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DEPARTMENT OF PHYSICS AND TECHNOLOGY

Circulation and Exchanges at High-latitude Ocean Margins: Dynamical Models and Observations from Instrumented Seals

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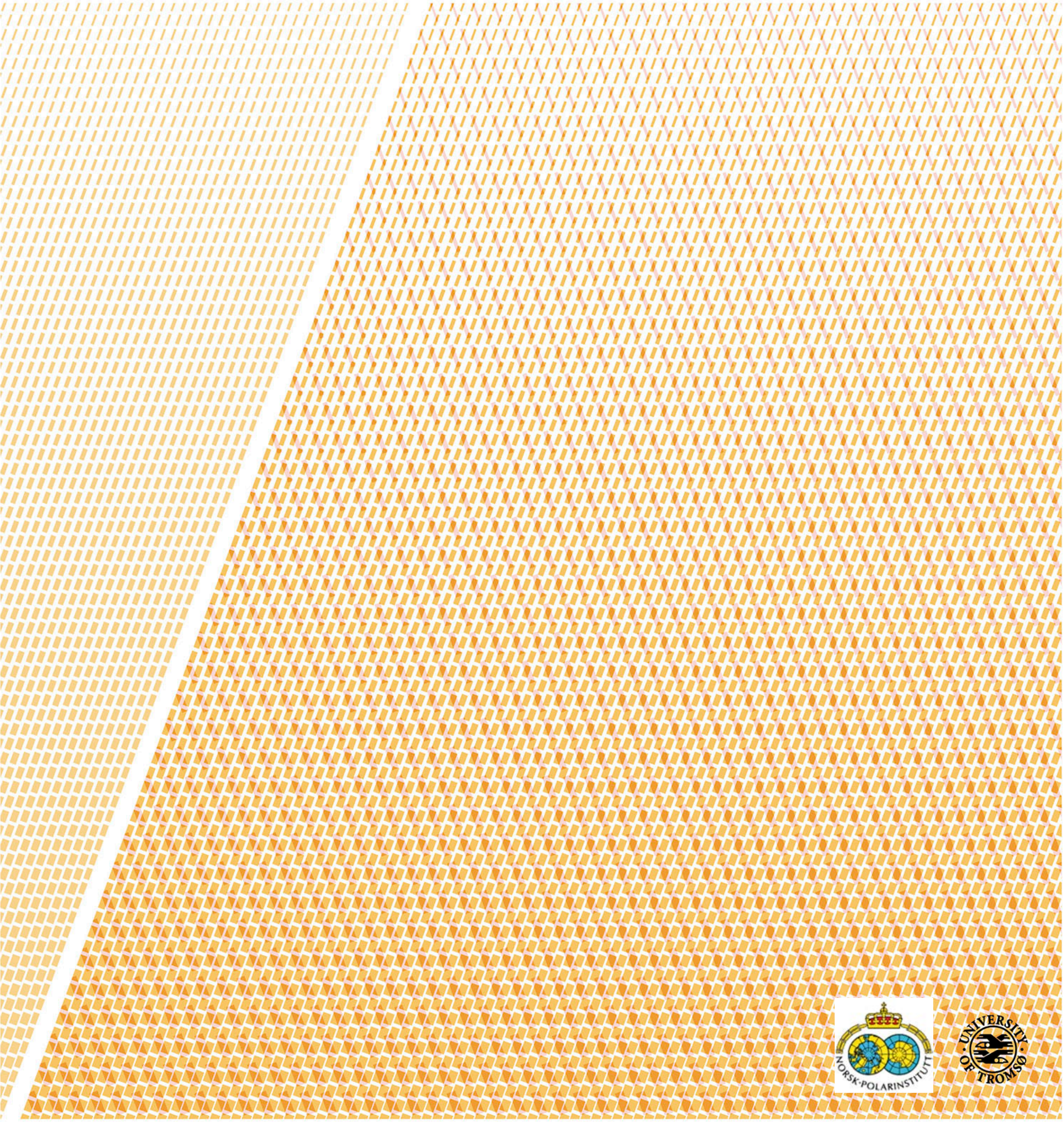
A dissertation for the degree of Philosophiae Doctor – September 2013



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Abstract

Circulation and exchange processes at high-latitude ocean margins are investigated in this thesis, by using analytical models, numerical simulations and hydrographic data. In the Northern Hemisphere, the establishment of Atlantic Water transport as a topographically steered slope current has been investigated. A simplified analytical model based on geostrophic balance predicts that buoyancy loss over a sloping boundary leads to a cross-slope baroclinic flow transformed into an along-slope barotropic flow. And the resulting transport changes can be estimated from hydrographic data. Over the continental slope off Scotland, the diagnosed transport changes in the barotropic flow is in agreement with the observed transport changes. The results emphasize that geostrophy can be used to diagnose topographically steered barotropic flow, which makes it especially useful for high latitudes where topographic steering of ocean circulation is strong. In the Eastern Weddell Sea in the Atlantic Sector of Antarctica, the processes controlling the exchanges of water masses over the continental slope have been studied, by taking advantage of over 11,000 hydrographic profiles collected by instrumented seals in this region from February to November 2008. The proposed mechanism, that the wind-driven downwelling is responsible for the accumulation of Antarctic Surface Water near the ice front and its further spreading beneath the ice shelf along the coast of Eastern Weddell Sea, is revisited by a combination of detailed analysis of the data collected by the seals, an analytical model and numerical simulations. The results show that the Antarctic Surface Water enters the ice shelf cavity after being brought on-shore by wind-driven surface Ekman transport, and being spread below the depth of the ice base within a regime of coastal downwelling. The results also suggest a complex picture of water mass exchange processes along the coast of Eastern Weddell Sea, in which mesoscale eddies play a central role. Finally, the data collected by the seals are employed to evaluate the performance of a global coupled ocean-ice model incorporated with a parametrization of wave-induced mixing in simulating the upper ocean properties in the Southern Ocean. The results suggest that wave-induced mixing is important to modify the upper ocean properties. Since coastal water properties in the Eastern Weddell Sea are mainly determined by the onshore Ekman transport of surface waters, the wave-induced mixing also plays a role in preconditioning the coastal water masses in this region.

