Modeling the dynamics and drift of icebergs in the Barents Sea

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Preface

This synthesis and collection of papers is submitted for the degree of Philosophiae Doctor in oceanography at the Geophysical Institute, University of Bergen. This work was carried out at the Nansen Environmental and Remote Sensing Center, in the Mohn Sverdrup department. An iceberg forecasting system for the Barents Sea is developed and evaluated. The system is used to improve our understanding and potential predictability of iceberg drift in the area. The thesis consists of an introduction, where the motivations, objectives and results are presented, and three papers that build on each other, listed below:

Paper I Parameterization of an iceberg drift model in the Barents Sea, **Keghouche, I., Bertino, L. and Lisæter, K. A.**, *Journal of Atmospheric and Oceanic Technology*, 2009, 26(10), 2216-2227

Paper II Modeling dynamics and thermodynamics of icebergs in the Barents Sea from 1987 to 2005, **Keghouche I., Counillon, F. and Bertino, L.**, *Journal of Geophysical Research*, revised and re-submitted

Paper III Adaptive estimation of iceberg parameters using the Ensemble Kalman Filter, **Keghouche I., Counillon, F. and Bertino, L.**, to be submitted

Contents

Introduction

The World Meteorological Organisation sea ice nomenclature defines an iceberg as a massive piece of ice of varying shape, protruding more than 5 m above sea-level, which may be afloat or aground. It has broken away from a glacier or an ice shelf[1], which is a process known as iceberg calving. This process involves the propagation of fractures which can be triggered by ice stresses, tides, waves, bottom melting and ablation. The calving rate is controlled by the glacier speed, the geometric changes at the terminus region and submarine melting (Rignot et al., 2010; Straneo et al., 2010; Van der Veen, 2002).
The shape and size of the icebergs is determined by formation or deterioration processes. They are subdivided into different categories (see Figure 1 and Table 1).
The drift of icebergs is influenced mainly by ocean currents, winds, the Coriolis force, waves, sea ice (concentration and drift) and bathymetry (by grounding). The acceleration of water entrained in the turbulent wake of the iceberg also has a small influence (Sodhi and El-Tahan, 1980; Smith, 1993). Atmospheric and oceanic forces act on the areas above and below the water line, respectively. Form drag forces act on the vertical plane and surface drag forces act on the horizontal plane of the iceberg. In general, form drag forces dominate surface drag forces. The surface drag forces become the dominant forces if the horizontal surface drag area exceeds about 250 times the sail area of the iceberg (Smith and Banke, 1983). This may occur for ice islands or huge tabular icebergs. Sea ice, if sufficiently packed with strong internal ice stresses, may lock the iceberg and the iceberg then drifts only with the sea ice (Lichey and Hellmer, 2001). Generally, during its drift, the iceberg undergoes strong modification through ablation and melting, depending on the season and the region. The wave erosion, calving of overhanging slabs, lateral melting, basal melting and melting due to solar radiation are the most important iceberg deterioration processes (Kubat et al., 2007).
Iceberg dynamics and thermodynamics are of great interest because they potentially represent

[1]Floating glacier of large dimensions extending beyond the coastline.

Descriptive name	Freeboard height (m)	Length (m)
Growler	< 5	< 5
Bergy Bit	1 - 5	5 - 15
Small Berg	5 - 15	15 - 60
Medium Berg	16 - 45	61 - 120
Large Berg	46 - 75	121 - 200
Very Large Berg	> 75	> 200

Table 1: Iceberg size classification used by the International Ice Patrol.

