yields:

$$-\langle u'w'\rangle \frac{\partial U}{\partial z} - \langle v'w'\rangle \frac{\partial V}{\partial z} - \frac{g}{\rho}\langle \rho' w'\rangle = \frac{\partial}{\partial z}\left(\frac{1}{2}\langle u_i' u_i' w'\rangle + \frac{1}{\rho}\langle p' w'\rangle\right) + \upsilon \left\langle \left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i}\right)\frac{\partial u_j'}{\partial x_i}\right\rangle \qquad (2)$$

In (2), u', v', w', ρ' and p' are the turbulent fluctuation of along stream and cross stream horizontal velocity, vertical velocity, density and pressure, respectively, i and j indicate summation and angle brackets indicate averaging. υ is the kinematic viscosity. The two first terms on the left hand side are the shear production and the third is the buoyancy production. On the right hand side, first term includes the divergence of TKE and pressure-velocity covariance, respectively and the last term is the dissipation rate of TKE. Generally, the divergence terms are assumed to be small and negligible. However, for the outer boundary layer, *McPhee* [2004] estimated the divergence of TKE to account for about 3/4 of the observed discrepancy between shear production and dissipation. For neutral conditions, velocity shear is the main driver of turbulence in the boundary layer and the balance of TKE is a simplified balance between shear production and dissipation.