List of papers

Q. Zhou and O. A. Nøst, 2013. The establishment of Atlantic Water transport as a topographically trapped slope current off Scotland. Tellus A.

Q. Zhou, T. Hattermann, O.A. Nøst, M. Biuw, K. V. Kovacs, C. Lydersen, 2013. Wind-driven spreading of fresh surface water beneath ice shelves in the Eastern Weddell Sea. A manuscript ready to be submitted.

Q. Zhou and Q. Shu, 2013, The effect of wave-induced mixing in a coupled ocean-ice model in the Southern Ocean. A manuscript in preparation.

O. A. Nøst, M. Biuw, V. Tverberg, C. Lydersen, T. Hattermann, Q. Zhou, L. H. Smedsrud and K. V. Kovacs, 2011. Eddy Overturning of the Antarctic Slope Front controls glacial melting in the Eastern Weddell Sea. Journal of Geophysical Research.

M. Biuw, O. A. Nøst, A. Stien, Q. Zhou, C. Lydersen and K. V. Kovacs, 2010. Effects of Hydrographic Variability on the Spatial, Seasonal and Diel Diving Patterns of Southern Elephant Seals in the Eastern Weddell Sea. PLoS ONE.

Abbreviations

ASF	Antarctic Slope Front
ASW	Antarctic Surface Water
AW	Atlantic Water
EWS	Eastern Weddell Sea
seal data	a hydrographic dataset collected by instrumented seals in the Eastern Weddell Sea during 2008
WDW	Warm Deep Water
ACC	Antarctic Circumpolar Current
CTD	Conductivity-Temperature-Depth
JEBAR	Joint Effect of Baroclinic and Relief
SRDls	Satellite Relay Data Loggers

Contents

Part I

Summary

1 Introduction

The aim of this dissertation is to investigate the circulation and exchanges of water masses at high-latitude ocean margins. High-latitude ocean margins are the transitional zones between the ocean and continental shelves poleward of 55^o latitude in both hemispheres. They represent dynamic systems in which physical processes in the ocean and atmosphere at the continental shelf edge shape the climate and thus impact human environment. In Northern Europe, poleward warm ocean currents along the eastern ocean boundaries carry large amount of heat which is released to the atmosphere in high-latitude regions. The annual mean air temperature off Scandinavia thus exceeds the zonal average by about 10^oC (Rahmstorf and Ganopolski, 1999). Furthermore, ocean margins at Greenland and Antarctica are often fringed with floating ice shelves, which are the floating extensions of grounded ice sheets. The interaction of ice shelves with warm seawater may have significant impacts on the global sea level (Pollard and DeConto, 2009; Holland et al., 2008; Straneo et al., 2010). Moreover, ventilation of the deep ocean depends highly on the production of dense water around high-latitude ocean margins. For instance, the Antarctic Bottom Water, which occupies the abyssal layer of the global ocean, is formed along the continental shelf around Antarctica (Orsi and Whitworth, 2004).

In recent years, the northward transport of warm Atlantic Water (AW) into the Arctic Ocean has received a great deal of attention. One reason is that, as a major heat supply to the Arctic Ocean, this AW inflow appears to be directly responsible for the observed general warming and sea ice loss in the Arctic (Quadfasel et al., 1991; Polyakov et al., 2005; Årthun et al., 2012). Furthermore, future projections of climate-oriented studies suggest that this inflow will decline in response to an anticipated global warming (Rahmstorf, 2000). At present, it is well known that the AW inflow is mainly a topographically steered slope current both in the Nordic Seas and the Arctic Ocean, which is following the continental slope between 100 metres and 800 metres depth (Aagaard and Carmack, 1989; Hansen and Østerhus, 2000; Helland-Hansen and Nansen, 1909). It is also known that the slope current along the Norwegian coast is an extension of the slope current in the eastern North Atlantic. However, the establishment of the AW transport as a topographically steered flow still remains unknown. This leads to the first research question:

How and where does the Atlantic Water get trapped over the continental slope?

Another phenomenon in high-latitude ocean margins that arouses great concerns is the basal melting of Antarctic ice shelves. Thinning of ice shelves is related to acceleration of inland ice streams and thereby global sea level rise (Shepherd et al., 2002; Straneo et al., 2010). Furthermore, basal melting also affects the dense water formation by releasing fresh water to the ocean (Hellmer, 2004). Along the coast of Eastern Weddell Sea (EWS) in the Atlantic sector of Antarctica, ice shelf fronts are often hanging over the continental shelf break. Wind-driven onshore Ekman transport results in a convergence of surface water at the ice front and induces a regime of coastal downwelling. This implies that the amount of basal melting in this region is directly related to the wind-driven downwelling. First of all, the downwelling creates the Antarctic Slope Front (ASF) , which is comprising substantial horizontal density gradients. It is the ASF that keeps the Warm Deep Water (WDW) away from the ice shelves (Sverdrup, 1953; Heywood et al., 1998; Smedsrud et al., 2006). The WDW is residing in the deep-ocean below the continental shelf break with a temperature maximum of about 0.9^{o}C. In addition, the downwelling has been proposed as a major reason for the accumulation of Antarctic Surface Water (ASW) near the ice shelf front and its possible spreading beneath the ice shelf (Sverdrup, 1953; Hattermann et al., 2012). The ASW is produced by solar heating and melting of sea ice during summer. However, the wind-driven downwelling and its related processes have not been well investigated due to a lack of oceanic observations. In 2008, instrumented southern elephant seals have collected over 11,000 oceanic profiles in the EWS, and over 2,000 profiles are located within a short distance of the ice front. This unique oceanic dataset (seal data, hereafter) allows us to revisit the wind-driven coastal downwelling processes in a finer resolution. Thus, the second research question is:

Is the wind-driven downwelling the main mechanism for the accumulation of Antarctic Surface Water near the ice front and its spreading beneath the ice shelf?