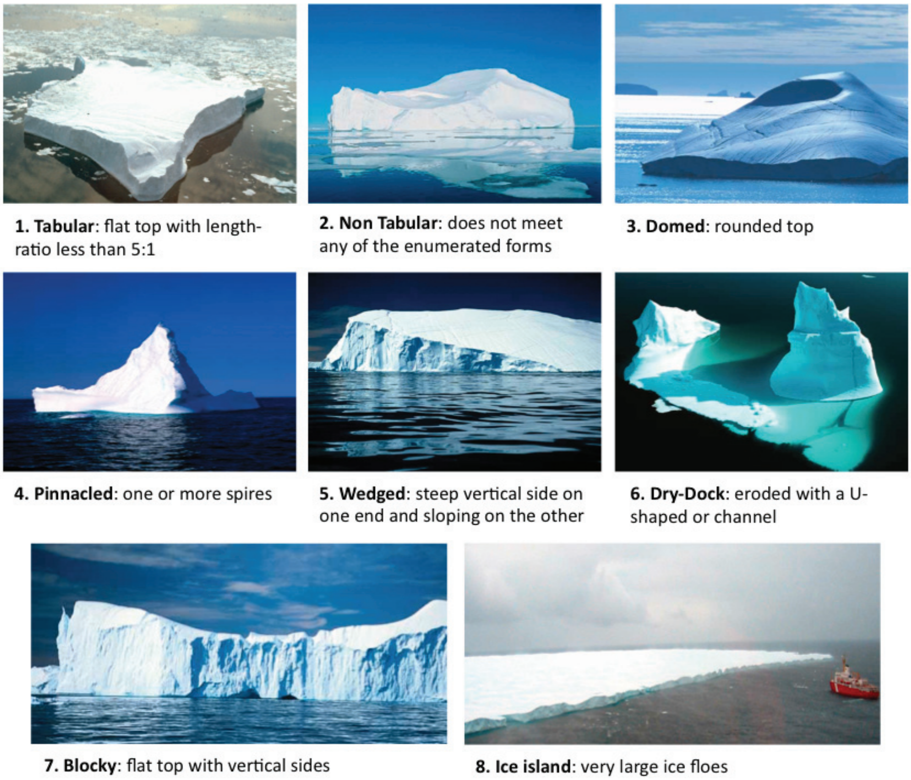

Figure 1: Iceberg shape classification used by the International Ice Patrol. The first seven iceberg pictures are taken from the Canadian Ice Service website (`http://www.ec.gc.ca/glaces-ice/default.asp?lang=En&n=40E178A1-1`, the ice island picture credit goes to Dan Crosbie).

severe marine hazards and impact the ecosystem (Teixidó et al., 2007), the geology (Freiwald et al., 1999) and the hydrography of the world's oceans (Heinrich, 1988; Jansen et al., 2007; Wiersma and Jongma, 2009). They can be dangerous through a collision or via scouring[2] of the ocean floor. The latter process damages deep sea life (Gerdes et al., 2003), offshore installations and reshapes the sea bed (Barnes and Lien, 1988). Icebergs are also a source for marine life: inland ice collects materials during its advance towards the coast. Hence, while melting in the ocean, icebergs provide nutrients for the ocean's euphotic zone (Lichey and Hellmer, 2001). Additionally, they leave sediments and stones on the sea floor that can be used as paleo-climate indicators (Alvarez-Solas et al., 2010; Heinrich, 1988). Finally, they are a source of fresh water for the world's oceans that may impact the ocean circulation (Jansen et al., 2007). When icebergs calve from land into the sea, they furthermore have an impact on the global sea level. West Antarctica and Greenland have experienced recent mass loss acceleration. Since 2003, their contribution to the global annual sea level rise (3.3 ±0.4 mm) has nearly doubled and

[2]Plough marks made by icebergs keels as they pass over sea beds.

represents almost 30% of the total rise (Nicholls and Cazenave, 2010).

Icebergs in the world's oceans

Southern Ocean

The major source of icebergs from the Southern Ocean are the ice shelves that make up to 44% of the Antarctic coastline (Barnes and Lien, 1988). Icebergs from Antarctica are often relatively big tabular icebergs (see Figure 1) with a surface area of several tens of squared kilometres and several hundred meters thick.
They represent about 2000 Gt of glacial ice released each year in the Southern Ocean. It is about four times bigger than the fresh water flux due to basal melting beneath the ice shelves (Jacobs et al., 1992; Jansen et al., 2007). Hence, icebergs may influence the ocean circulation by affecting deep water formation. During their melting, they stabilize the weakly stratified water column. Fresh waters released from deep iceberg bases enhance heat transfer and upwell nutrient-rich waters from below the pycnocline to the surface (Jenkins, 1999; Lichey and Hellmer, 2001). In the late seventies, the potential freshwater source from Antarctic icebergs interested scientists, engineers and entrepreneurs. Two international conferences[3] were held to investigate the feasibility of transporting Antarctic icebergs towards arid regions such as Australia, California or Saudi Arabia. This controversial idea did not materialize but fortunately initiated iceberg modeling studies.
Antarctic icebergs also have a non-negligible impact on waves. A wave forecast model needs to include iceberg distributions to limit the errors in the Southern Ocean. Indeed, Ardhuin et al. (2010) show that iceberg distribution, after wind and sea ice, is an essential component for wave forecast.
Icebergs drifting northward are hazardous for ships off the Cape Horn. They may also be a threat for research and tourist ships operating in Antarctic waters. Their implication in the Southern Ocean circulation and the danger that they represent motivated the development of detection techniques that aim to become systematic.
Antarctic iceberg observations are available through ship or aircraft reconnaissance, GPS buoys (Schodlok et al., 2006) and satellite observations. The National Ice Center (NIC; Washington D.C., USA) systematically tracks icebergs longer than 18.5 km. More recently, Silva and Bigg (2005) presented a method to identify and track icebergs that are only 200 m long using the Synthetic Aperture Radar (SAR). Finally, (Tournadre et al., 2008) demonstrated the capability of radar altimetry to detect icebergs less than 1 km in size. The recent launch of Cryosat 2 by the European Space Agency is expected to strengthen this latter approach.

