The circulation of the Norwegian Sea- An investigation from space and ocean

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Preface

An introductory part and a collection of papers constitute my thesis presented in partial fulfilment of the requirements for the degree philosophiae doctor (PhD) in physical oceanography at the Geophysical Institute, University of Bergen, Norway.

In this thesis, the circulation of the Norwegian Sea known for its influence on the local climate in the northwestern Europe, is studied using a suite of different satellite, hydrographic, numerical ocean model, surface drifter and re-analysis datasets. The findings of this thesis are presented in the form of four scientific papers. Paper 1 focuses on the circulation of the Norwegian Sea, its seasonal and inter-annual variability, connecting flows between the two branches of the Norwegian Atlantic Current, the relationship between the surface flows and the Atlantic Water beneath, and the volume transports at six key locations. Paper 2 zooms into the Lofoten Basin, and addresses the processes influencing the spatial and temporal evolution of dense water formation in the basin and its link to the overflow waters exiting at the Faroe Shetland Channel. Paper 3, zooms further into the western Lofoten Basin and presents a comprehensive study focusing on a most anomalous anticyclonic vortex of the Nordic Seas. In a step towards more precise satellite measurements, Paper 4 shows estimates of a new mean dynamic topography (MDT) for the North Atlantic and the Arctic from Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite gravity anomaly data. Employing the newly estimated data, the circulation of the region is revisited.

This introductory part is organised as follows: The first chapter describes the background for the research done here. The second chapter gives the motivation for the research work and the main objectives. The next chapter presents the different datasets and methods used in this research. The final two chapters present the summary of the four papers of this thesis and future perspectives.

Acknowledgements

First of all I thank my supervisor and good friend Jan Even Øie Nilsen for working with me, teaching me and motivating me all through the time during the last five years. I am also grateful to my co-supervisors Tor Eldevik and Tore Furevik for their guidance and friendliness. Without the help of my supervisors this thesis would have been a distant dream.

I express my sincere gratitude to Prof. Johnny. A. Johannessen with whom I am currently working with, for his continuous support and encouragement. I also thank Anne Britt Sandø and Yongqi Gao for helping me with the MICOM model.

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Last but not the least I thank my dear wife, Dhanya and our parents and sisters for their support and prayers.

Roshin Pappukutty Raj
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Contents

Abbreviations

ADT	Absolute Dynamic Topography
AMOC	Atlantic Meridional Overturning Circulation
ATL12	North Atlantic and Mediterranean Sea Mercator-Océan model
AVHRR	Advanced Very-High Resolution Radiometer
AVISO	Archiving, Validation and Interpretation of Satellite Oceanographic data
AW	Atlantic Water
BF	Bjørnøya-Fugløya
Chl	Chlorophyll
CLS	Collecte, Localisation, Satellites
CNES	The Centre national d'études spatiales
CO	Crossover flows
CTD	Conductivity, Temperature, Depth
DIR	Direct approach
DTU	Technical University of Denmark
EGC	East Greenland Current
EI	Eddy Intensity
EKE	Eddy Kinetic Energy
ELB	Eastern Lofoten Basin
ESA	European Space Agency
FC	Faroe Current
FN	Faroe North
FSC	Faroe Shetland Channel
FSCOW	Faroe Shetland Channel Overflow Waters
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GRACE	Gravity Recovery and Climate Experiment
GUT	GOCE User Toolbox
HPF	High level Processing Facility
HYCOM	The Hybrid Coordinate Ocean Model
ICES	International Council for the Exploration of the Seas

ICESat	Ice Cloud and Land Elevation Satellite
IFR	Iceland Faroe Ridge
LAGEOS	Laser Geodynamics Satellites
LS	Lofoten Slope
MDT	Mean Dynamic Topography
MICOM	Miami Isopycnic Coordinate Ocean Model
MLD	Mixed Layer Depth
MODAS	Modular Oceanographic Data Assimilation System
MR	Mohn Ridge
MSS	Mean Sea Surface
NAW	North Atlantic Water
NCC	Norwegian Coastal Current
NCEP	National Centers for Environmental Prediction
NISE	Norwegian Iceland Seas Experiment
NNAW	Norwegian North Atlantic Water
NwAC	Norwegian Atlantic Current
NwAFC	Norwegian Atlantic Front Current
NwASC	Norwegian Atlantic Slope Current
RMS	Root Mean Square
SeaWiFS	Sea-viewing Wide Field-of-view Sensor
SC	Shetland Current
SLA	Sea Level Anomaly
SPW	Space Wise
SSH	Sea Surface Height
SST	Sea Surface Temperature
SV	Svinøy
TW	Time Wise
VJ	Vøring Jet
WLB	Western Lofoten Basin
WOCE	World Ocean Circulation Experiment
WSC	West Spitsbergen Current

Abstract

The Norwegian Sea circulation plays a key role in maintaining the mild climate of the northwestern Europe via the transport of warm Atlantic Water pole-ward. The first paper addresses the advective currents connecting the two branches of the Norwegian Atlantic Current and shows the general spin up of the Norwegian Sea circulation during winter with the exception of the flow over the Mohn Ridge. The variability in the surface velocities in the Norwegian Sea is found to be deep reaching, which supports the use of altimetry to monitor the variability of the poleward transport of Atlantic Water. A strengthening and weakening of the Atlantic inflow east of the Faroe Islands has a consistent response along the entire slope current. However, a stronger western inflow, observed north of the Faroe Islands, is associated with more flow of Atlantic Water into the slope current. This finding suggest that a substantial fraction of Atlantic Water that eventually enters the Barents Sea or the Arctic through the Fram Strait, may originate from the western inflowing branch of Atlantic Water to the Nordic Seas, and that the two branches of northward flowing Atlantic Water cannot be considered as separate flows. Paper 2 examines the influence of the surface circulation, eddy activity and local heat loss on the spatial distribution and temporal evolution of dense water formation in the Lofoten Basin. Evidence of intrusion of Atlantic Water into the central Lofoten Basin due to buoyant waters in the eastern part of the basin is found. With the support of hydrographic and satellite datasets, the concept of separate western and eastern regions of the Lofoten Basin is introduced and a link between the western Lofoten Basin and Faroe Shetland overflow waters is identified. Paper 3 addresses an anomalous anticyclonic vortex in the Nordic Seas, which is situated in the western Lofoten Basin. The vortex' surface and vertical characteristics on seasonal, inter-annual, and climatological time-scales are quantified, relevant forcing mechanisms are addressed, and its uniqueness in the Nordic Seas is documented. In the final paper, a new mean dynamic topography (MDT) is estimated for the North Atlantic and the Arctic from the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite gravity anomaly data. The new GOCE-based MDT is assessed and compared to independent steric height observations, other state-of-the-art

MDTs and three coupled sea-ice-ocean models, showing its usefulness in studies of high latitude ocean circulation.

List of publications

1. **Raj, R. P**., J. E. Ø. Nilsen and T. Furevik (2013): The two-branch structure of the Norwegian Atlantic Current-transport variability and connecting flows. *Journal of Geophysical Research-Oceans, in revision.*

2. **Raj, R. P**., and J. E. Ø. Nilsen (2013): Processes influencing the dense water formation in the Lofoten Basin. *Journal of Geophysical Research-Oceans, in revision.*

3. **Raj, R**. **P**., L. Chafik, J. E. Ø. Nilsen and T. Eldevik (2013): The Lofoten vortex of the Nordic Seas. *Deep Sea Research, Part 1, in revision*.

4. Johannessen, J.A., **R. P. Raj**, J. E. Ø. Nilsen, T. Pripp, P. Knudsen, F. Counillon, L. Bertino, D. Stammer, N. Serra and N. Koldunov (2013): Towards improved estimation of the dynamic topography and ocean circulation in the high latitude and Arctic Ocean: The importance of GOCE, in The Earth's Hydrological Cycle. *Surveys in Geophysics, in press.*

Chapter 1

Introduction

The Norwegian Sea circulation (see Figure 1) with its transport of warm Atlantic Water pole-ward is a key component in maintaining a relatively mild climate in the northwestern Europe (e.g., *Rhines et al.,* 2008). This heat further regulates the local climate by its influence on the sea ice cover in the Barents Sea (*Årthun et al.,* 2012) and near Svalbard (*Walczowski and Piechura,* 2011). The circulation of the Norwegian Sea also plays a key role on the biological productivity of the region which in turn is linked to the fisheries (*Mork and Skagseth,* 2010). In a global perspective, the Atlantic Water entering the Norwegian Sea and its densification are important to the formation of overflow waters in the Nordic Seas which further contributes to the North Atlantic Deep Water and maintains the Atlantic Meridional Overturning Circulation (AMOC; *Dickson and Brown,* 1994; *Medhaug et al.,* 2011). Thus the circulation of the Norwegian Sea is important to the global climate.