Last, a number of recent studies on ocean modeling show that simulations of upper ocean properties in low-latitude and mid-latitude oceans are improved by incorporating a parametrization of vertical mixing due to surface waves in the ocean circulation models (Qiao et al., 2004; Song et al., 2007). However, similar studies have not been performed in high-latitude oceans mainly due to the lack of observations. Thus, the seal data provides a great opportunity to evaluate the effect of wave-induced mixing in the Southern Ocean. Therefore, the third research question is:

How does the parametrization of wave-induced mixing affect the simulations of upper ocean properties in the Southern Ocean ?

In this thesis, the first research question has been investigated by combining an analytical model and hydrographic observations. We find that it is the interplay between northward buoyancy loss in the AW layer and sloping boundary that gives rise to a flow being locked to the continental slope. The second research question has been resolved by using a combination of the seal data, an analytical model and numerical simulations. We find that the wind-driven downwelling is the main mechanism for the accumulation of the warm ASW near the ice shelf front and its further spreading beneath the ice shelf. Regarding the third research question, we have validated a global ocean-ice coupled model incorporated with the parametrization of wave-induced mixing in the Southern Ocean, by comparing the simulated upper ocean properties with the seal data and observations from other traditional approaches. The investigation of surface wave-mixing in the Southern

Ocean is beyond the scope of the title, which focuses on the circulation and exchanges of water masses at high-latitude ocean margins. However, the examination of the second research question suggests that coastal water properties in the EWS region is mainly determined by the onshore Ekman transport of surface waters. This implies that the wave-induced mixing, which modifies the upper ocean properties in the open ocean, plays a role in determining the coastal water properties.

The investigation of these research questions has lead to five manuscripts on the topic of circulation and exchanges at high-latitude ocean margins, which are presented in **Part II**. The remainder of **Part I** is: **Chapter 2** presents basic background information on ocean dynamics and data related to this thesis; **Chapter 3** presents the results of this thesis, consisting of three published peer-reviewed papers and two manuscripts currently in draft version; **Chapter 4** presents the overall discussion and conclusion of this dissertation.

2 Background

2.1 Oceanic processes at high-latitude ocean margins

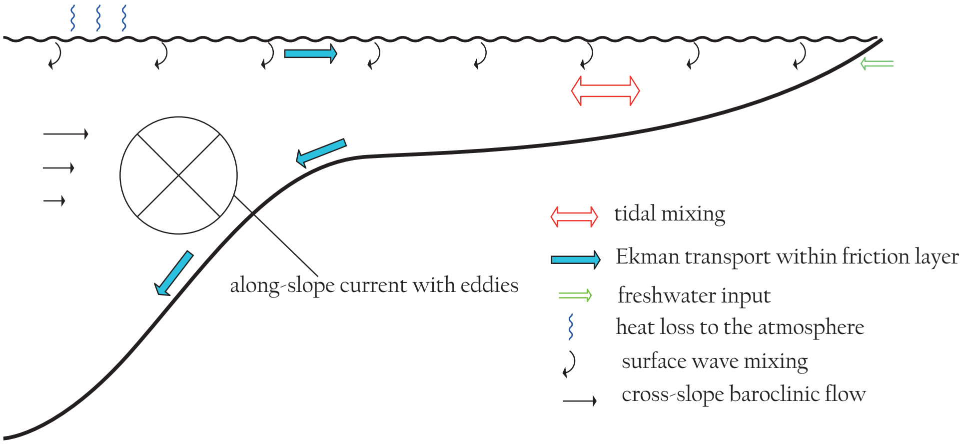

Figure 2.1: *A schematic of main oceanic processes at high-latitude ocean margins in the presence of downwelling wind in the Northern Hemisphere, adapted from Huthnance et al. (2009).*

The purpose of this section is to highlight a few oceanic processes that affect circulation and exchanges at high-latitude ocean margins as a background for this thesis. A comprehensive overview of physical processes at the ocean margins is provided by Huthnance (1995).

Figure 2.1 presents a schematic of the oceanic processes at high-latitude ocean margins in the Northern Hemisphere. As illustrated in the figure, the dominant process over the slope is the along-slope current, and a detailed description of this current is presented in Section 2.1.1. The blue arrows in Figure 2.1 show the onshore Ekman transport of surface waters by surface winds and offshore Ekman transport at the bottom. This Ekman loop, termed as the Ekman drain, is an important mechanism for the exchange of water masses between the shelf and the deep ocean at the eastern boundary of northern Atlantic (Huthnance, 1995; Holt et al., 2009; Simpson and McCandliss, 2013). Moreover, onshore Ekman transport leads to convergence of surface water near the coast and induces downwelling. The wind-driven downwelling is closely related to mesoscale eddies, which also play an important role in cross-slope exchanges in high-latitude ocean boundaries. The interaction between wind and mesoscale eddies is described in Section 2.1.2. The surface winds not only drive surface Ekman transport, but also create surface waves. A short description of the role of surface waves in turbulent mixing is presented in Section 2.1.3.

Further shoreward at the shallow shelf, tides play a major role for water mass modification and cross-slope exchanges. For instance, along the coast of Ross Sea in the Pacific sector of Antarctica, the energetic tides are critical to both formation of high salinity shelf water and cross-slope transport of this dense water out of the shelf (Whitworth and Orsi, 2006; Padman et al., 2009). Along the EWS coast, tidal mixing may cause a significant increase in ice shelf melting (Nicholls et al., 2008a).

Aside from the winds and tides, high-latitude ocean margins are also subject to buoyancy forcing, such as heat loss to the atmospheric, effect of eddy exchange, freshwater input from river, sea ice melting and freezing or ice shelf melting. The imposed buoyancy forcing leads to along-stream density variations in the flow. A combination of bottom density variations and sloping topography has important dynamic effects on the boundary current, which is explained in detail in Section 2.1.1.

2.1.1 Analytic representation of geostrophic flow over sloping topography

The large-scale and time-mean circulation along the ocean margins is a geostrophic flow, in which the horizontal pressure gradient force is balanced by the Coriolis force. This can be expressed as

$$\boldsymbol{k} \times f\boldsymbol{v} = -\frac{1}{\rho_0}\nabla p, \tag{2.1}$$

where $\boldsymbol{v}$ is the horizontal velocity, f is the Coriolis parameter (assuming it is a constant in this thesis), ρ_0 is the reference density, ∇ is the horizontal gradient operator and p is the pressure. In the vertical, the flow obeys hydrostatic balance

$$\frac{\partial p}{\partial z} = -g\rho, \tag{2.2}$$

where ρ is the density and g is the acceleration of gravity. In addition, the mass of the flow has to be conserved, which results in the continuity equation

$$\nabla \cdot \boldsymbol{v} + \frac{\partial w}{\partial z} = 0, \tag{2.3}$$

where w is the vertical velocity. According to vector calculus identities, the first term on the left hand side of Eq. 2.3 equals zero, if $\boldsymbol{v}$ satisfies Eq. 2.1.