North Atlantic and Arctic oceans

Icebergs are common in Arctic waters, along the Baffin Bay, the Labrador Coast, and on the Grand Banks of Newfoundland. Icebergs found in the North Atlantic mainly originate from the western and eastern Greenland glaciers. Icebergs found in the "central" Arctic such as in the Beaufort Sea come from Arctic ice shelves. The biggest Arctic ice shelves are located on

[3] Iceberg Utilization for Fresh Water Production, Weather Modification and Other Application, 1977; Conference on use of icebergs, 1980.

Ellesmere Island. Finally icebergs found on the eurasian side of the Arctic come from glaciers located on islands surrounding the Barents Sea. Their initial size varies from growler size (see Table 1) to icebergs 1 km long and over 200 m high. Ice islands can be found in the Beaufort Sea Gyre. Note that on 5 August 2010, a huge ice island, with an area of 270 km^2, detached from Petermann floating ice shelf, north east of Greenland. It is the biggest calving event in the Arctic in nearly 50 years. The Greenland ice sheet is the most important source of icebergs in the northern hemisphere. Its estimated iceberg calving rate is about 200-400 Gt per year (Reeh, 1994; Bigg, Grant R., 1999; Rignot and Kanagaratnam, 2006).

Icebergs near the Atlantic shipping lanes are of greatest concern. International cooperative actions for safety started after the RMS TITANIC collided with an iceberg south of the Grand Banks on 15 April 1912, causing the death of more than 1500 people. Since then, the International Ice Patrol (IIP, `http://www.uscg-iip.org/cms/`) was established. Each year, the IIP reports the position of icebergs and estimates their probable courses. Today, satellite images from RADARSAT-2, reconnaissance flights and ships, and an iceberg forecast model are used to define the southern limit of the iceberg area and to track individual icebergs over the Grand Banks. The iceberg forecast model (Kubat et al., 2005) is developed by the Canadian Ice Service (CIS).

Another area where human activities are expected to increase is the Barents Sea. As this is the focus area of the thesis, its case is presented in more details in the next section.

Scope of the thesis

In recent years, the high north and in particular the Barents Sea has become an important strategic area for Norway. Its policy is intended to protect the environment, assure safety and promote the developments of sustainable exploitation and management of ocean resources, such as the oil and gas industry and fisheries. One of the world's largest natural gas fields, Shtokman Gaz Condensate Field (SGCF), lies south east of the Barents Sea (Figure 2). Pipeline gas production might start in 2016 and will intensify ship traffic. The potential collision with an iceberg represents the highest risk for floating platforms and ground installations, not to mention the additional difficulties associated with the cold environment, such as the presence of sea ice and intense ice frost. For these reasons, there is a need for an adequate iceberg monitoring and forecasting system for the region.

The Barents Sea

Barents Sea icebergs evolve in a region with irregular topography and complicated ocean, sea ice and wind conditions that are challenging to forecast. In the following, an overview of the local iceberg characteristics precedes a description of the climatic context on seasonal and interannual time scales.