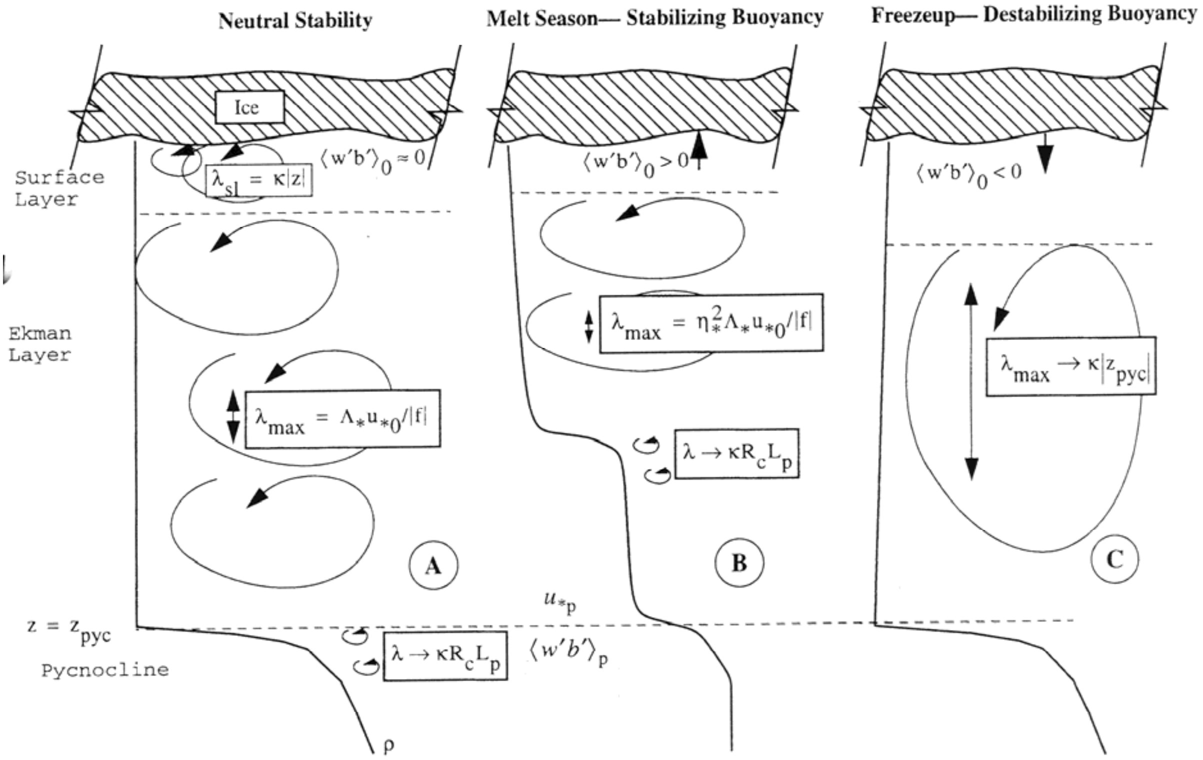

Figure 3. Structure mixing lengths in the under-ice boundary layer, from *McPhee and Morison* [2001]. In case of neutral stability (A), buoyancy flux $\langle w'b' \rangle$ = 0, mixing length increases with distance from interface within the surface layer. Outside the surface layer, mixing length is limited by the planetary length scale where Λ_* is a similarity constant. In the melting case (B), stratification is stabilized by fresh water input on the surface and mixing length is limited by the planetary length scale modified by the stability factor η_*. During freezing (C), mixing length is only limited by the depth of the pycnocline. L is the Obukhov length.

When melting or freezing is present at the interface, both the stratification and the terms of TKE are altered. By melting, an input of fresh water at the top of the boundary layer makes the stratification stable and mixing lengths will be limited by the layering. Hence, work against stratification will enter as a sink in the balance of TKE. On the other hand, freezing releases salt at the interface and lead to a temporal unstable stratification. Mixing lengths increases as a result of convective overturning and buoyancy production will be an additional source of TKE.

In general, the assumption of horizontal homogeneity is met for the open ocean. However, some areas can have a quite significant horizontal heterogeneity in temperature and salinity, e.g. within the marginal ice zones, estuaries or fjords with strong tidal flows. For these boundary layers, either under ice or at the bottom, a horizontal density gradient combined with the logarithmic velocity profile will lead to differential horizontal advection which can alter the initial stratification and hence the TKE terms. This is reported for the under-ice boundary layer in case of strong tidal flows [*Crawford et al.*, 1999] and for estuaries with strong tidal flows and strong horizontal density gradients [e.g. *Ralston and Stacey*, 2005; *Rippeth et al.*, 2001]. In case of *Ralston et al.* [2005], the horizontal density gradient introduced an extra source of TKE that accounted for up to 50 % of the total TKE in the bottom boundary layer.

By considering the conditional statistics of the Reynolds stress for the boundary layer close to a rough surface, it is found that a significant fraction of the stress originates from “bursting events” which are several times more energetic than the average [*Nakagawa and Nezu*, 1977]. These events, called “ejections” and “sweeps” and their relative contribution to the local Reynolds stress, correspond to a vertical divergence of TKE [*Raupach*, 1981].

The turbulent fluxes of kinematic heat and salt in the ocean boundary layer are generally measured as the covariances $\langle w'T' \rangle$ and $\langle w'S \rangle$, respectively. At the ice/ocean interface, the flux of heat is balanced by heat conduction through the ice and latent heat from freezing or melting. Similarly, conservation of salt at the interface means that an oceanic salt flux is balanced by a flux of salt or freshwater from the ice. Additional sources of heat and salt complicates this simple balance, e.g. input of solar radiation through thin ice or open leads and input of melt water from flushing melt ponds during summer [*Eicken*, 2003].

Due to the logistical effort and complexity of measuring these fluxes *in situ*, parameterizations are useful and necessary tools for relating turbulent fluxes to mean properties of the ocean and atmosphere boundary layer as well as properties of the ice cover. Relating the kinematic heat flux to the temperature elevation above freezing for the mixed layer and the interface friction velocity [*McPhee*, 1992]

$$\langle w'T'\rangle = c_H u_{*0}\left(T_{ml} - T_f\right) \tag{3}$$

is done for a large range of field experiments where turbulent fluxes and background conditions are measured. The parameterizations includes the interface friction velocity and an exchange coefficient, the turbulent Stanton number c_H, and has proven to be robust for a wide variety of conditions with a fairly uniform c_H in the range 0.005 – 0.006 [*McPhee*, 1992]. For some conditions, these simplified parameterizations do not hold. An example is the marginal ice zones, where drifting sea ice often encounters mixed layers with temperatures well above freezing. Earlier drifting experiments observed that ice was melting at a much slower rate than expected once drifting into these warm mixed layers. This mechanism was explained by so called molecular sublayers at the ice/ocean interface in which the transfer of heat and salt is determined by molecular diffusivities and not only the turbulent transfer. When this is the case, molecular diffusivity of salt is several orders smaller than for heat, hence heat transfer (and melting) at the interface is rate limited by the salt transfer [*Notz et al.*, 2003; *Steele et al.*, 1989]. This has implications for estimated melting rates under such conditions.