Integrating Eq.2.2 from bottom ($z = -H$) to a depth z gives the pressure relative to bottom pressure, p_b. Then using this into the geostrophic relation (Eq. 2.1) gives the following expression for geostrophic velocity,

$$\boldsymbol{v} = \frac{1}{f\rho_0}\boldsymbol{k} \times \nabla p_b - \frac{g}{f\rho_0}\rho_b\boldsymbol{k} \times \nabla H - \frac{g}{f\rho_0}\boldsymbol{k} \times \int_{-H}^{z} \nabla\rho dz, \tag{2.4}$$

where ρ_b is the bottom density. In Eq. 2.4, the first term is a flow determined by bottom pressure with no vertical variations. This depth-independent flow is termed as the barotropic flow. The second term is also a barotropic flow which is following the depth contours. The third term is the integrated thermal wind relative to bottom. This flow is termed as the baroclinic flow, which is depth-dependent with zero-flow at bottom. The last two terms depend on local densities and can be estimated from density field. Actually, a classical approach to diagnose geostrophic flow is to use the thermal wind relation to estimate the baroclinic flow from density, assuming the barotropic flow is known at some depth. Moreover, the divergence of the sum of the last two terms equals zero. This indicates that a divergence (convergence) of the along-slope barotropic flow will lead to a convergence (divergence) of the baroclinic flow. In particular, bottom density variations over sloping topography always leads to changes in the along-slope barotropic flow, which are transformed from the cross-slope baroclinic flow. This transformation between barotropic and baroclinic flows has been elucidated by Walin et al. (2004) (Figure 2.2) and later successfully applied to the Nordic Seas and Arctic Ocean (Walin et al., 2004; Nilsson et al., 2005; Schlichtholz, 2007; Aaboe and Nøst, 2008; Aaboe et al., 2009). In the first paper of this thesis, we propose that this transformation due to bottom density variations over sloping topography is the mechanism for the establishment of AW transport as a topographically steered slope current.

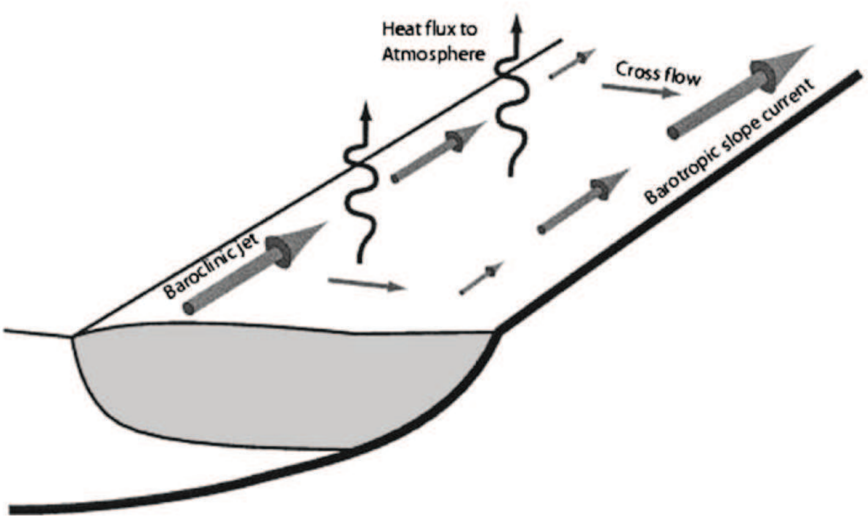

Figure 2.2: *Illustration of the transition between baroclinic and barotropic flows over sloping boundary (Walin et al., 2004). The downstream densitification leads to: 1) a decrease in the volume of the along-slope baroclinic flow; 2) a cross-slope baroclinic flow; and 3) an increase in the volumn of along-slope barotropic current.*

The sloping boundary is a central dynamical agent for the transformation between baroclinic and barotropic flows. The second term on the right hand of Eq.2.4 vanishes in the case of flat bottom, and the transformation is now between baroclinic flows of different directions. In this case, density variations can lead to displacement of the geostrophic flow (Nof, 1983), but cannot give rise to a barotropic flow. More importantly, the sloping boundary keeps the process, that the geostrophic flow adjusts itself to the exposed bouyancy forcing, within the frame of geostrophy. In the case of a vertical wall, non-geostrophic process such as friction will come into play to satisfy the condition of zero normal flow, and the geostrophic balance breaks down.

Another common representation of density variations over sloping topography is the Joint Effect of Baroclinic and Relief (JEBAR) terms, often described as a forcing like wind stress (Huthnance, 1984; Mertz and Wright, 1992). Here I show that the JEBAR appears as an effect using the depth-averaged velocity instead of the explicit velocity. Define the depth-averaged velocity as

$$\overline{\boldsymbol{v}} = \frac{1}{H}\int_{-H}^{0} \boldsymbol{v} dz. \tag{2.5}$$

Taking the curl of $\overline{\boldsymbol{v}}$ gives

$$\boldsymbol{k}\nabla \cdot \overline{\boldsymbol{v}} = \frac{1}{f} JEBAR. \tag{2.6}$$

The $JEBAR$ results from a combination of Eq. 2.1 and Eq. 2.2.