The main source of icebergs in the Barents Sea is the Svalbard Archipelago and especially the Austfonna ice cap (Dowdeswell et al., 2008). The Franz Josef Land glaciers and in particular the Renown Glacier on Wilczek Land (Kubyshkin et al., 2006) are among the secondary sources. A smaller contribution of icebergs migrates from glaciers of the northern tip of Novaya Zemlya (Figure 2). Observational campaigns under the Ice Data Acquisition Program (Spring,

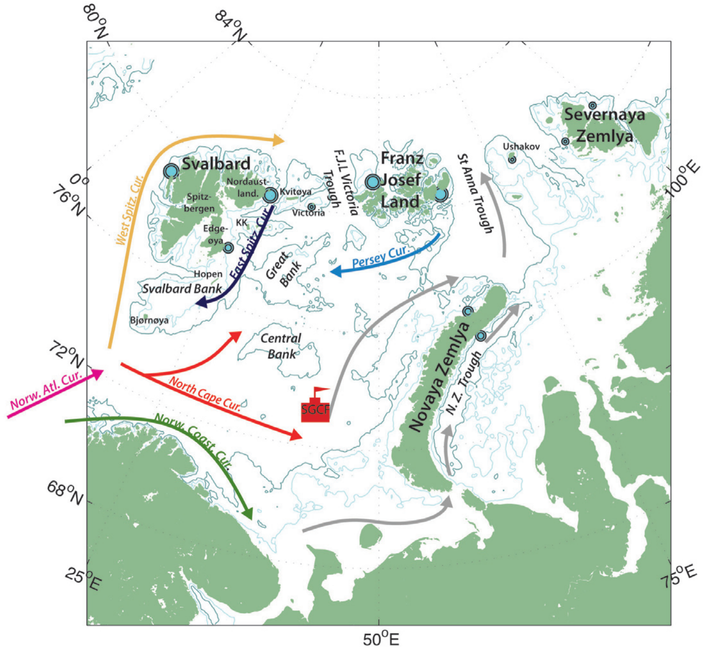

Figure 2: Locations of the different sources of icebergs (filled blue circles) and the main ocean currents. Light and dark blue contour lines are the isobaths at 100 and 200 m respectively. The location of the Shtockman Gaz Condensate Field is identified with the red symbol and abbreviation.

1994, IDAP) from 1988 to 1993 reported that their average and maximum size above the sea surface was: 91 m length $\times$ 64 m width $\times$ 15 m height and 320 m $\times$ 279 m $\times$ 40 m, respectively. Although a great proportion are grounded or melt close to their calving area, icebergs were found as far south as 67.2°N during the summer of 1929 (Abramov and Tunik, 1996) and more recently close to the SGCF, south east of the Barents Sea in May 2003 (Zubakin et al., 2004).

The Barents Sea is a shallow shelf sea, with connections to the Norwegian Sea to the west and the Kara Sea to the east. It is only 230 m deep on average, with deeper trenches up to ~500 m deep and shallow banks of ~100 m deep (Figure 2). Shallow areas such as the Great Bank and Central Bank influence the current patterns. Water mass modification and dense water formation occurs also in shallow areas. For instance, dense water formation by cooling and freezing is most effective on the shelves, Storfjorden and Novaya Zemlya bank (Vinje and Kvambekk, 1991).

The ocean currents distribution is dominated by the presence of Atlantic Water (AW) and the Polar Water (PW). Their junction defines the location of the Barents Sea Polar Front: the dominant large scale feature of the central Barents Sea. The warm and saline AW, coming from the Norwegian Sea, splits into several branches while crossing the western boundary of the Barents Sea. One branch continues northward entering the Arctic Ocean west of Svalbard as the West Spitsbergen Current while another branch enters the Barents Sea as the North Cape Current