3 This study

3.1 Objectives

This PhD-project was planned as a continuation of the work of my Cand.Scient. thesis; ”Turbulence and heat exchange under ice”, finished in 2003. The present thesis is based on data from several field campaigns; the WARPS data from 2003, the MaudNESS data from 2005 in addition to data obtained during cruises with RV Lance in 2005 and 2007 (sections 3.2.2 - 3.2.4). The main scientific objectives have been:

- Study the various terms of TKE in the under-ice boundary layer and their adjustment to external forcing such as under-ice topography, wind, ice drift, heat and salt exchange and changing properties of the mean flow.
- Investigate ice/ocean interaction at the interface related to melting and freezing.
- Use obtained data to evaluate and improve existing parameterizations of air/sea/ice interaction.

The study has been fully based on in-situ measurements, mostly made from drifting sea ice, of small scale turbulence in and below the under-ice boundary layer. Main instrument systems used are the Turbulence Instrument Cluster (TIC), which is described briefly below, and a loosely tethered microstructure profiler (MSS). Ancillary measurements have been Conductivity Temperature Depth (CTD), sea ice and snow temperatures and thicknesses, Acoustic Doppler Current Profiler measurements, both ship based and ice based, in addition to standard ship-based meteorological measurements such as air temperature and wind speed and direction.

3.2 Field work

3.2.1 Instrumentation

An important part of the data collection during this PhD project has been the use of the so called Turbulence Instrument Cluster (TIC, Figure 4). The TIC consists of a suite of sensors mounted to measure small scale variations of velocity, temperature and salinity at a given level in the under-ice boundary layer and comprises an Acoustic Doppler Velocimeter (5MHz ADVOcean) from Sontek/YSI that measures 3-D velocity in a small water volume of ~2 cm^3. At the same vertical level, fast response temperature (SBE3) and conductivity (SBE7) sensors are mounted to resolve the fluctuations in temperature and salinity.

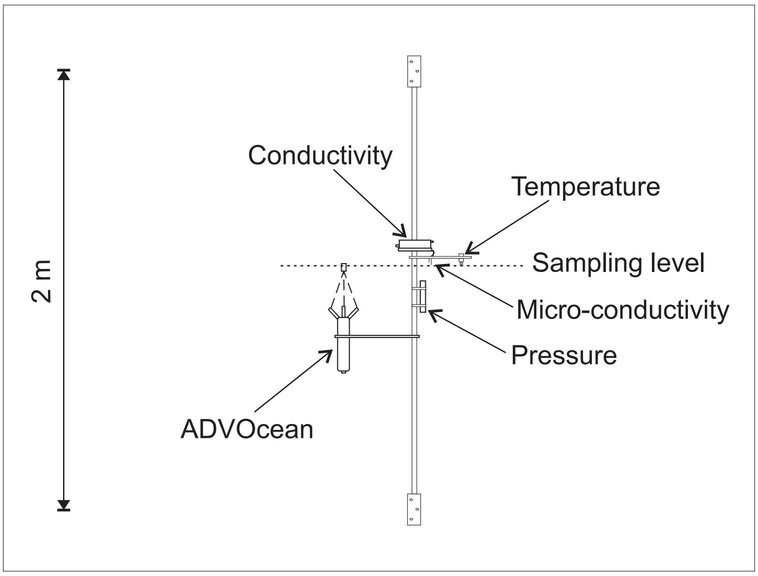

Figure 4. Schematic sketch of the assembly of the Turbulence Instrument Cluster.

Since the fast response SBE7 tends to drift in absolute value over a relatively short period of time, a SBE4 ducted conductivity cell, also from SeaBird Electronics, is mounted ~20 cm above the others to capture the absolute conductivity accurately. Sensor sampling rate is at least 2 Hz, depending on the configuration, which resolves turbulent fluctuations well into the inertial sub-range.

TICs are used in several configurations. The simplest setup is one TIC deployed through a hydro hole with a fixed orientation to the ice, which was used during the RV Lance cruise in 2007 and during the MaudNESS campaign, as described in **Paper II** and **Paper III**. For this setup, the mast has to be aligned manually to orient the sensors towards the mean flow and orientation has to be measured manually on the ice surface. For the WARPS experiment and for the MaudNESS mid-layer turbulence mast, two TICs were mounted on the same mast with a vertical spacing of 4 m and lowered through the ice using a motorized or manual winch. In this setup, the turbulence mast is equipped with a vane which continuously orient the sensors towards the mean current and a compass to measure the orientation. This two-TIC configuration was used for collecting data presented in all papers, **I – IV**.