1.1. The Region

The Nordic Seas (Figure 1) is a buffer zone between the North Atlantic Ocean to the south and the Arctic Ocean to the North. The surface layers of the Nordic Seas are dominated by relatively salty and warm Atlantic Water to the east while it is dominated by rather fresh and cold Polar Water to the west. This thesis primarily focuses on the circulation of the Norwegian Sea situated in the eastern part of the Nordic Seas. The Norwegian Sea is comprised of the Norwegian Basin and the Lofoten Basin, of which the latter is the largest heat reservoir in the Nordic Seas since it is occupied by the Atlantic Water, down to 800 m depth (*Blindheim and Rey,* 2004; *Skagseth and Mork,* 2012). Geographically, the Lofoten Basin is separated from the Greenland Basin by the Mohn Ridge and from the Norwegian Basin by the Vøring Plateau and the Helgeland Ridge stretching towards Jan Mayen. In the Lofoten Basin, the Atlantic Water has a bowl shaped structure having a width of 800 km (e.g., *Orvik,* 2004). In the Norwegian Basin the penetration of Atlantic Water is limited to shallower depths.

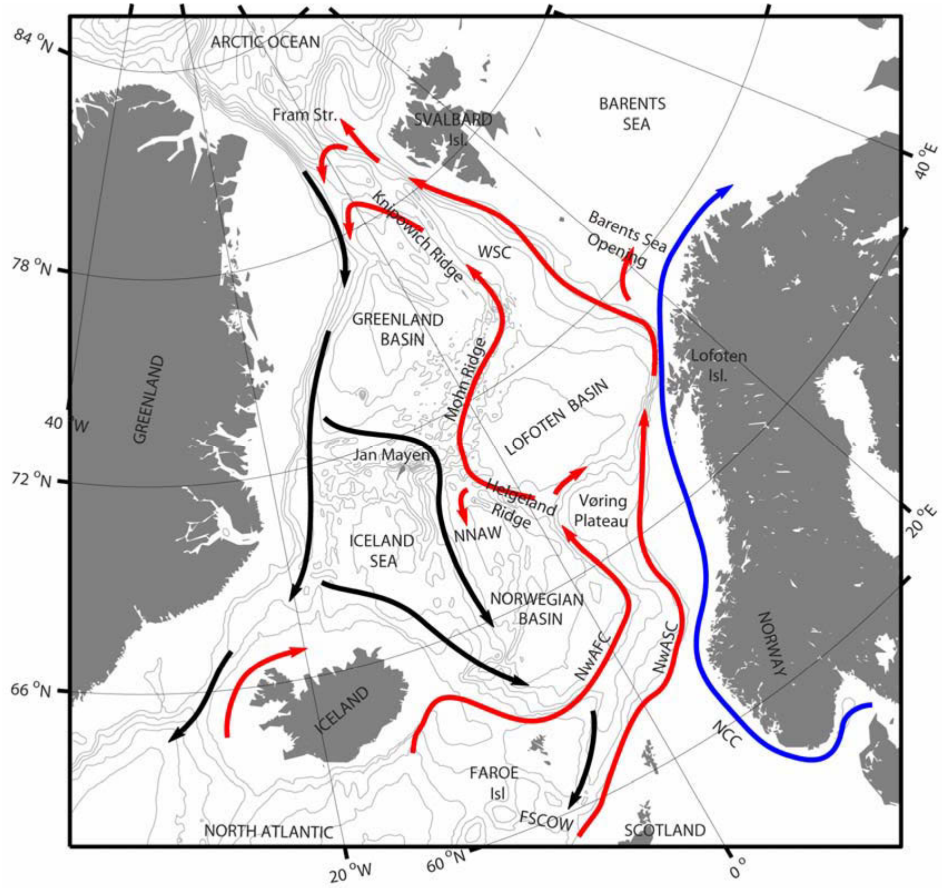

Figure 1. The Nordic Seas with schematic water pathways showing its overturning circulation from inflowing Atlantic Water in the surface (red) to deeper transformed waters returning to become overflows to the deep North Atlantic (black). The Norwegian Atlantic slope current (NwASC), Norwegian Atlantic front current (NwAFC), and West Spitsbergen Current (WSC) are represented by red arrows. The fresh Norwegian Coastal Current (NCC) is indicated in blue. The Norwegian North Atlantic Water (NNAW), and the overflow waters exiting at Faroe Shetland Channel (FSCOW) are also indicated. Grey isobaths are drawn for every 600 m. Surface circulation in this figure is based on the review of the Nordic Seas circulation presented in *Furevik and Nilsen* (2005), while deep flows (in black) are simplified from *Hansen and Østerhus* (2000).

1.2. Norwegian Sea circulation

The circulation of the Norwegian Sea was first comprehensively described by *Helland-Hansen and Nansen* in 1909. The Norwegian Atlantic current (NwAC) is the extension of the Gulf Stream in the Nordic Seas and is fed into the Norwegian Sea mainly via two inflows (see Figure 1): The Faroe-Shetland inflow and the Iceland-Faroe inflow. The NwAC which is considered as the northern limb of AMOC is the source for salt and heat into the Norwegian Sea (e.g., *Rhines et al.,* 2008). The NwAC is a two branch current system of which the eastern branch follows the Norwegian shelf edge as a barotropic slope current, while the western branch is topographically guided from the Iceland-Faroe front (*Poulain et al.,* 1996; *Orvik and Niiler,* 2002). Atlantic Water fills the volume between the two branches of NwAC. The western and eastern branches of NwAC are known as the Norwegian Atlantic Front Current (*Mork and Skagseth,* 2010) and the Norwegian Atlantic Slope Current (*Skagseth and Orvik,* 2002), respectively (see Figure 1). In this thesis, the terms "front current" and "slope current" are used to represent the two branches respectively. At the inflow, the volume of Atlantic Water transported poleward by the slope current and front current respectively are in the range of 2.7-4.4 Sv (*Orvik and Skagseth,* 2003; *Hughes et al.,* 2006; *Sherwin et al.,* 2008; *Berx et al.,* 2013) and 1.7-3.5 Sv (*Orvik et al.,* 2001; *Hansen et al.,* 2010; *Mork and Skagseth,* 2010). The heat transport associated with the inflow of Atlantic Water to the Norwegian Sea (relative to 0°C) is estimated to be in the order of 250 TW (*Hansen et al.,* 2003; *Furevik et al.,* 2007; *Segtnan et al.*, 2011). About half of this is heat is lost due to air-sea interaction or lateral eddy mixing before the Atlantic Water leaves the Norwegian Sea to the Barents Sea Opening or through the Fram Strait (*Segtnan et al.*, 2011). While the variability of the slope current has been found to be associated with both the local wind field (*Gordon and Huthnance,* 1987; *Skagseth and Orvik,* 2002) and the large-scale wind field (e.g., *Skagseth et al.,* 2004; *Chafik,* 2012), the variability of the front current, at its beginning, is associated with local wind stress and sea surface height near the Iceland-Faroe Ridge (*Hansen et al.,* 2010; *Richter et al.,* 2012).

Further downstream in the Norwegian Sea, the front current and the slope current form the western and eastern boundaries of the Lofoten basin (Figure 1). The front current flows along the Mohn Ridge while the slope current continues along the continental slope, partly branching into the Barents Sea, and flows northwards as the West Spitsbergen Current (WSC; *Saloranta and Haugan,* 2001; *Walczowski and Piechura,* 2011). The strongest topographic steering of the front current is along the western slope of the Vøring Plateau (*Nilsen and Nilsen*, 2007). A returning branch of the front current to the east of Jan Mayen flows southward into the Norwegian Basin (*Read and Pollard,* 1992). This is part of the cyclonic circulation of Atlantic Water in the Norwegian Basin. This recirculation of Atlantic Water together with the northward flowing NwAC and Norwegian Coastal Current (NCC) which flows along the coast of Norway into the Barents Sea constitute the surface circulation of the Norwegian Sea.

1.3. Eddies in the Norwegian Sea

Mesoscale eddies in the ocean are vortices or flows with scales ranging from the baroclinic Rossby radius of deformation to as large as hundred kilometre. Mesoscale eddies contribute to the stirring of water masses and thus results in mixing. Eddies are known to feed momentum and energy back into the mean flow and help drive the deep ocean circulation (*Morrow et al.,* 1994; *Lozier,* 1997). Eddies also carry heat, salt, carbon, and nutrients and play an important role in the global budgets of these tracers. Most of the eddy energy is generated by instabilities of the mean flow (*Stammer and Wunsch,* 1999), and by fluctuating winds (*Frankignoul and Muller,* 1979).