$$JEBAR = \boldsymbol{J}(\int_{-H}^{0} g\frac{\rho}{\rho_0} z dz, \frac{1}{H}), \tag{2.7}$$

where $\boldsymbol{J}$ is the Jacobian operator. However, the $JEBAR$ vanishes if we first take the curl of the velocity $\boldsymbol{v}$ and then take a depth-average, as

$$\frac{1}{H}\int_{-H}^{0} \boldsymbol{k}\nabla \cdot \boldsymbol{v_b} dz = \frac{1}{H}\boldsymbol{v_b} \cdot \nabla H = 0, \tag{2.8}$$

were $\boldsymbol{v_b}$ is the bottom velocity given by the bottom pressure. Eq. 2.8 is reached by combining Eq. 2.1 and Eq. 2.3. Now I illustrate that the JEBAR can also appear in Eq. 2.8 by expressing $\boldsymbol{v_b}$ in term of $\overline{\boldsymbol{v}}$. This is because the bottom velocity is actually a difference between the depth-averaged velocity and those velocity components related to the local density (the last two terms on the right hand side of Eq. 2.4). By doing so and several steps of mathematical manipulating, Eq. 2.8 can be rewritten as

$$\frac{1}{H}\boldsymbol{v_b} \cdot \nabla H = \frac{1}{H}\overline{\boldsymbol{v}} \cdot \nabla H + \frac{1}{f} JEBAR. \tag{2.9}$$

Eq. 2.9 implies that the JEBAR is a measure of the deviation of the true depth-averaged motion from the hypothetical depth-averaged motion. Therefore, the JEBAR need not be a proper measure of the influence of density variations over sloping topography on large-scale circulation, as pointed out by Cane et al. (1998).

2.1.2 Ekman overturning and eddy overturning

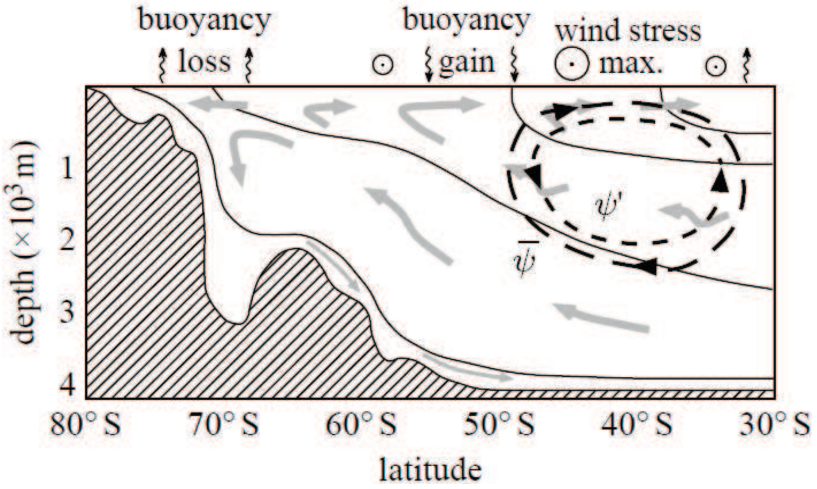

Figure 2.3: *Schematic of a meridional section of the ACC and its associated meridional overturning circulation. The grey arrows indicate transport and the solid lines are constant density. The circular curves represent the sense of Ekman overturning* $\overline{\psi}$ *and eddy overturning* ψ' *in the residual-mean theory. Patterns of wind and bouyancy forcing at the surface are also shown. The figure is taken from Thompson (2008).*

In the ocean, surface winds pump the buoyant surface waters down into the interior, leading to Ekman overturning of isopycnals (density contours). These sloping isopycnals give rise to a baroclinic flow, which is generally unstable to small perturbations. These small perturbations grow exponentially into mesoscale eddies, which counteract the Ekman overturning and tend to flatten the sloping isopycnals. A balance between the Ekman overturning and the eddy overturning can set ocean stratification (Marshall et al., 2001). And an imbalance between the Ekman overturning and the Eddy overturning gives rise to a residual overturning, which determines the actual movement of a water particle. The concept of the residual overturning is a central element for understanding the dynamical and thermodynamical balances of the Antarctic Circumpolar Current (ACC) (Karsten et al., 2002; Marshall and Radko, 2003). Here I use the ACC as an example to illustrate these overturning circulations. Figure 2.3 shows a schematic of a meridional section of the ACC and its associated overturning circulation. As shown in the figure, the westerly wind stress leads to northward Ekman transport and induces the Ekman overturning circulation $\overline{\psi}$, which acts to tilt fronts and increases potential energy in the system. The mesoscale eddies, acting to release the potential energy stored in the fronts and relax the tilted fronts, lead to the eddy overturning circulation ψ'. Both observations (Phillips and Rintoul, 2000) and numerical studies (Ivchenko et al., 1996) provide evidence to show that the balance between the Ekman overturning and the eddy overturning is the dominant balance of the ACC. The residual overturning circulation arises from the summation of $\overline{\psi}$ and ψ', and is therefore typically much smaller than its components due to cancellation. Because the ACC is primarily zonal and unfit to transport much heat poleward, it is actually the the residual overturning circulation in the ACC that advects heat and other tracers meridionally (Karsten et al., 2002; Marshall and Radko, 2003). In this thesis, we have investigated the role of the interaction between the Ekman overturning and the eddy overturning in controlling the processes of water mass exchange and thus heat supply for basal metling along the EWS coast.

At high-latitude ocean margins, bottom topography can have an influence on the eddy-induced circulation (Eden and Greatbatch, 2008; Spall, 2010; Isachsen, 2010; Stewart and Thompson, 2013). When a boundary current flows from regions of moderate to steeper bottom slopes, the isopycnal slopes appear to mimic the steepness of topography, leading to an increase in the cross-slope eddy heat flux (Spall, 2010). Furthermore, eddies over sloping topography can cause upward-sloping isopycnals near the seabed (Greatbatch and Li, 2000; Adcock and Marshall, 2000). The upward-sloping isopycnals have been observed along the coast of EWS (Chavanne et al., 2010), and are likely to advect modified WDW into the ice cavity.