3.2.2 WARPS - Winter Arctic Polynya Study

The Winter Arctic Polynya Study (WARPS) consisted of a field project based on the German research ice breaker *FS Polarstern* from 28 February to 24 April 2003. It covered the areas of Storfjorden, western Barents Sea, Whaler’s Bay, Yermak Plateau and Fram Strait and facilitated several ice based drift stations, ship based CTD stations as well as open water stations. WARPS was an international and interdisciplinary study with main objective to study the exchange between the atmosphere, ice and ocean and the consequences for biogeochemistry and biological processes in water and ice. In this context the turbulence mast played an important role in determining oceanic fluxes.

Data presented here concentrates on two drift stations, one in the so called Whaler’s Bay at the shelf area north of Svalbard 1 – 2 April (**Paper I, II** and **IV**) and one on the eastern flank of the Yermak Plateu 10 – 17 April (**Paper II**).

3.2.3 MaudNESS - Maud Rise Non-linear Equation of State Study

The Maud Rise Non-linear Equation of State Study (MaudNESS) was a field experiment conducted in the area of Maud Rise, a topographic feature in the eastern Weddell Sea centred at 65ºS and 3ºE, during the austral winter of 2005. This is an area of intense air/sea/ice interaction and also where the Weddell Polynya formed and persisted for several years in the late 70’s [e.g. *Carsey*, 1980]. The main objectives were to investigate how non-linearity in the equation of state for seawater contributes to create instabilities and break down stratification, as well as how the circulation around Maud Rise preconditions the water column for deep convection.

The field experiment was based on US research ice breaker *RVIB Nathaniel B. Palmer* 21 July – 18 September 2005 and consisted of several phases. Phase 1 was to map the general hydrography across the Maud Rise by a series of relatively shallow CTD stations. During Phase 2 two drifts were established on the ice in order to make high resolution measurements of the turbulence in the under-ice boundary, in the mixed layer and across the pycnocline. Based on the hydrography obtained during Phase 1, an area where water masses were assumed to be close to instability was chosen during Phase 3 and a series of short duration drifting stations were performed where instrumentation was solely ship-based and focussed on mixed layer and pycnocline.

In **Paper III**, measurements from the two drifts in Phase 2 are presented and discussed. Measurements were obtained using a shallow turbulence mast close to the ice/ocean interface as well as a mid-layer mast which was situated close to the surface for the first drift and at about 30 m for the second drift.

3.2.4 Svalbard drift stations

As part of the course AGF-211, air/sea/ice interaction, the University Centre in Svalbard arranges an annual cruise in order to let the students get hands-on training using modern oceanographic instrumentation. In 2005 and 2007 this cruise was based on the research vessel *RV Lance* and during the period 23 April – 6 May 2005 and 16 – 30 April 2007, ice based work was conducted in the Fram Strait, over the Norwegian Bank as well as on fast ice in fjords on the western, northern and eastern side of Spitsbergen.

In 2005, the microstructure profiler was used on all stations, deployed from the ship with ~150 m profiles every 10 – 15 min throughout every drift at two locations in the Fram Strait and over the Norwegian Bank. In 2007, a turbulence mast consisting of one TIC was deployed in a short drift across the Norwegian Bank. These measurements, along with ship ADCP data are presented in **Paper II**.