Helland-Hansen and Nansen (1909) first observed mesoscale eddies in the Norwegian Sea and termed these ocean features as ‘‘puzzling waves’’. In the Norwegian Sea, eddies are found to play an important role in heat exchanges and dense water formation (*Rossby et al.,* 2009b; *Spall,* 2010). The eddies form due to baroclinic instability (*Ikeda et al.,* 1989; *Spall,* 2010) and also through a combination of topographic steering, vortex stretching and barotropic instability (*Johannessen et al.,* 1989). The Lofoten Basin is the highest eddy active region in the Nordic Seas (*Poulain et al.,* 1996; *Jakobsen et al.,* 2003). *Volkov et al.* (2013) recently termed Lofoten Basin as a “hot spot” of intense synoptic scale variability. The key feature of the Lofoten Basin circulation is the spinning of anticyclonic eddies from the slope current and its southwestward propagation towards the deep Lofoten Basin (*Köhl,* 2007; *Andersson et al.,* 2011). Other main eddy active regions in the Norwegian Sea are the two inflows (*Sherwin et al.,* 2006; *Richter et al.,* 2009; *Koszalka et al.,* 2011).

1.4. Dense water formation in the Norwegian Sea

Overflow waters from the Nordic Seas and Arctic Ocean is the main source of North Atlantic Deep Water (*Dickson and Brown,* 1994). Several studies have shown the gradual transformation of Atlantic Water along its advective path in the Nordic Seas to play a major role in the formation of overflow waters (*Mauritzen,* 1996a,b; *Isachsen et al.,* 2007; *Eldevik et al.,* 2009). The importance of water mass transformation in the Norwegian Sea is highlighted by *Isachsen et al.* (2007), where they showed that the bulk of the light to dense water mass transformation occurring in the Nordic Seas takes place in the deep Lofoten and Norwegian Basin. Later *Eldevik et al.* (2009) showed that dense waters formed in the Norwegian Basin may have a direct influence on the overflow waters exiting at the Faroe Shetland Channel (FSC). The residence time of Atlantic Water circulating in the Lofoten Basin is longer than in any other region of the Nordic Seas possibly due to the deep cyclonic recirculation prevailing there (*Gascard and Mork,* 2008). The longer residence time combined with strong atmospheric cooling results in densification of Atlantic Water in the Lofoten Basin, which in turn has been argued to influence overflow waters. However, the link between the Atlantic Water in the Lofoten Basin and the overflow waters has not been shown yet.

Chapter 2

Motivation and Objectives

The motivation of this research stems from the potential importance of the Norwegian Sea circulation (see Figure 1) to the Atlantic Water transformation. The overall aim of the thesis is to revisit the circulation of the Norwegian Sea and to add new insight to our current understanding of the flow pattern, eddy activity, hydrography, deep convection and dense water formation in the region. The motivations and objectives for the four manuscripts included in this thesis are listed below.

Paper 1. **The two-branch structure of the Norwegian Atlantic Current-transport variability and connecting flows.**

The circulation of the Norwegian Sea has been subject to investigations since *Mohn* (1887) and *Helland-Hansen and Nansen* (1909). In recent years, the variability in Atlantic Water transport in the Norwegian Sea has received much attention due to its significance influence on the sea ice cover in the Barents Sea (*Sandø et al.,* 2010; *Årthun et al.,* 2012) and near Svalbard (*Walczowski and Piechura,* 2009). *Mork and Skagseth* (2010) estimated Atlantic Water volume transport from satellite derived surface velocities and hydrography, which showed the usefulness of satellite data for studies of variability in Atlantic Water transport. Although their analysis was limited to Svinøy section, the results suggested that the method could be consistently applied for other locations in the Norwegian Sea, as done here. Unlike the temporal variability, the spatial features of the circulation in the Norwegian Sea, has been thoroughly studied using drifters and floats (e.g., *Jakobsen et al.*, 2003; *Rossby et al.,* 2009a*; Andersson et al.,* 2011; *Koszalka et al.,* 2011, 2013). However, still it remains to be decided whether the two branches of NwAC can be considered as separate flows after entering on each sides of the Faroe Islands (*Helland-Hansen and Nansen*, 1909; *Orvik and Niiler,* 2002*; Nilsen and Nilsen,* 2007). *Rossby et al.* (2009a) using floats showed connecting flows and mixing between the two branches of NwAC and argued that the two branches cannot be considered as separate. However, evidence of persistent flow between the front current and the slope current based on long term and continuous data like altimetry, has not yet been presented. The main objectives of Paper 1 are:

- To examine the spatial and temporal variability of the surface circulation of the Norwegian Sea using satellite altimetry;
- To examine the vertical structure of the circulation observed from satellites, using hydrography;
- To identify regions where flow (surface waters in this study) between the two branches of the Norwegian Atlantic Current may take place;
- To assess effects of these inter-connections on the downstream flow variability.

Paper 2. **Processes influencing the dense water formation in the Lofoten Basin.**

In recent times, the Lofoten Basin, which is the largest heat reservoir in the Nordic Seas, has received some attention due to the dense water formation there and its possible link to the overflow waters exiting from the Nordic Seas. The identification of the Lofoten Basin as a major location in the Nordic Seas where strong dense water formation takes place (*Isachsen et al*., 2007), further highlights the importance of dense waters formed there. However, a thorough description of the water mass distribution or a link between the Lofoten Basin and overflow waters from the Nordic Seas has not been shown in earlier studies. The main objectives of Paper 2 are:

- To identify the influence of surface circulation, eddy activity, and heat loss of the Lofoten Basin on the spatial distribution and temporal evolution of dense water formation in the Lofoten Basin;
- To study the temporal variability in the hydrographic properties of Atlantic Water in the Lofoten Basin during a six decade time period;
- To quantify the influence of North Atlantic inflow and atmospheric heat loss on the Atlantic Water density in the Lofoten Basin;
- To assess the Atlantic Water transformation in the Lofoten Basin as an integral part of the cyclonic overturning loop in the Nordic Seas, which is part of AMOC.

Paper 3. **The Lofoten vortex of the Nordic Seas.**

A most anomalous circulation feature in the Nordic Seas is the anticyclonic vortex seated in the deep part of the Lofoten Basin. Since the vortex is also situated in the deep convective region in the basin it is likely to play an active role in the ventilation of Atlantic Water. Several studies have observed the existence of this quasi-permanent Lofoten vortex (*Ivanov and Korablev*, 1995a, b; *Kohl*, 2007; *Rossby et al.,* 2009a; *Andersson et al.,* 2011; *Koszalka et al.,* 2011; *Søiland and Rossby,* 2013; *Volkov et al.,* 2013). This study performs a more comprehensive observational based quantitative analysis of the vortex using satellite and long-term hydrographic datasets. The main objectives of Paper 3 are:

- To document the uniqueness of the Lofoten Vortex in the Nordic Seas;
- To quantify the vortex' surface and vertical characteristics;
- To quantify its variability on seasonal, inter-annual, and climatological time-scales;
- To assess relevant forcing mechanisms.

Paper 4. Towards improved estimation of the dynamic topography and ocean circulation in the high latitude and Arctic Ocean: The importance of GOCE.

Changes in the North Atlantic and the Arctic have far reaching influences on regional and global environment and climate variability, thus emphasizing the need for advanced quantitative understanding of the ocean circulation and transport variability in the high latitude and Arctic Ocean. The main objectives of Paper 4 are:

- To estimate a new mean dynamic topography for the North Atlantic and the Arctic from the highly precise gravity field from GOCE data, to facilitate improvements in future analyses of the circulation in the Nordic Seas and Arctic Ocean;
- To assess the quality, usefulness and validity of the new GOCE derived MDT for studies of the ocean circulation and transport estimates in the Nordic Seas and Arctic Ocean;
- To estimate the barotopic contribution to the mean dynamic topography in the Nordic Seas.

Chapter 3

Data and Methods

3.1. Ocean Currents from remote sensing

3.1.1. Satellite altimetry

Accurate measurements of the sea surface relative to a reference ellipsoid have been provided by several (TOPEX/POSEIDON, ERS-1 and 2, Envisat, JASON-1 and 2) satellite altimeter missions (e.g., *Fu et al.,* 2001) for the past two decades. An altimeter emits signal to the earth surface and receives the reflected echo and thus measures the sea surface height (SSH). Instantaneous SSH is measured relative to a reference ellipsoid (Figure 2). Sea level anomalies (SLA) are estimated from the instantaneous SSH after subtracting the mean sea surface (MSS). Currently, MSS derived from altimetry is known with a centimeter accuracy (*Schaffer et al.,* 2012).