2.1.3 Surface wave mixing

Perhaps the most important role of surface waves in the ocean is to modify upper layer water properties. Both breaking and non-breaking waves can contribute to vertical turbulent mixing. The vertical mixing induced by breaking waves is mainly confined within the upper few meters, which is in a depth order of wave height (DAlessio et al., 1998). In contrast, the vertical mixing induced by non-breaking waves can reach a much greater depth, which is in a depth order of wavelength (Qiao et al., 2004; Dai et al., 2010; Huang and Qiao, 2010). Thus the non-breaking waves are more effective in modifying water properties. The important role of non-breaking waves in vertical mixing has been recognized recently, and a parametrization of the wave-induced mixing has been developed and incorporated in a number of Ocean General Circulation Models as well as coupled climate models (Song et al., 2007; Shu et al., 2011; Huang et al., 2012). In this thesis, this parametrization has been incorporated into a global coupled ocean-ice model in order to identify the role of surface waves in modifying the upper ocean properties in the Southern Ocean.

2.2 Animals as platform to collect CTD profiles

A comprehensive overview of the instrumented animals for collecting ocean observations in last ten years is provided by Fedak (2013). This section briefly summaries the development of the animal platform and shortly describes the data collected by instrumented southern elephant seals for in this study.

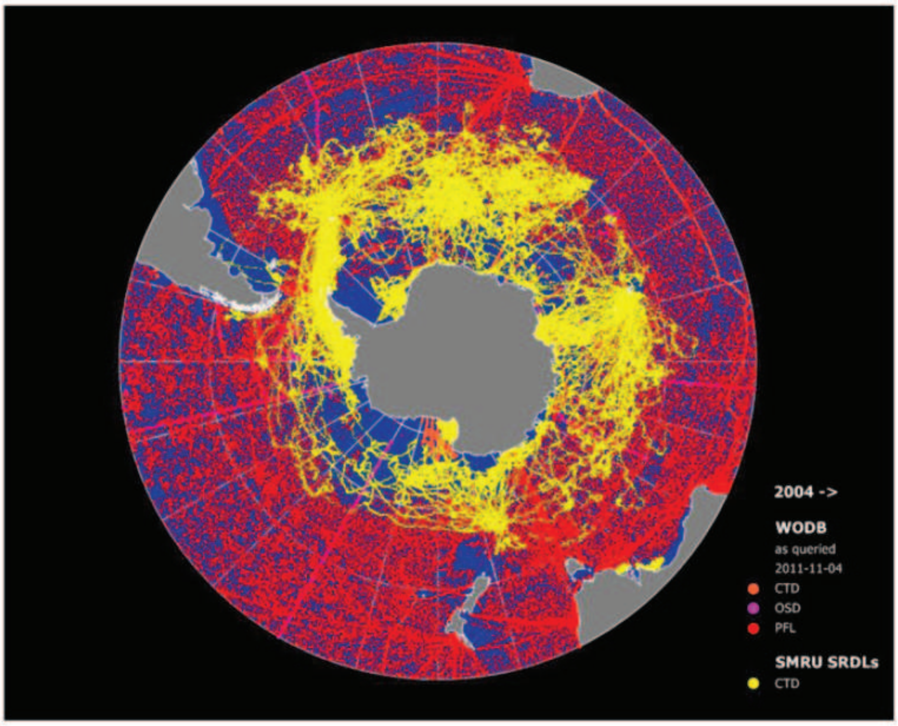

Figure 2.4: *Map showing the locations of available CTD profiles in the Southern Ocean. Yellow dots indicate profiles collected by seals, red dots indicate profiles from Argo profiling floats (PFL), orange dots indicate ship-based CTD casts and magenta dots indicate ocean station data (OSD). The figure is taken from Fedak (2013).*

The idea of tagging marine animals to record their diving behaviour can be dated back to the 1940 s when Per Scholander developed a mechanical depth gauge to record the diving depth of whales. It was not until 1990s that the feasibility of using tagged animals as platform for oceanographic measurements was explored by a number of researchers (Ancel et al., 1992; Weimerskirch et al., 1995; McCafferty et al., 1999). Although these studies provided valuable oceanographic information, they required recapture of the animals to collect the data which only include temperature and not conductivity measurements. With the technological development, today the data can be transmitted and received almost in real-time via satellite (Fedak et al., 2001, 2002). The first use of an animal platform to collect real-time oceanographic Conductivity-Temperature-Depth (CTD) profiles was conducted by Lydersen et al. (2002) in a freezing Arctic fjord. Since then, instrumented animals have collected more than 270,000 CTD profiles. In the Southern Ocean, about 70% of the oceanographic data south of 60^o are collected by instrumented animals (Fedak, 2013). Figure 2.4 shows the location of all the available CTD profiles in the Southern Ocean, color coded by the type of platform which provided them.

Animal platform data not only bring new insight into the behaviour of the instrumented seals, but also contribute to complementing global ocean observing system from traditional approaches, providing a wide variety of uses for oceanographic studies (Fedak, 2013). The data have been incorporated into a variety of ocean and weather models (Fedak, 2013). They also make it possible to monitor the ocean processes in high-latitude oceans at a finer scale. A combination of data from instrumented animals and from other conventional approaches allows researchers to examine frontal processes (Boehme et al., 2008; Roquet et al., 2009; Nøst et al., 2011), to analyse transient local events (Padman et al., 2010, 2012), and to address interaction between the ocean and the ice shelf (Nicholls et al., 2008b; Straneo et al., 2010; Arthun et al., 2012; Hattermann et al., 2012; Arthun et al., 2013).

Figure 2.5: *A southern elephant seal tagged with a miniature SRDL-CTD. Photo: Martin Biuw*