(Figure 2). The North Cape Current continues eastward or north-eastward while bifurcating into smaller branches. The position of the Polar Front is closely tied to the topography on the southern flank of Svalbard Bank and the width of the North Cape Current (Johannessen and Foster, 1978; Ingvaldsen, 2005). The latter is strongly modified by cooling, mixing and freezing during winter before entering the Arctic Ocean. In addition to its seasonal variability, its interannual variability is pronounced (Ingvaldsen et al., 2004; Furevik, 2001). The Persey and the East Spitsbergen Currents transport cold PW from Arctic origin southward into the Barents Sea (Pfirman et al., 1994). Tides in that region are among the strongest tides of the entire Arctic Ocean (Kowalik and Proshutinsky, 1993), and play an important role by contributing to the non uniform transformation of water masses. Maximum tidal amplitudes occur close to Spitsbergbanken, Bear Island, Hopen Island and in the White Sea (Kowalik and Proshutinsky, 1995).
Meteorological conditions of the Barents Sea are dominated by cyclones formed in the North Atlantic, which transport heat and moisture from lower latitudes towards the Barents Sea. In winter, close to the polar front, polar lows form with typical wind speeds reaching storm force in a short time. East Siberian Cyclones generate favorable conditions for strong northerly wind anomalies in the Kara and Barents Sea region (Sorteberg and Kvingedal, 2006). In summer the pressure gradients are weaker and the wind direction is more variable.
A large part of sea ice in the Barents Sea is formed locally, generally starting in September/October. It is affected by the salinity of the sea water, topography, wind, currents, sea state conditions, air temperature and the heat flux. The most active places of sea ice formation are on the shelves such as Storfjorden, southeast of Spitsbergen, Novaya Zemlya bank and Franz Josef Land. The annual cycle of the sea ice extent is characterized by a minimum in September and a maximum in April with large interannual variability (Sorteberg and Kvingedal, 2006).

Objectives

The main objective of this thesis is to implement and validate an advanced iceberg drift model for the Barents Sea and use the system to determine characteristics of iceberg distribution on seasonal and interannual time scales. The specific objectives are to:

- Implement an iceberg-sea ice-ocean nested model for the the Barents Sea.
- Analyze and characterize the limitations of the system
- Provide a simulated climatology of iceberg characteristics in the Barents Sea to complement and extend sparse observations from oceanographic fields campaigns, ice reconnaissance flights and satellite observations in the region.
- Find mechanisms controlling the seasonal and interannual variability of iceberg extension and particularly the extreme southernmost extension.
- Improve the predictive skills of the model system by using an advanced data assimilation method in a step towards an operational iceberg drift model for the region.

Methods

Several modeling studies hindcast the drift of icebergs using forcing fields derived from observations (Smith and Banke, 1983; Kubat et al., 2005). Observations of ocean currents and iceberg characteristics in the Barents Sea are largely insufficient to represent their complex dynamics. The lack of data motivated for the set-up of a coupled ice-ocean model to force the iceberg drift model. An ensemble is used to simulate the non-linear properties of iceberg trajectories.

Iceberg model

The dynamics of the iceberg module implemented in this thesis are based on the iceberg drift model introduced by Smith and Banke (1983) and further developed by Lichey and Hellmer (2001).

Dynamics

The iceberg acceleration is proportional to the forces from the atmosphere ($\mathbf{F}_{\mathrm{AT}}$), the water drag ($\mathbf{F}_{\mathrm{W}}$), the Coriolis force ($\mathbf{F}_{\mathrm{C}}$), the force due to the sea surface slope ($\mathbf{F}_{\mathrm{SS}}$) and the force due to interaction with the sea ice cover ($\mathbf{F}_{\mathrm{SI}}$):

$$M\frac{d\mathbf{u}}{dt} = \mathbf{F}_{\mathrm{AT}} + \mathbf{F}_{\mathrm{W}} + \mathbf{F}_{\mathrm{C}} + \mathbf{F}_{\mathrm{SS}} + \mathbf{F}_{\mathrm{SI}}, \tag{1}$$

where M is the iceberg mass and $\mathbf{u}$ is the iceberg velocity. The atmospheric force is

$$\mathbf{F}_{\mathrm{AT}} = \left[\frac{1}{2}(\rho_a c_{\mathrm{a}} A_{\mathrm{va}}) + (\rho_{\mathrm{a}} c_{\mathrm{da}} A_{\mathrm{ha}})\right] |\mathbf{v}_{\mathrm{a}} - \mathbf{u}|(\mathbf{v}_{\mathrm{a}} - \mathbf{u}). \tag{2}$$

The oceanic force $\mathbf{F}_{\mathrm{W}}$ is defined by the same quadratic drag law as $\mathbf{F}_{\mathrm{AT}}$ for each ocean model layer through the depth of the iceberg,

$$\mathbf{F}_{\mathrm{W}} = \sum_{k=1}^{n}\left[\frac{1}{2}(\rho_{\mathrm{w}} c_{\mathrm{w}} A_{\mathrm{vw}}(k))|\mathbf{v}_{\mathrm{w}}(k) - \mathbf{u}|(\mathbf{v}_{\mathrm{w}}(k) - \mathbf{u})\right] + (\rho_w c_{\mathrm{dw}} A_{\mathrm{hw}}(n))|\mathbf{v}_{\mathrm{w}}(n) - \mathbf{u}|(\mathbf{v}_{\mathrm{w}}(n) - \mathbf{u}). \tag{3}$$