4 Summary of papers

4.1 Paper I: Turbulent exchange coefficients for the ice/ocean interface in case of rapid melting

Anders Sirevaag

Submitted to Geophysical Research Letters

In the marginal ice zones, drifting sea ice often encounters water with temperatures well above freezing which leads to large melting rates. Flow in the ocean boundary layer is assumed to be fully turbulent, hence not affected by molecular effects as the turbulent transfer is far more efficient than molecular diffusion. However, several studies discuss how a thin molecular sublayer close to the ice/ocean interface affects the turbulent transfer of heat and salt. Since the molecular diffusivity of salt is two orders of magnitude smaller than the diffusivity of heat, salt transfer at the ice/ocean interface is the limiting factor in determining melting rates of sea ice. From literature, this double diffusive effect at the interface explains how sea ice often observed in mixed layers with temperatures several degrees above freezing. In this paper, observations of heat and salt fluxes from the marginal ice zone are used to determine the strength of double diffusion at the ice/ocean interface. The ratio of turbulent transfer of heat to turbulent transfer of salt is found to be about 33, which shows that double diffusion plays an important role in determining melting rates. For a range of interface friction velocities and mixed layer temperatures, melting rates are calculated using (i) a traditional bulk parameterization based on mixed layer temperature and interface friction velocity and (ii) by including the double diffusion effects at the interface. By ignoring double diffusion, melting rates are significantly overestimated by up to several cm per day for the given range of mixed layer temperatures and interface friction velocities.

4.2 Paper II: Early spring oceanic heat fluxes and mixing observed from drift stations north of Svalbard

Anders Sirevaag and Ilker Fer.

Submitted to Journal of Physical Oceanography

The West Spitsbergen current is the main supplier of heat and salt to the Arctic. It has its main pathway along the western coast of Svalbard and then it splits in two branches where one continues northwards along the isobaths of the Yermak Plateau and the other continues eastward across the shallow shelf areas north of Svalbard. This paper presents and discusses turbulent fluxes and mixing observed from 6 drifting experiments within, in close proximity of and outside the branches of the West Spitsbergen Current. Average heat fluxes are found for the ice/ocean interface, the mixed layer, across the pycnocline as well as over the different water masses found in the area. For the drifts within the main paths of the West Spitsbergen Current and for the drifts in the shallow areas, surface fluxes are one to two orders of magnitude larger than fluxes encountered in areas far off the main branches. For all drifts, average heat fluxes are smallest in the water masses of Atlantic Water origin and increases towards the surface where they have their maximum and mixed layer heat content is found to be largely affected by entrainment from deeper layers and horizontal advection and diffusion.

4.3 Paper III: Wintertime mixed layer measurements at Maud Rise, Weddell Sea

Anders Sirevaag, Miles G. McPhee, James H. Morison, William J. Shaw and Timothy P. Stanton.

Submitted to Journal of Geophysical Research – Oceans

This paper presents boundary layer and mixed layer measurements during Phase 2 of the wintertime 2005 MaudNESS field campaign. Main focus is flux measurements from TIC data, from the boundary layer and deeper in the mixed layer which is complemented by high temporal resolution CTD data, current profiler data, ice and snow measurements and ship meteorological and position data. The ice drift velocity to wind velocity ratio is found to match those of previous experiments in the area, about twice the ratio encountered for Arctic pack ice. This indicates that the ice under-surface is hydraulically very smooth, which is also consistent with stress measurements in the boundary layer. However, measurements are most likely made to close to the surface to be representative for the entire ice floe. Heat fluxes at the ice/ocean interface balance roughly, hence little freezing or melting is observed and small salt fluxes are observed as well. The main source and sink of turbulent kinetic energy is found to be shear production and dissipation. However, presence of horizontal density gradients, larger upstream roughness elements and an increasing fraction of open water introduce additional sources of TKE which contribute significantly for a short period. A 1-D steady state model is initialized with the observed temperature, salinity and velocity at 20 m.

The model reproduces the observed fluxes fairly well, however fails in periods where horizontal gradients are significant.

4.4 Paper IV: Conditional statistics of the Reynolds stress in the under-ice boundary layer

Ilker Fer, Miles G. McPhee and Anders Sirevaag
Geophysical Research Letters, Vol. 31, L15311 (2004).

For the under-ice boundary layer, large flux events are often explained by “bursting” phenomena which are responsible for most of the average turbulent fluxes. Coherent structures of eddy motions called “ejections” and “sweeps” are often found to be significant fractions of the Reynolds stress. From velocity measurements in the under-ice boundary layer, conditional statistics of the Reynolds stress is examined and it is found that ejection and sweep events dominate in contributing to the Reynolds stress. Close to the ice/ocean interface, at 1 m, the stress fractions due to sweeps are about twice as due to ejections. This is related to a vertical divergence in turbulent kinetic energy. Using cumulant expansion methods successfully relates the observed increase in stress with depth and the larger relative importance of sweeps close to the surface.