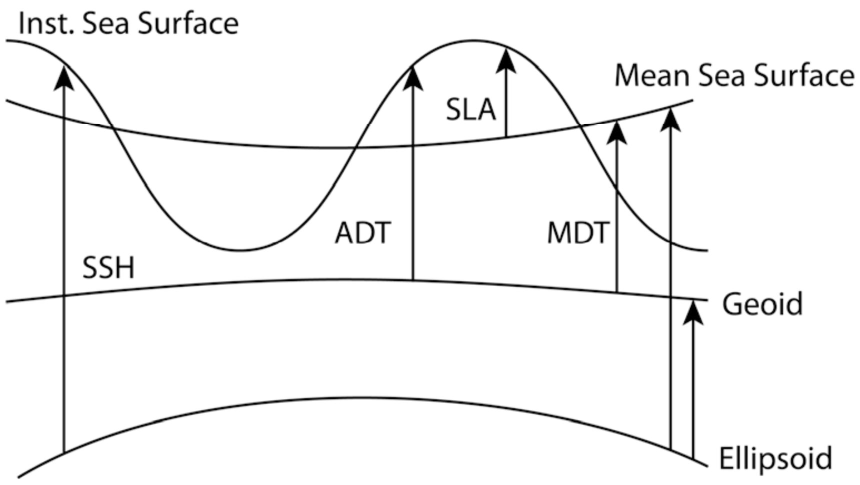

Figure 2. Schematic illustration of the relationship between the mean dynamic topography (MDT), the mean sea surface and the geoid referenced to the same ellipsoid.

The SLA fields, corrected for the inverted barometer effect, tides, and tropospheric effects (*Le Traon and Ogor,* 1998) are based on merged TOPEX/POSEIDON (T/P), ERS-1 and 2 and Envisat data (*Ducet et al.,* 2000; *Volkov and Pujol,* 2012). Note that the TOPEX/POSEIDON data is not available north of 66°N. The SLA fields and the errors associated with it are obtained from AVISO. AVISO stands for Archiving, Validation and Interpretation of Satellite Oceanographic data, and was set up in 1992 to process, archive and distribute ocean radar altimeter data. In the Norwegian Sea, the SLA fields provided are of roughly 12 to 18 km resolution. Figure 3 shows an example of a (randomly chosen) weekly SLA field in the Norwegian Sea and the magnitude of its errors. The root mean square (RMS) difference between the altimeter data and tide gauge measurements in the Norwegian Sea is generally 3 cm (*Volkov and Pujol*, 2012).

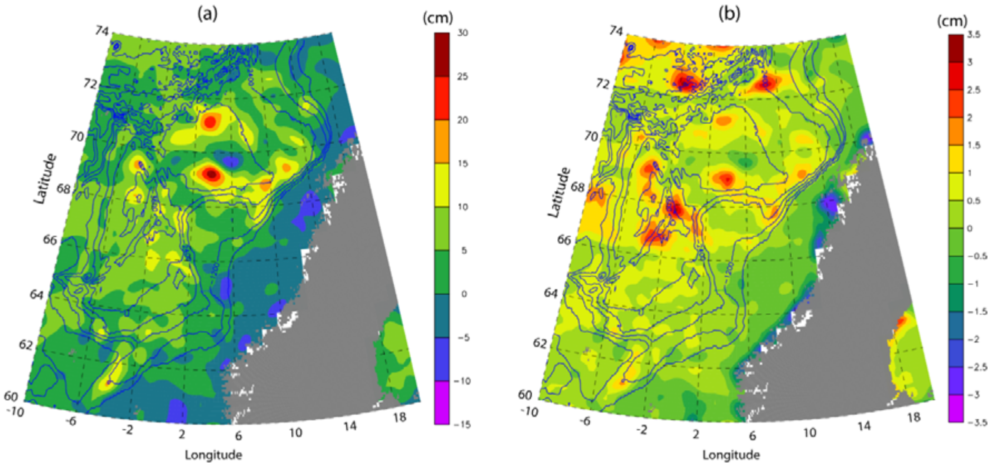

Figure 3. (a) An example of weekly sea level anomaly data and (b) the error associated with it during 19-25 June 2008. Blue lines are isobaths drawn for every 600 m.

3.1.2. Mean Dynamic Topography

Mean dynamic topography used to study the circulation of the global ocean, is the difference between MSS and the geoid (Figure 2; *Knudsen et al.*, 2011). The geoid is the equipotential surface of earth's gravity field, or more precisely it is the sea surface in the absence of winds, currents and tides and only influenced by gravity. Thus, MDT yields the long term averaged strength of the ocean currents, i.e. the mean circulation. The lack of an accurate geoid has until recently prevented precise computation of the ocean's geostrophic circulation from satellite altimetry (*Knudsen et al.,* 2007*; Bingham et al.,* 2008). Various methods have been used to calculate the MDT from *in* *situ* ocean data. The simplest method is to compute dynamic height relative to an assumed level of no motion from climatology of temperature and salinity, based on measurement profiles made over many decades (*Levitus and Boyer*, 1994; *Levitus* et al*.,* 1994). A modification of this method uses an inverse model with certain dynamical constraints to get the barotropic signal (*LeGrand et al.,* 2003). However, these two methods cannot represent a uniform time average due to the inhomogeneity of hydrography data. In another approach, *Niiler* et al. (2003), from a 10-year set of near-surface drifter velocities derived MDT which is corrected for temporal bias using altimeter data*.* Later, *Rio & Hernandez* (2004) created another MDT (Rio03 MDT) by blending ocean observation without the use of a model. During the last decade, the introduction of satellite gravity measurements from Gravity Recovery and Climate Experiment (GRACE) drastically improved the knowledge of the marine geoid (*Rio et al.,* 2005; *Maximenko et al.,* 2009). An update of Rio03 MDT (Rio05 MDT) was released after the incorporation of the GRACE geoid model (*Rio et al.,* 2005). Currently, the CNES-CLS09 MDT (*Rio et al.,* 2011; Figure 4a), an updated version of Rio05 MDT, is the state-of-the-art MDT.

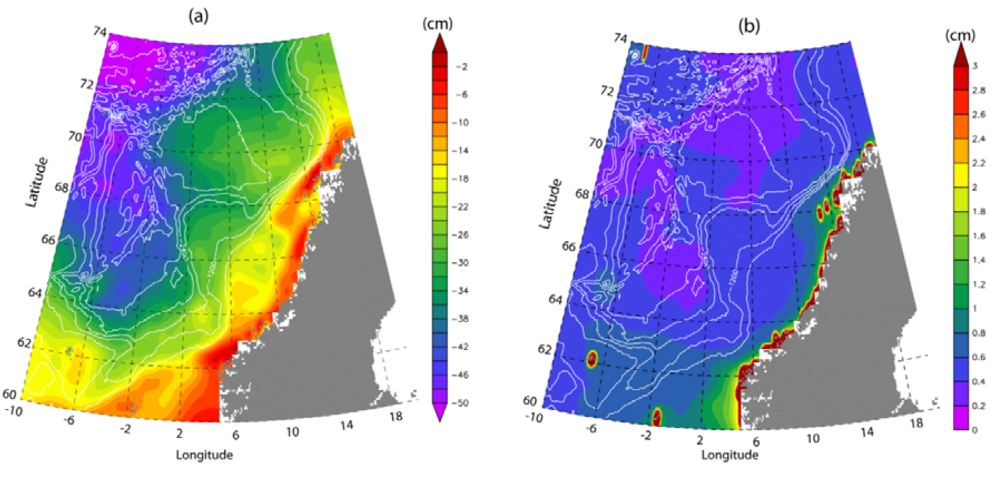

Figure 4. Spatial distribution of MDT from (a) CNES-CLS09 MDT, and (b) the error associated with it in the Norwegian Sea. White lines are isobaths drawn for every 600 m.

The CNES-CLS09 MDT is based on altimetry, surface buoys, Argo floats, in situ measurements, and a GRACE geoid model. This MDT has been estimated on a 1/4^{o} regular grid using a combination of direct and synthetic methods (*Rio and Hernandez*, 2004; *Rio et al.*, 2005). The main improvements from the previous Rio05 MDT are: (1) the use of 4.5 years of GRACE gravity anomaly data instead of 2 years; (2) updated drifting buoy velocities (1993-2008) and dynamic heights estimated from Conductivity, Temperature and Depth (CTD) casts and Argo floats (1993-2008); (3) an improved Ekman model for the extraction of the geostrophic component of the buoy velocities; (4) an improved processing method for the estimation of dynamic heights; (5) the estimation of the MDT is done on a $1/4^{\circ}$ resolution grid instead of $1/2^{\circ}$. Figure 4 shows the MDT in the Norwegian Sea, which ranges from -45 cm to 5 cm. The errors associated with the estimation of MDT are provided together with the dataset (*Rio et al.,* 2011). These errors are computed using multivariate objective analysis of both observational errors and the a-priori MDT covariance field (see *Rio et al.,* 2011, for more details). In the Norwegian Sea, from the continental plateau and outwards, the errors are less than 1.0 cm (Figure 4b).