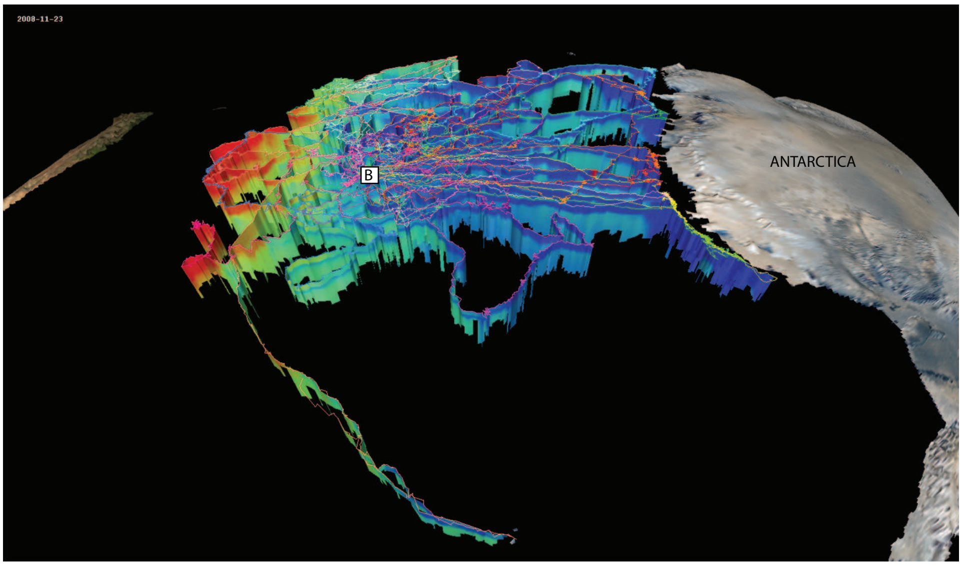

Figure 2.6: *Hydrographic sections recorded by 19 Southern elephant seals in 2008. B indicates Bouvet Island. This imagine was created using MamVisAD and provided by Martin Biuw.*

During the project Marine Mammal Exploration of the Oceans Pole to Pole of Norway, twenty southern elephant seals were captured and equipped with CTD-Satellite Relay Data Loggers (SRDLs) on Bouvetøya ($54^o25'S, 3^o21'E$) in February 2008 (Figure 2.5). These CTD-SRDLs are developed and built by the Sea Mammal Research Unit, St Andrews, Scotland. During the seals' migration between breeding, foraging and resting locations, the CTD-SRDLs report vertical profiles of salinity, temperature and pressure to a depth up to 2000 m. From February to November 2008, these instrumented seals have collected over 11,000 CTD profiles at a mean depth of about 600 m, providing transect-type sections from Bouvetøya to the EWS coast and longitudinal mooring-like data along the coast (Figure 2.6).

The seal data is a central element for this thesis. It has been used to investigate coastal processes in the EWS (paper II and paper IV), to validate simulations from a global ice-ocean coupled model in the Southern Ocean (Paper III) and finally to study the movements and diving behaviour of instrumented southern elephant seals themselves (Paper V).

3 Results

3.1 Summary of Paper 1

This paper investigates the establishment of Atlantic Water transport as a topographically steered slope current, by examining the conversion between baroclinic to bartropic flows over the continental slope off Scotland. Geostrophy predicts that with a northward decreasing bouyancy, baroclinic boundary current is transformed into a topographically steered slope current. The conversion between barotropic and baroclinic flow can be diagnosed from local density fields. In particular, the bottom density variations determine the barotropic transport changes. We use hydrographic data from two sections crossing the continental slope, one located in the Rockall Channel and another in the Faroe-Shetland Channel, to estimate barotropic and baroclinic transport changes over the slope. Our results indicate that about 1 Sv of the cross-slope baroclinic flow is mainly converted to northward barotropic transport above the 200-500 m depth contours. This is consistent with observed transport changes between the two channels.

Our study provides an understanding of how and where the AW, transported by the baroclinic North Atlantic Current, establishes itself as a barotropic flow over the slope. The geostrophic flow over the continental slope experiences buoyancy loss leading to a conversion from baroclinic to barotropic flow trapped over the slope. In the region where the Wyville Thomson Ridge meets the slope and further northward, the along-slope bottom density field experiences significant increase. It implies that most of the baroclinic flow of Atlantic Water is converted to barotropic flow in this region. This qualitatively support the inference of Huthnance and Gould (1989) that the large transport increase of the slope current is related to the AW coming from west over the Wyville Thomson Ridge.

3.2 Summary of Paper 2

This paper investigates if the wind-driven downwelling is the mechanism for the accumulation of the Antarctic Surface Water near the ice shelf front and its further spreading beneath the ice along the coast of Eastern Weddell Sea , by combining observations, scaling arguments and numerical simulations.

First, detailed data analysis of over 1000 salinity profiles of the seal data near the coast clearly shows the onshore Ekman transport, accumulation and downwelling of the

ASW near the ice front during late summer and autumn. With a zonal-mean downwelling depth of more than 200 m along the EWS coast, the ASW penetrates deeper throughout the coastal water column than the front of most ice shelves in this region. Next, an analytical two layer model based on the balance between Ekman overturning and eddy overturning is formulated. Scaling analysis from the analytical model tell that the wind-driven downwelling is capable to depress the buoyant surface water below the ice shelf depth. Last, an eddy-resolving numerical ice shelf-ocean model has been set up in order to simulate the wind-driven downwelling and spreading of the Antarctic Surface Water. Results from both idealized and realistic setups show that the Antarctic Surface Water are spreading beneath the ice shelf once the downwelling depth exceeds the ice front draft depth. And the spreading is strongly guided by the ice shelf topography. Therefore, this provides a valid explanation for the mechanism responsible for the Antarctic Surface Water observed beneath the Fimbul Ice Shelf (Hattermann et al., 2012).

Furthermore, it is highly likely that the spreading of ASW below the ice shelf occurs all along Antarctica where the onshore Ekman transport dominates the cross-shore coastal circulation during summer. The relation between the downwelling depth and the wind stress developed in this study can be used as a tool to find such locations, by examining the wind field and the ice shelf draft.

3.3 Summary of Paper 3

This paper investigates the role of the parametrization of wave-induced mixing in simulating the upper ocean properties in the Southern Ocean, by comparing the simulations from a global coupled ocean-ice model with the seal data, as well as other in-situ observations from the Argo floats and field cruise.

Two numerical experiments have been carried out with the Modular Ocean Model version 4 (MOM4) to evaluate the effect of the wave-induced vertical mixing, one with the parametrization of vertical mixing due to surface waves and the other without the parametrization. After ninety years integration, the temperature deviations of the upper 200 m to Levitus data have been remarkable reduced during austral summer in the Southern Ocean, by adding the wave-induced vertical mixing into the model. Comparisons between the model results from 2008 and the seal data and other in-situ observations also suggest that the numerical experiment with wave-induced vertical mixing has better performance on simulating the upper layer temperatures and mixed layer depths than the one without it. In addition, a significant improvement can be achieved in simulating mixed layer depths even under ice by introducing the wave-induced vertical mixing.