5 Conclusions

5.1 Main results

Throughout this study, heat flux measurements are made for a variety of background conditions. Within the West Spitsbergen Current northwest of Svalbard, surface heat fluxes of O(100) W m^{-2} are measured which is in line with estimates of heat loss from of the West Spitsbergen Current from literature. Averaging heat fluxes over the various water masses found in the area shows that heat flux from the core of Atlantic Water is less than at the surface, which is surprising since the Atlantic Water is considered the main source of heat for vertical mixing. This result is explained by the importance of entrainment and horizontal advection and diffusion. For the Weddell Sea, wintertime heat fluxes are found to be within the same magnitude range as previously observed and correspond well with measured salt fluxes and observed melting or freezing at the interface.

In general, oceanic heat fluxes presented in this study, are found to be well represented by bulk parameterizations based on mixed layer temperatures and surface friction velocities. The exception is conditions with high melting rates. Under these conditions, ice/ocean exchange is affected by the molecular sublayer close to the ice in which transfer of heat and salt relies on molecular diffusivities. Heat is diffused faster than salt, i.e. melting at the interface is rate limited by diffusion of salt in the molecular sublayer. It is shown that for a range of commonly encountered friction velocities and mixed layer temperatures, not considering double diffusion at the interface would overestimate melting rates by several cm per day.

In this study, stress in the ocean boundary layer under drifting sea ice is found to be impacted by distant sources turbulent kinetic energy such as horizontal variation in under-ice topography or presence of nearby convecting leads. Variation in stress also illustrates the heterogeneity of the ice pack. By conditional statistics it has been shown that the structure of the Reynolds stress is dominated by coherent eddy structures, so called sweeps and ejections, as suggested by literature and found in other geophysical flows. The relative fraction of sweeps is found to be larger close to the surface which also corresponds to the increase in total stress with depth.

The heterogeneity of the marginal ice zones and also in the Maud Rise region in the Weddell Sea violates the general assumption of horizontal homogeneity of turbulence theory. The Weddell Sea measurements showed that distant sources of TKE, such as large roughness elements or nearby convection leads may introduce an additional source of turbulent kinetic energy. It is also found that a horizontal density gradient together with the logarithmic velocity profile of the under-ice boundary layer may stabilize/destabilize the boundary layer temporarily, as found from boundary layer studies in estuarine environments.

5.2 Future work

The double diffusion effects at the ice/ocean interface are important for understanding the melting process of sea ice, which is found in this study by applying data from a short drifting experiment. To resolve this issue, more careful measurements in regions where rapid melting occurs are required. It can be approached by observing the migration of so called false bottoms as suggested by *Notz et al.* [2003], but are also an interesting problem to be addressed by a laboratory experiment.

In this study the conditional statistics of the Reynolds stress was found to be an attractive tool in analysing the boundary layer dynamics. Future work includes extending the existing analysis to scalar fluxes.

When doing field experiments based on sea ice, sites are often chosen in order to ease the logistics and efforts in getting the instrument in the water. Always choosing the “easiest” sites for deployment tends to bias the measurements towards the smoother range of under-ice topography. Measurements are also usually based on one location and the horizontal distribution is inferred from assuming advective turbulence. We now have the instrumentation and knowledge to make measurements to address the horizontal structure of turbulence and the horizontal variance of turbulence caused by variations in under-ice topography. It has also been shown that horizontal heterogeneity in water masses affects the under-ice turbulence dynamics. This topic should be addressed more properly for the under-ice boundary layer and designated studies in e.g. fjords with strong tidal currents, where a horizontal array of instruments are deployed, is assumed to be a promising way of performing such studies.

Both the TIC and MSS instrumentation give valuable measurements of turbulence in the mixed layer. However, their measurements complement each other and future field campaigns should exploit the advantage of both direct and indirect measurements in the turbulent boundary layer.

There is still a way to go in implementing turbulence parameterizations in numerical models. It is believed that using simplified models of the under-ice boundary layer or the entire water column and atmosphere in conjunction with detailed measurements is a promising way of doing this. It is also necessary to consider what the “numerical need” of data is when designing future field experiments.

References

Aagaard, K., A. Foldvik, and S. R. Hillman (1987), The West Spitsbergen Current - Disposition and Water Mass Transformation, *J Geophys Res-Oceans*, *92*(C4), 3778-3784.