3.1.3. Absolute Dynamic Topography

SLA added to MDT gives Absolute Dynamic Topography (ADT) which can be further used to determine the surface velocities (u_s and v_s):

$$ADT=SLA+MDT, \quad (1)$$

$$u_s=\frac{-g}{f}\frac{\partial ADT}{\partial y}, \quad (2)$$

$$v_s=\frac{g}{f}\frac{\partial ADT}{\partial x}, \quad (3)$$

where g is the acceleration due to gravity, f is the Coriolis parameter, h is SLA, and x and y are the longitudinal and latitudinal directions. ADT and surface geostrophic velocities determined from the CNES-CLS09 MDT and the AVISO SLA are used in Paper 1, 2 and 3, in order to study the circulation of the Norwegian Sea.

Eddy kinetic energy, *EKE,* is computed using the relation (*Chaigneau et al.,* 2008):

$$EKE=\frac{u'^2+v'^2}{2}, \quad (4)$$

where u' and v' are geostrophic velocity anomalies determined using only the altimeter derived SLA instead of the full ADT in equations (2) and (3). The SLA derived EKE is used to quantify the Lofoten Vortex of the Nordic Seas in Paper 3.

3.1.4. Evaluation of the absolute velocities

Volkov and Pujol (2012) validated this satellite data in the Norwegian Sea and argued that the velocities can be successfully used to study the variability in the surface circulation of the region.

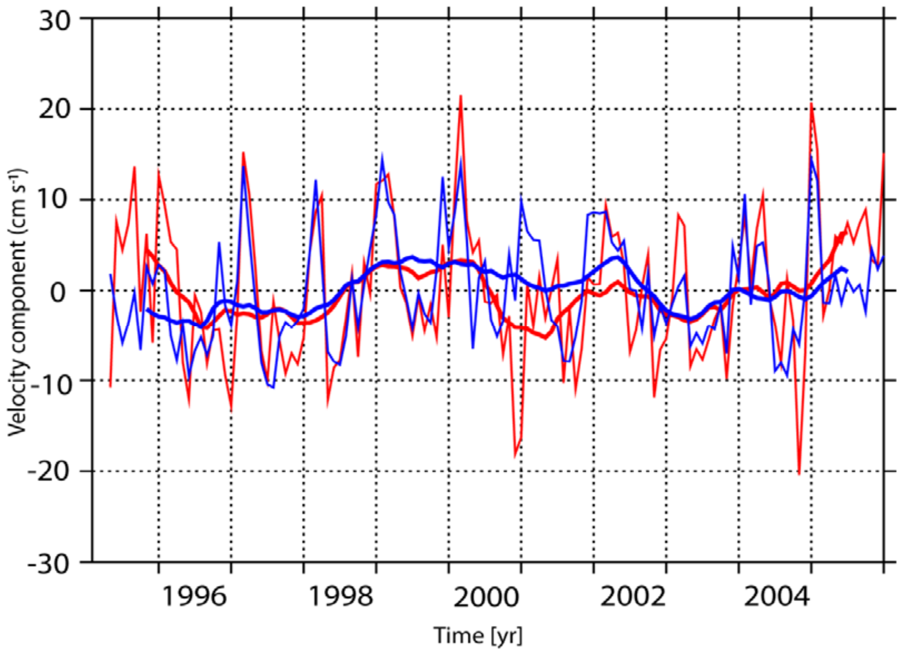

Figure 5. Monthly surface geostrophic velocity anomaly from altimetry (blue) and independent current meter velocity anomaly at 100 m depth (red) in the slope current at Svinøy section. Thick lines are 12 month running mean of their respective datasets. The monthly velocity anomalies are determined after removing the time-mean. This figure is from Paper 1 of this thesis.

Mork and Skagseth (2010) compared the temporal mean of satellite derived absolute velocities across the Svinøy Section to the temporal mean of independent current measurements and found good similarity between the satellite and current meter velocities. We compared the monthly variability of altimeter derived surface velocities with the current meter velocities in the slope current at Svinøy Section (Figure 5). The figure shows good comparison and there is a significant correlation (r=0.61) between the two independent velocity measurements (correlation obtained after de-trending and de-seasoning). Note that this comparison between satellite and current meter data is done in a location very near to the coast (Figure 2a in Paper 1). It is known that the errors in the altimeter data near to the coast are higher than in the open ocean. However, the good agreement between the altimeter data and current meter at Svinøy demonstrate the usefulness and validity of the dataset in studies of the variability in the circulation of the Norwegian Sea.

3.2. A New Mean Dynamic Topography of the North Atlantic and Arctic Ocean from the new GOCE data

The first three scientific papers of this thesis used the CNES-CLS09 MDT dataset (*Rio et al.,* 2011; Section 3.1.2). As a step towards higher precision, a new mean dynamic topography estimated from GOCE (Paper 4) is described below.

The gravity field over the earth's surface varies from place to place due to the rotation of the earth, positions of mountains and ocean trenches and variations in density of the ocean interior. The GOCE mission of the European Space Agency (ESA) was successfully launched in October 2009. GOCE is dedicated to measuring the Earth's gravity field and the geoid with unprecedented accuracy (gravity: ~1-2 mgal; geoid: ~1-2 cm) at a spatial resolution of ~100 km. Recent studies show the improvements of the GOCE derived geoid and MDT over the GRACE satellite data at higher spatial resolution of around 100 km (*Bingham et al.* 2011; *Knudsen et al.* 2011; *Bruinsma et al.,* 2013).

3.2.1. The GOCE geoid

The GOCE High level Processing Facility (HPF) delivers the level 2 global gravity model from which geoid heights can be determined (*Johannessen et al.,* 2003*; Koop et al.,* 2007; *Bingham et al.,* 2011). Three versions of the GOCE gravity model are provided by three distinct methods: the direct approach (DIR), the space-wise (SPW), and time-wise (TW) methods (see *Bruinsma et al.*, 2010 and *Pail et al.*, 2011 for details). Here we use the third release of the DIR and TW models. While the TW model is a GOCE-only model (12 months of GOCE data), i.e., no external gravity field information has been used, neither as reference model, nor for constraining the solution, the DIR gravity field model is constructed with 12 months of GOCE data and 7 years of GRACE and Laser Geodynamics Satellites (LAGEOS) data. Thus, the TW gravity model is the GOCE-only product which gives the best demonstration of the capabilities of GOCE. The TW and DIR geoids (0.25º latitude and 0.25º longitude grids) are herein determined from their respective gravity models in the mean-tide system and relative to the Topex-ellipsoid, in order to be consistent with the two different MSS datasets used in this study. All technical details associated with the estimation of the geoid from gravity anomalies are given in *Johannessen et al.* (2003). The two different MSS data sets used in this study are: (1) CNES-CLS11 MSS (*Schaffer et al.,* 2012) and DTU10 MSS (*Knudsen et al.,* 2011).

3.2.2. Estimation of Mean Dynamic Topography and velocity fields

As explained in section 3.1.2, the computation of MDT from MSS and geoid is conceptually very simple as expressed by the equation *MDT = MSS – geoid*. However as indicated by *Benveniste et al.,* (2007) there are several issues that must be considered in order to obtain a good MDT product. All these issues are considered in the estimation of MDT shown below (Table 1). The computation of the MDT is done according to the recommendations from the GOCE User Toolbox (GUT) tutorials and is carried out using GUT tools (*Benveniste et al.,* 2007; *Knudsen et al.,* 2011).

Table 1. Mean Dynamic Topography products (first column) and the geoids (second column) and the mean sea surfaces (third Column) they are based on.

MDT	Geoids	MSS
TW_CNES	TW	CNES-CLS11
TW_DTU	TW	DTU10
DIR_CNES	DIR	CNES-CLS11
DIR_DTU	DIR	DTU10

After the estimation, a filter should be applied to the MDT in order to remove the noise. In a recent study, *Knudsen et al.,* (2011) applied a Gaussian filter (140 km) to the MDT. However in the high latitudes, it is found that large spatial filtering removes signatures of ocean currents. The influence of the spatial filtering on the estimation of MDT is demonstrated in Figure 6 comparing profiles of MDT across the Greenland Basin (a), the Lofoten Basin (b), the Norwegian Basin (c) and the Greenland-Scotland ridge (d). Although, the maximum difference between the MDTs is less than 5 cm, the signatures of the mesoscale circulation features in the Nordic Seas are gradually lost as the filter-width increases from 80 km. This is particularly evident for the two branches of the Norwegian Atlantic Current (panel b and c) as well as for the inflow of Atlantic Water in the Denmark Strait (panel d). Hence, for high latitudinal studies, a Gaussian filter of 80 km is chosen.