3.4 Summary of Paper 4

In this paper, the seal data have been used to investigate the process controlling the water mass exchanges over the continental slope in the Eastern Weddell Sea. Analysis of the seal data reveals variations of salinity and temperatures through winter near the coast. Furthermore, the seal data is used as input parameters to a conceptual model of the coastal salt budget. Based on two opposing overturning circulations, wind-driven Ekman overturning and eddy overturning, the conceptual model quantifies the main exchange processes. That is, the Ekman overturning brings surface freshwater onto the shelf in the surface layer, whereas eddy overturning brings more saline water onto the shelf in the bottom layer. In addition, results from a high-resolution model of an idealized Antarctic Slope Front-continental shelf-ice shelf system support the conclusions from the data analysis.

Note that, among the contributions for this paper, only the work of calibrating the seal data can be regarded as contribution to the dissertation. However, the results and related discussions from this paper provide ideas and inspirations for developing the work of the second paper.

3.5 Summary of Paper 5

In this paper, the seal data are used to investigate the importance of hydrographic variability on the movements and diving behaviour of southern elephant seals in the Eastern Weddell Sea region. The results show that seals feeding in pelagic ice-free waters during the summer months displayed clear diel variation, with daytime dives reaching 500 to 1500 m and night-time targeting of the subsurface temperature and salinity maxima characteristic of Circumpolar Deep Water around 150 to 300 meters. This pattern was especially clear in the Weddell Cold and Warm Regimes within the gyre, occurred in the Antarctic Circumpolar Current, but was absent at the Dronning Maud Land shelf region where seals fed benthically. Diel variation was almost absent in pelagic feeding areas covered by winter sea ice, where seals targeted deep layers around 500 to 700 meters. Thus, elephant seals appear to switch between feeding strategies when moving between oceanic regimes or in response to seasonal environmental conditions. While they are on the shelf, they exploit the locally-rich benthic ecosystem, while diel patterns in pelagic waters in summer are probably a response to strong vertical migration patterns within the copepod-based pelagic food web. Behavioural flexibility that permits such switching between different feeding strategies may have important consequences regarding the potential for southern elephant seals to adapt to variability or systematic changes in their environment resulting from climate change.

Note that, among the contributions to this paper, only the work of calibrating the seal data can be regarded as a contribution to the dissertation.

4 Concluding Remarks

In this thesis, the circulation and exchanges of water masses at high-latitude ocean margins have been investigated. The presented work has provided a three-fold contribution for a better understanding of the oceanic processes in high-latitude ocean margins.

Firstly, we find that it is the interplay between northward buoyancy loss and sloping topography that leads to the establishment of Atlantic Water transport as a topographically steered slope current off Scotland. Further north in the Nordic Seas, the same process leads to more and more Atlantic Water being trapped over the slope, verified by the barotropic transport increase in the slope current from the Fareo-Shetland Channel to the Fram Strait (Aaboe et al., 2009). Further south along the eastern Atlantic margin, similar processes are also likely to occur. Therefore, this work provides a better understanding why high latitude circulation is often topographically steered with a strong barotropic component. It is because high latitude flow mainly loses buoyancy to its surroundings, leading to a conversion from baroclinic flow to topographically trapped barotropic flow. This is a process in which the geostrophic flow along ocean boundary adjusts itself to imposed buoyancy forcing.

Secondly, we find that the interaction between Ekman overturning and eddy overturning is a key process in determining surface water exchange between the open ocean and the ice shelf cavities along the coast of Eastern Weddell Sea. This work, together with the work of Nøst et al. (2011) that focuses on the ocean exchange at depth (the fourth paper), provides a comprehensive picture of coastal overturning processes and their effects on the ice-ocean interaction in this region. The wind-driven overturning creates the Antarctic Slope Front which separates the Winter Water and the underlying Warm Deep Water. It is the eddy overturning of the Antarctic Slope Front that leads to the modified Warm Deep Water into the ice shelf cavity to melt the ice shelves. This process mainly occurs in winter and spring. In the late summer and fall, besides the Antarctic Slope Front, the wind-driven Ekman overturning creates another front between the Antarctic Surface Water and the underlying Winter Water. The associated eddy overturning determines the amount of Antarctic Surface Water that is spreading into the ice shelf cavity for basal melting at a shallower depth. Furthermore, the interaction between these two fronts play a key role in determining the total amount of water mass exchanges over the continental slope and thus the heat supply for basal melting along the coast of Eastern Weddell Sea.

Thirdly, we find that turbulent mixing due to non-breaking surface waves plays an important role in modifying the upper ocean properties in the Southern Ocean. Thus the effect of wave-induced mixing has to be incorporated into ocean circulation models in order to better simulate upper ocean properties such as the mixed layer depth in high-latitudes. Although this contribution is less related to the exchange processes in the ocean margins, we emphasize that the coastal water properties along the coast of Antarctica, at least in the Eastern Weddell Sea, is closely linked to the turbulence mixing due to surface waves in the Southern Ocean.

The presented work may be criticized for its loose relation between two main individual studies: one focuses on the circulation dynamics over the continental slope in the eastern North Atlantic and the other focuses on the water mass exchanges over the continental slope in the Eastern Weddell Sea. However, this limitation can be turned into an opportunity to identify objectives which need to be addressed in future work. Topographic steering of ocean currents occurs almost everywhere over the continental slope, and thus the simplified dynamics used in this study may be useful for understanding the boundary circulation around Antarctica. For instance, it would be interesting to apply the dynamics to the coastal current in the Southern Weddell Sea. In this region, the continental shelf of nearly 500 km wide is separating the Warm Deep Water, carried by the coastal current along the continental slope, from the Filchner-Ronne Ice Shelf. Recently Hellmer et al. (2012) have suggested that future changes due to global warming may increase basal melting of the ice shelf, by redirecting the coastal current onto the continental shelf and thus transporting more Warm Deep Water toward the ice shelf front. However, the underlying mechanisms of those changes are still uncertain and our simplified geostrophic theory may provide a better understanding of these processes.

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Part II

Papers

Paper I

Paper IV

Paper II

Paper III

Paper V