Akitomo, K. (2006), Thermobaric deep convection, baroclinic instability, and their roles in vertical heat transport around Maud Rise in the Weddell Sea, *J Geophys Res-Oceans*, *111*(C9).

Blindheim, J., and S. Østerhus (2005), The Nordic Seas, Main Oceanographic Features, in *The Nordic Seas. An Integrated Perspective*, edited by H. Drange, et al., pp. 11 - 38, American Geophysical Union, Washington DC.

Bourke, R. H., A. M. Weigel, and R. G. Paquette (1988), The Westward Turning Branch of the West Spitsbergen Current, *J Geophys Res-Oceans*, *93*(C11), 14065-14077.

Boyd, T. J., and E. A. D'Asaro (1994), Cooling of the West Spitsbergen Current: Wintertime observations west of Svalbard, *J Geophys Res*, *99*(C11), 22597-22618.

Carsey, F. D. (1980), Microwave Observation Of The Weddell Polynya, *Monthly Weather Review*, *108*(12), 2032-2044.

Cokelet, E. D., N. Tervalon, and J. G. Bellingham (2008), Hydrography of the West Spitsbergen Current, Svalbard Branch: Autumn 2001, *J Geophys Res-Oceans*, *113*(C1), C01006, doi:10.1029/2007jc004150.

Crawford, G., L. Padman, and M. McPhee (1999), Turbulent mixing in Barrow Strait, *Cont Shelf Res*, *19*(2), 205-245.

Eicken, H. (2003), From the microscopic to the macroscopic to the regional scale: Growth, microstructure and properties of sea ice, in *Sea ice and introduction to its physics, biology, chemistry and geology*, edited by D. Thomas and G. S. Dieckmann, pp. 22 - 81, Blackwell Science, London.

Foster, T. D., and E. C. Carmack (1976), Frontal zone mixing and Antarctic Bottom Water formation in the southern Weddell Sea, *Deep-Sea Research*, *23*(4), 301-317.

Gordon, A. L. (1991), Two stable modes og Southern Ocean winter stratification, in *Deep Convection and Deep Water Formation in the Oceans*, edited by P. C. Chu and J. C. Gascard, pp. 17-35, Elsevier, Amsterdam.

Holland, D. M., and A. Jenkins (1999), Modeling thermodynamic ice-ocean interactions at the base of an ice shelf, *J Phys Oceanogr*, *29*(8), 1787-1800.

Holland, M. M., C. M. Bitz, and B. Tremblay (2006), Future abrupt reductions in the summer Arctic sea ice, *Geophysical Research Letters*, *33*(23), L23503, doi:10.1029/2006gl028024.

Manley, T. O. (1995), Branching Of Atlantic Water Within The Greenland-Spitsbergen Passage - An Estimate Of Recirculation, *J Geophys Res-Oceans, 100*(C10), 20627-20634.

Maslanik, J. A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery (2007), A younger, thinner Arctic ice cover: Increased potential for rapid, extensive sea-ice loss, *Geophysical Research Letters*, *34*(24), doi: 10.1029/2007GL032043.

McPhee, M., and J. H. Morison (2001), Under-ice boundary layer, in *Encyclopedia of Ocean Sciences*, edited by M. Steele, et al., Academic Press, San Diego.

McPhee, M. G., G. A. Maykut, and J. H. Morison (1987), Dynamics and Thermodynamics of the Ice Upper Ocean System in the Marginal Ice-Zone of the Greenland Sea, *J Geophys Res-Oceans*, *92*(C7), 7017-7031.

McPhee, M. G. (1992), Turbulent Heat-Flux in the Upper Ocean under Sea Ice, *J Geophys Res-Oceans*, *97*(C4), 5365-5379.

McPhee, M. G. (2000), Marginal thermobaric stability in the ice-covered upper ocean over Maud Rise, *J Phys Oceanogr*, *30*(11), 2710-2722.

McPhee, M. G. (2003), Is thermobaricity a major factor in Southern Ocean ventilation?, *Antarctic Science*, *15*(1), 153-160.

McPhee, M. G. (2004), A spectral technique for estimating turbulent stress, scalar flux magnitude, and eddy viscosity in the ocean boundary layer under pack ice, *J Phys Oceanogr*, *34*(10), 2180-2188.