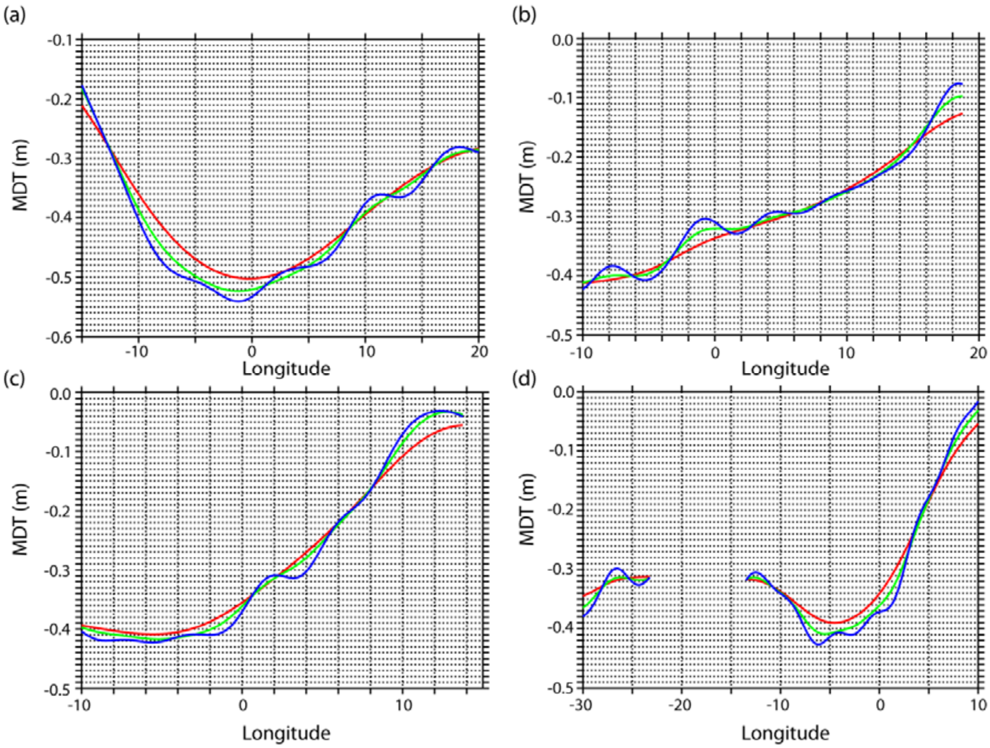

Figure 6. DIR_DTU mean dynamic topography with a spatial resolution of 140 km (red), 100 km (green), 80 km (blue) across (a) 75°N, (b) 70°N, (c) 67°N and (d) 65°N. The discontinuous lines in panel d is due to presence of land.

The four MDTs (Table 1) of the North Atlantic and the Arctic prepared from two GOCE geoid models and MSS are shown in Figure 7. All four MDTs reproduced the distinct minima in MDT in the Labrador Sea and the Greenland Sea as well as the maxima in the Beaufort Gyre and in the northern Pacific Ocean. The comparison of the four solutions show that the MDT estimated from the DIR geoid and DTU10 MSS provides the best representation of known circulation features in the Arctic Ocean and Nordic Seas (Figure 7a). Interestingly, the TW_DTU MDT (based solely on the GOCE geoid) is comparable to DIR_DTU MDT, south of about 85ºN. All in all, this clearly demonstrates the potential of the GOCE mission for studying high latitude ocean circulation. Note that in Paper 4, MDT is estimated (as described above) from the Eigen 6C gravity model which uses the combination of DIR gravity model and terrestrial data (*Förste et al.,* 2011).

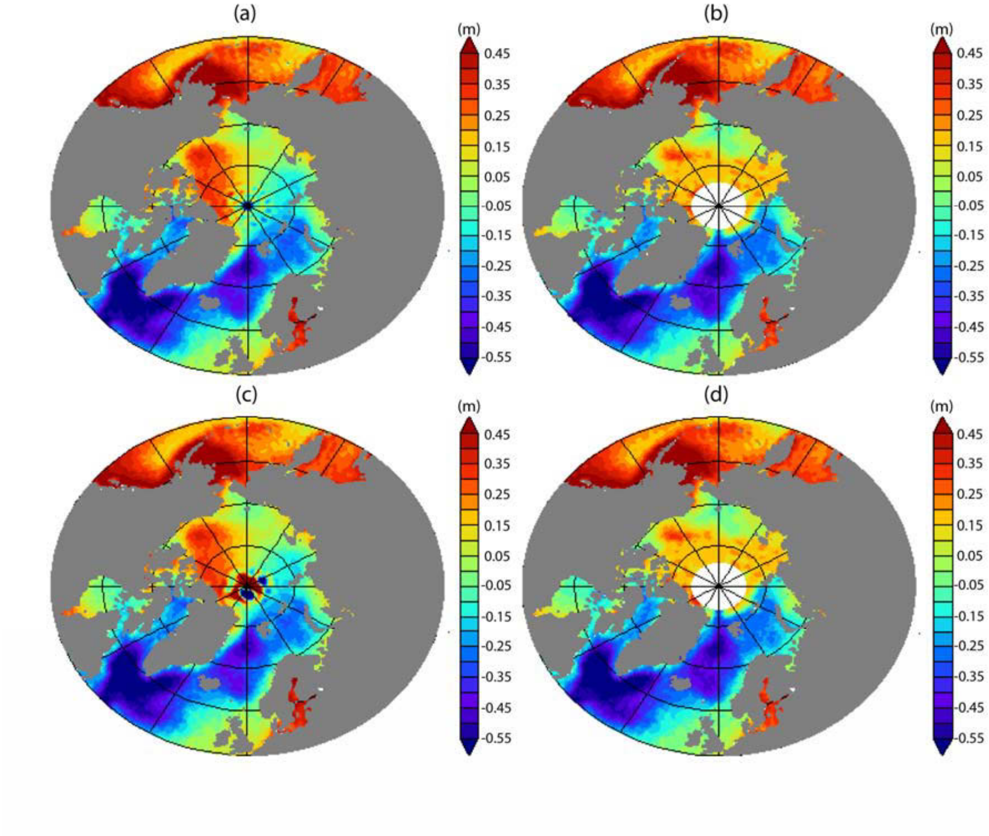

Figure 7. Mean dynamic topography of the North Atlantic and the Arctic Ocean: (a) DIR_DTU MDT, (b) DIR_CNES MDT, (c) TW_DTU MDT, (d) TW_CNES MDT.

3.3. Other remote sensing data

Sea surface temperature (SST; 1993-2010) is obtained from 1/8º global fields of SST produced by the Modular Ocean Data Assimilation System (MODAS). MODAS SST is produced by an optimal interpolation of Advanced Very-High Resolution Radiometer (AVHRR) nonlinear SST observations (*Barron and Kara*, 2006). Note that the spatial coverage of AVHRR SST is influenced by cloud cover. Hence, MODAS SST is used in this study. MODAS SST is used as a proxy to show the effect of buoyancy forcing on the eddy intensity of the anticyclonic vortex of the Lofoten Basin (Paper 3).

Chlorophyll-a (chl-a; 1997-2010; 9 km grid) pigment concentration is obtained from Sea-viewing Wide Field-of-view Sensor (SeaWiFS). SeaWiFS chl-a data has been used to study phytoplankton blooms in the Nordic Seas (*Engelsen et al.,* 2002). In this thesis (Paper 2), it is used as a proxy to study the surface circulation pattern of the Lofoten Basin.

3.4. Hydrography

Hydrographic data is obtained from the long term (1949-2008) hydrographic NISE database (Norwegian Iceland Seas Experiment; *Nilsen et al.,* 2008). Similar to the satellite altimetry, the NISE data is a major dataset used in all four papers of this thesis. The NISE dataset consists of CTD data decimated to 5 m, and bottle data. The hydrographic variables included in the latest version (V3) of the NISE dataset are temperature and salinity. The major source of the NISE dataset is the public database maintained by the International Council for the Exploration of the Seas (ICES). The NISE database also includes data obtained from the Marine Research Institute, Iceland; Institute of Marine Research, Norway; the Faroese Fisheries Laboratory, Faroe Islands; Geophysical Institute, University of Bergen, Norway and the World Ocean Circulation Experiment (WOCE). The NISE dataset has been used to study the variability of different water masses in the Nordic Seas (e.g., *Eldevik et al.,* 2009). The spatial distribution of the number of observations (salinity samples) in the NISE dataset is shown in Figure 8.

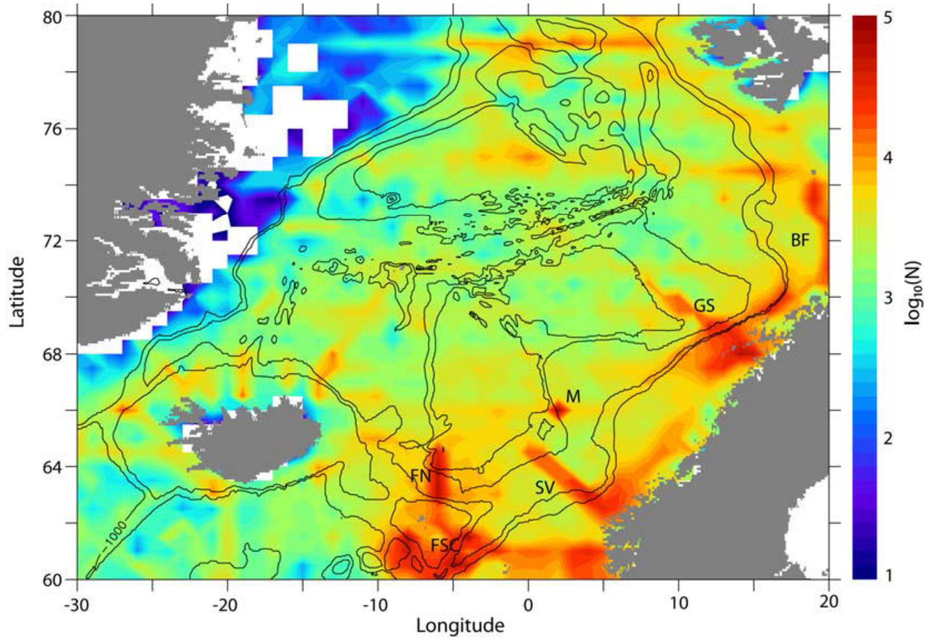

Figure 8. Number of observations (salinity samples; N) included in the NISE dataset. Colour (logarithmic scale) indicates number of observations on 1° x 0.5° longitude and latitude grids. White areas have no data. The symbols FN, FSC, SV, GS, BF respectively denotes the Faroe North, Faroe Shetland Channel, Svinøy, Gimsøy and Bjørnøya-Fugløya hydrographic sections. The hydrographic station Mike is denoted by the symbol 'M'. Black lines represent isobaths for 500, 1000, 2500 and 3000 m depths.

In this thesis, bin averaging methods are used for creating homogeneous fields from in-homogeneously sampled data. A "bin" is a limited area in space or time, and the division into bins are done by making a grid of points (evenly or unevenly distributed) to which mean values are assigned. The mean values determined using the regular population (POP) mean are from those data with positions nearer than halfway to the next grid point in all directions. In doing so, the geographical cells are represented by a mean value positioned in the middle of the cell. The variance of the population mean is calculated by the single observations' squared standard deviation divided by the number of observations. More details of the bin averaging methods are given in *Nilsen* (2003). Different length units can form the basis for a division of an area into bins. The vertical binning of the data is done to the 'standard' depths 0, 10, 25, 50, 75, 100, 150, 200, 300, 400, 500, 600, 800, 1000, 1200, 1300, 1400, 1500 m. However, the horizontal binning of the dataset is done differently according to the objective of the study. In Paper 1, the length of the sections are selected to cover the study region, and horizontal bin sizes are selected according to the availability of observations to give the best spatial resolution while still ensuring that climatic monthly mean sections can be made in order to eliminate seasonal bias. For some sections the horizontal bins are centered on stations on standard repeated sections, and are thus small, while for others the data are much more scattered, and larger bins are used. In Paper 2, hydrographic properties of Atlantic Water in the eastern and western Lofoten Basin are estimated as area averages of the two regions. In Paper 2 and 4, 1° x 0.5° longitude and latitude horizontal bins are used to estimate the spatial variability of steric height. In Paper 3, a hydrographic section along 70°N is selected in order to study the hydrographic properties of an anticyclonic vortex situated in the Lofoten Basin. Mixed layer depth (MLD) in Paper 2 and 3 are estimated on 1° x 0.5° horizontal bins. The time dimension is also incorporated when binning. Binning on separate weeks is done in Paper 1 for composite studies. Binning on inter-annual time scales is used in Paper 2 to study the inter-annual variability of hydrographic properties of Atlantic Water in the Lofoten Basin.

Mixed layer depths are calculated by a finite density difference method, following *Nilsen and Falck* (2006). In the same way as the maximum gradient method, a finite difference method finds the pycnocline, and not the depth of the homogeneous layer per se. A difference criterion between the surface density and MLD-base density is calculated by subtracting a temperature of 0.8°C from the surface value, and applied to individual density profiles. The climatological mean MLD is calculated by horizontally binning the individual MLD estimates. Steric heights from hydrographic climatologies are calculated according to *Siegismund et al.* (2007), where the steric height is referenced to depths (e.g., 500 m in Paper 2), and a constant density ρ_0 from salinity of 35 and temperature of 0°C. More information on the concept and application of steric height is given by *Tomczak and Godfrey* (2003). Subsurface velocities are calculated using the surface geostrophic velocities (v_s) and the thermal wind relation according to *Mork and Skagseth* (2010):

$$v(z) = v_s + \frac{g}{\rho_0 f} \int_z \frac{\partial \rho}{\partial x} dz \,, \qquad (5)$$

where, f is the Coriolis parameter, g is the acceleration due to gravity, ρ is the density and ρ_0 is a reference density and x is directed along the section. Volume transports of Atlantic Water are found by integrating the velocities vertically over the depth interval with salinities 35 and above, and then laterally between defined limits.

3.5. Surface drifter and Re-analysis datasets

Surface drifter tracks used in Paper 1 are obtained from the WOCE surface drifter expedition database (*Schlitzer,* 2000). WOCE drifter tracks have been used in several studies of the near surface circulation in the Nordic Seas (e.g., *Jakobsen et al*., 2003). Surface geostrophic velocities (1ºx1º grid) and the errors associated with it obtained from the dataset "Drifter derived climatology of global near-surface currents" are used in Paper 2 and 4. The dataset obtained is derived from satellite-tracked surface drifting buoy observations (*Lumpkin and Garraffo*, 2005).

Heat flux datasets (short wave radiation, long wave radiation, latent heat flux, and sensible heat flux; 1949-2008) obtained from National Centers for Environmental Predictions (NCEP; *Kalnay et al*., 1996) are the re-analysis datasets used in this thesis (Paper 2). The NCEP heat flux data, one of the widely referenced re-analysis dataset in studies related to air-sea interaction in the Nordic Seas, are also used in many numerical ocean models as the atmospheric forcing (e.g., *Sandø et al*., 2010).

3.6. Numerical Ocean Model

The output from a regional version of Miami Isopycnic Coordinate Ocean Model (MICOM; *Sandø et al.,* 2012) covering the North Atlantic, the Nordic Seas, and the Arctic Ocean during the time period 1993-2007 is used in Paper 4. The model data is used for the estimation of volume transports in the Norwegian Sea and for the estimation of MDT (time-mean of model SSH) in the North Atlantic and the Arctic. A brief description of the MICOM model is given below.

Output data from a global version of MICOM (*Orre et al.,* 2009) is used as boundary conditions. The global model has a grid spacing of about 40 km whereas the resolution of the regional model is about 13 km in the Nordic Seas. The model has 35 vertical layers of fixed potential densities, and an uppermost mixed layer with temporal and spatial varying density. The nesting boundaries are located in the South Atlantic and in the Bering Strait. A dynamic and thermodynamic sea-ice model is coupled to MICOM (*Bentsen*, 2002). The models share the horizontal grid, the exchange of fluxes are handled internally and hence the sea-ice model can be considered as an integrated part of MICOM. The atmospheric forcing is taken from daily NCEP/NCAR reanalysis fields (*Kalnay et al.,* 1996) and the forcing scheme and procedure are described in *Bentsen and Drange* (2000). For more detailed description of the model physics and performance, see *Hátún et al.* (2005); *Sandø and Furevik* (2008); *Sandø et al.* (2010) and *Sandø et al.* (2012). The regional version of the MICOM model has been evaluated with good results at FSC and Barents Sea Opening (*Sandø et al*., 2010, 2012).

Chapter 4

Summary of results

The present study revisits the circulation of the Norwegian Sea using measurements taken from space and in the ocean. A summary of the thesis is given below.

In the Norwegian Sea (Figure 1), there is a general spin up of the surface circulation during winter, with the exception of the flow along the Mohn Ridge, which is strongest in summer. This seasonal intensification is due to more buoyant waters in the Lofoten Basin during summer, which results in the elevation of sea surface height there. Similarly, buoyant waters in the eastern Lofoten Basin results in a weak mean surface flow in the central Lofoten Basin, but stronger during winter. In the Norwegian Sea, topographic steering results in local intensification of the slope current at the Svinøy and Lofoten slope regions. In the front current, topographic steering is prominent at the western slope of the Vøring Plateau and along the northern part of the Mohn Ridge.

Four major surface flows connecting the front current and the slope current are identified, out of which two show distinct seasonality (Paper 1). The major factors influencing these flows are: topographic steering, surface winds and buoyancy loss. A strengthening of the front current upstream of the Lofoten Basin is associated with a larger eastward flow of Atlantic Water towards the slope current, which also increases the probability of Atlantic Water from the front current to enter the Barents Sea. This implies that the Iceland-Faroe inflow of Atlantic Water may have more importance for the Barents Sea and Arctic Ocean than previously assumed, and the two branches of northward flowing Atlantic water in the Nordic Seas cannot be considered as two independent flows.