Nakagawa, H., and I. Nezu (1977), Prediction of Contributions to Reynolds Stress from Bursting Events in Open-Channel Flows, *J. Fluid Mech.*, *80*(APR4), 99-128.

Nghiem, S. V., I. G. Rigor, D. K. Perovich, P. Clemente-Colon, J. W. Weatherly, and G. Neumann (2007), Rapid reduction of Arctic perennial sea ice, *Geophysical Research Letters*, *34*(19), doi: 10.1029/2007GL031138.

Notz, D., M. G. McPhee, M. G. Worster, G. A. Maykut, K. H. Schlunzen, and H. Eicken (2003), Impact of underwater-ice evolution on Arctic summer sea ice, *J Geophys Res-Oceans*, *108*(C7).

Notz, D., J. S. Wettlaufer, and M. G. Worster (2005), A non-destructive method for measuring the salinity and solid fraction of growing sea ice in situ, *Journal Of Glaciology*, *51*(172), 159-166.

Orsi, A. H., G. C. Johnson, and J. L. Bullister (1999), Circulation, mixing, and production of Antarctic Bottom Water, *Progress in Oceanography*, *43*(1), 55-109.

Ralston, D. K., and M. T. Stacey (2005), Stratification and turbulence in subtidal channels through intertidal mudflats, *J Geophys Res-Oceans*, *110*(C8).

Raupach, M. R. (1981), Conditional Statistics of Reynolds Stress in Rough-Wall and Smooth-Wall Turbulent Boundary-Layers, *J. Fluid Mech.*, *108*(JUL), 363-382.

Rippeth, T. P., N. R. Fisher, and J. H. Simpson (2001), The cycle of turbulent dissipation in the presence of tidal straining, *J Phys Oceanogr*, *31*(8), 2458-2471.

Saloranta, T. M., and P. M. Haugan (2004), Northward cooling and freshening of the warm core of the West Spitsbergen Current, *Polar Res*, *23*(1), 79-88.

Schauer, U., E. Fahrbach, S. Osterhus, and G. Rohardt (2004), Arctic warming through the Fram Strait: Oceanic heat transport from 3 years of measurements, *J Geophys Res-Oceans*, *109*(C6), doi: 10.1029/2003JC001823.

Schmidt, G. A., C. M. Bitz, U. Mikolajewicz, and L. B. Tremblay (2004), Ice-ocean boundary conditions for coupled models, *Ocean Modelling*, *7*(1-2), 59-74.

Schröder, M., and E. Fahrbach (1999), On the structure and the transport of the eastern Weddell Gyre, *Deep-Sea Research Part Ii-Topical Studies In Oceanography*, *46*(1-2), 501-527.

Serreze, M. C., M. M. Holland, and J. Stroeve (2007), Perspectives on the Arctic's shrinking sea-ice cover, *Science*, *315*(5818), 1533-1536, 10.1126/science.1139426.

Skagseth, O. (2008), Recirculation of Atlantic Water in the western Barents Sea, *Geophysical Research Letters*, *35*(11), L11606, doi: 10.1029/2008gl033785.

Smedsrud, L. H. (2005), Warming of the deep water in the Weddell Sea along the Greenwich meridian: 1977-2001, *Deep-Sea Res. Part I-Oceanogr. Res. Pap.*, *52*(2), 241-258.

Steele, M., G. L. Mellor, and M. G. McPhee (1989), Role of the Molecular Sublayer in the Melting or Freezing of Sea Ice, *J Phys Oceanogr*, *19*(1), 139-147.

Steele, M., and J. H. Morison (1993), Hydrography and Vertical Fluxes of Heat and Salt Northeast of Svalbard in Autumn, *J Geophys Res-Oceans*, *98*(C6), 10013-10024.

Widell, K., I. Fer, and P. M. Haugan (2006), Salt release from warming sea ice, *Geophysical Research Letters*, *33*(12), 5, L12501, doi: 10.1029/2006gl026262.

Woodgate, R. A., K. Aagaard, and T. J. Weingartner (2006), Interannual changes in the Bering Strait fluxes of volume, heat and freshwater between 1991 and 2004, *Geophysical Research Letters*, *33*(15), L15609, doi:10.1029/2006gl026931.