The variability in the surface velocities in the Norwegian Sea is found to be representative also of the subsurface Atlantic Water flow, and the relationship is more pronounced in the slope current. Compared to the front current, there is large variability in the amount of Atlantic Water transported pole-ward by the slope current (front current, the range being up to 1 Sv; slope current, the range being up to 5 Sv).

This thesis confirms the Lofoten Basin as the most eddy active region outside the boundary currents of the Nordic Seas. The northeastern part of the basin is found to be an important location of eddy shedding from the slope current (Paper 2). The eddy kinetic energy maxima in this region during early winter coincides with the maxima in the slope current transport during January, supporting the link between the strength of the slope current and eddy shedding. Two strong eddy active regions with distinctly different annual cycles on either side of the Lofoten Basin are found to exist. There is a two month lag between the eddy kinetic energy of the western and eastern region of the Lofoten Basin which indicates propagation of eddies from the east and into the western basin. The maxima in mergers between the quasi-permanent anticyclonic Lofoten Vortex situated in the western Lofoten Basin and other anticyclonic eddies during March is consistent with two months travel time of eddies into the western basin from the east. Observational evidence confirm transfer of energy from other anticyclones to the Lofoten Vortex via vortex merging process (Paper 3). The vortex merger further explains the seasonality in the *eddy intensity* of the Lofoten Vortex which is maximum during late winter-spring and minimum during late autumn-early winter. On the other hand, the long term variability in the *Eddy Intensity* of the Lofoten Vortex is significantly influenced by the buoyancy forcing. The Lofoten Vortex persistently residing in the deepest part of the basin, follows a cyclonic drift path, and also plays an active role in ventilating the Atlantic Water in the Nordic Seas.

The spatial distribution and temporal evolution of dense water formation in the Lofoten Basin is influenced by the surface circulation, eddy activity, and heat loss in the basin (Paper 2). The variability in temperature dominates the Atlantic Water density variability of the Lofoten Basin, which in turn is influenced by the variability in the inflowing North Atlantic Water and the heat loss in the basin. The inter-annual variability in both local heat loss and upstream North Atlantic Water density influences the Atlantic Water density of the eastern Lofoten Basin more than in the western. A lag of two years is found between the Atlantic Water densities in the Lofoten Basin and the North Atlantic Water density at Faroe Shetland Channel.

The density of Atlantic Water in the Lofoten Basin after 2000, which is the lightest during 60 year time-period, is linked to the warming of the inflowing North Atlantic Water since the mid 1990s. A strong connection is found between the Atlantic Water (in both salinity and temperature) in the western Lofoten Basin and the Norwegian North Atlantic Water (NNAW), and the further connection to the Faroe Shetland overflow found by *Eldevik et al.* (2009), points to the possibility of a returning circulation connecting the Lofoten Basin to the overflows.

A new mean dynamic topography is estimated for the North Atlantic and the Arctic from the GOCE gravity anomaly data (in Paper 4). The MDT resolves major circulation features in the North Atlantic and the Arctic concurring with previous knowledge. Combined with the steric height estimated from hydrographic data, the pure barotropic contribution to the MDT shows distinct features in consistence with the known existence of deep barotropic circulations in the central regions of the Norwegian and Greenland Seas. There is notable improvement in the representation of the circulation of the Western Nordic Seas compared to the current state-of-the-art MDTs. The slope current contains approximately 60% of the total volume flux across the Svinøy section with a distinct transport maximum in winter (Dec-Jan) and a minimum in summer (Jun-Aug). This transport is moreover dominated by the barotropic component. The outcome of GOCE MDT is also promising with respect to improving the capabilities to evaluate ocean models.

All in all, the results of this thesis add new insights into the ocean circulation of the Norwegian Sea. This thesis also shows the importance of the initiatives taken by different space agencies around the world for providing higher resolution and more accurate remote sensing observations.

Chapter 5

Future Perspectives

The importance of the circulation of the Nordic Seas to global climate has been mentioned in several studies (e.g., Rhines *et al.,* 2008). However, only few attempts has been made to study the circulation of the Nordic Seas using the state-of-the-art CNES-CLS09 MDT (*Mork and Skagseth,* 2010; *Chafik,* 2012; Paper 1, 2, 3 in this thesis). Notably, none of these studies analysed the circulation of the western Nordic Seas. Moreover, Paper 4 showed the limitation of the CNES-CLS09 MDT in reproducing the mean circulation of the northwestern Nordic Seas. As a solution, a new MDT is estimated for the North Atlantic and the Arctic from GOCE data in Paper 4. But, it should be noted that since a Gaussian filter (80 km) is applied to the MDT in order to remove the noise, this MDT cannot be used to study mesoscale circulation features of the Nordic Seas. In this section, a new more accurate high resolution MDT of the Nordic Seas is estimated (described below), facilitating future studies of both large-scale and mesoscale features.

In a recent study, *Bruinsma et al.* (2013) showed that the latest release (Release 4) of the GOCE data is found to be closer to observations compared to the previous releases. The Release 4 direct approach gravity anomaly (DIR4) data is constructed with 28 months of GOCE data, 9 years of GRACE data and 25 years of LAGEOS data. This is roughly two-times the amount of data used in the Release 3 DIR gravity anomaly data (Section 3.2.1).

In here, a new geoid is estimated from DIR4 data in the mean-tide system and relative to the Topex-ellipsoid (as described in Section 3.2.2). The DIR4 MDT is determined by subtracting this new geoid from DTU10 MSS (*Knudsen et al.,* 2011). The next step after low-pass filtering the DIR4 MDT with a Gaussian filter (80 km), is to re-incorporate smaller spatial scales of MDT (<80 km) back onto it. This is achieved using the CNES-CLS09 MDT used in Paper 1, 2, and 3. As mentioned in Section 3.1.2, this MDT is based on altimetry, in situ measurements, surface buoys, Argo floats, and a GRACE geoid model (*Rio et al.,* 2011). Its shorter spatial scales are obtained by high-pass filtering it with the 80 km Gaussian filter. Finally, the combined MDT is estimated by adding these shorter spatial scales (< 80 km) from the CNES-CLS09 MDT to the longer spatial scales (> 80 km) from the DIR4 MDT.

Compared to the CNES-CLS09 MDT, the new combined MDT significantly improves the estimation of the mean circulation of the Nordic Seas, mainly in the western Nordic Seas (Figure 9). The shape of the combined MDT and orientation of the dominant slopes reveals the distinct minima in the Greenland Basin and shows the circulation pathways including the northward flow of NwAC and southward flow of East Greenland Current (e.g., Jakobsen *et al*., 2003).

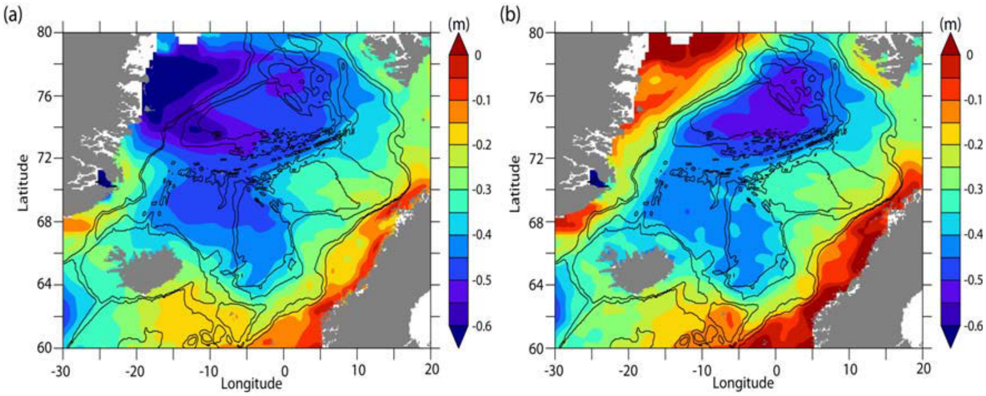

Figure 9. Mean dynamic topography of the Nordic Seas: (a) CNES-CLS09 MDT, (b) Combined MDT. Black lines represent the isobaths for 500, 1000, 2500 and 3000 m depths.

In future studies, this combined MDT together with sea level anomalies can be used to estimate more accurate ADTs. Surface velocities estimated from these ADTs can be further used to study the seasonal and inter-annual variability of the circulation of the Nordic Seas. In an upcoming project (GLOBCURRENT) funded by ESA, the circulation of the Nordic Seas will be investigated in detail using surface currents derived from GOCE, altimetry, Synthetic Aperture Radar data and microwave SST. In view of the promising GOCE-based results, they are also providing a new opportunity for the evaluation of Coupled Model Intercomparison Project Phase 5 (CMIP5) models. From such an evaluation, the best CMIP5 models in the Nordic Seas can be categorized, which further can be used to study changes in Nordic Seas circulation in scenarios, for e.g., enhanced greenhouse gas emission, additional fresh water input etc.

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