In Equations 2 and 3, $\mathbf{v}_{\mathrm{a}}$(resp. $\mathbf{v}_{\mathrm{w}}(k)$) is the air (resp. oceanic) velocity. The index k is the ocean layer number and n is the number of ocean layers in contact with the iceberg. The term A_{va} (resp. $A_{\mathrm{vw}}(k)$) is the vertical cross section area in the air (resp. water). The air and water densities are ρ_{a} and ρ_{w} respectively, c_{a} and c_{w} are the form drag coefficients, c_{da} and c_{dw} are the skin drag coefficients set to 0.0022 and 0.0055 respectively, the same values as used in the sea ice model. A_{ha} (resp. $A_{\mathrm{hw}}(n)$) is the horizontal area of the iceberg in contact with the air (resp. ocean layer n). The wind is assumed to be constant with height above sea level. However, the ocean currents vary with depth as given by the ocean model. Note that the form drag coefficients c_{a} and c_{w} are commonly introduced in the drag forces to account for errors in the estimated area of the vertical plane in contact with the ocean currents and the atmosphere. In addition those parameters include errors in the forcing and the parameterizations. Here, the acceleration of water entrained in the turbulent wake of the iceberg is assumed to be only depending on the mass and is therefore included through an adjustment of the form drags. The effect of wind waves is also included implicitly in the atmospheric forcing through an adjustment of the air form drag coefficient (Paper I & II).
The third force acting on the iceberg is the Coriolis force,

$$\mathbf{F}_{\mathrm{C}} = 2M\Omega(\sin\phi)\mathbf{k} \times \mathbf{u}, \tag{4}$$

where Ω is the angular velocity of the Earth, ϕ is the latitude, $\mathbf{k}$ is the unit vector perpendicular to the Earth's surface and $\mathbf{u}$ the iceberg velocity. The force due to the sea surface slope is,

$$\mathbf{F}_{SS} = -M\mathbf{g}\sin\alpha, \tag{5}$$

where $\mathbf{g}$ is the acceleration due to the gravity and α the tilt of the sea surface slope estimated from the modeled sea surface height. The force due to interaction with sea ice depends non-linearly on the sea ice concentration f, the sea ice strength P, a threshold P_s above which the iceberg moves entirely with the sea ice, and the relative velocity of the iceberg with the sea ice:

$$\mathbf{F}_{\mathrm{SI}} = \begin{cases} 0 & \text{if } f \leq 15\%, \\ -(\mathbf{F}_{\mathrm{AT}} + \mathbf{F}_{\mathrm{W}} + \mathbf{F}_{\mathrm{C}} + \mathbf{F}_{\mathrm{SS}}) + \frac{\mathbf{dv}_{\mathrm{si}}}{dt} & \text{if } f \geq 90\% \text{ and } P \geq P_s, \\ \frac{1}{2}(\rho_{\mathrm{si}} c_{\mathrm{si}} A_{\mathrm{si}})|\mathbf{v}_{\mathrm{si}} - \mathbf{u}|(\mathbf{v}_{\mathrm{si}} - \mathbf{u}) & \text{otherwise,} \end{cases} \tag{6}$$

where c_{si} is the sea ice coefficient of resistance set to one, A_{si} is the product of ice thickness by the iceberg width. The sea ice strength P is a measure of the resistance of sea ice. It is defined by the standard formulation from Hibler (1979),

$$P = P^{*}h\exp(-C(1-f)), \tag{7}$$

where h is the sea ice thickness. The empirical constants P^{*} and C are set to 20000 $\mathrm{N\,m^{-2}}$ and 20. This formulation makes the ice strength strongly dependent on the sea ice concentration, while also allowing the ice to strengthen as the thickness h increases.

Boundary conditions and stability criterion

When an iceberg hits the bottom, it remains stationary until it has either melted sufficiently to drift off or it is transported toward a deeper region by forces stronger than the frictional force. Based on experimental studies defining friction coefficients of a large ice block on a sand or gravel beach from Barker and Timco (2003), we used a static friction coefficient of 0.5 for grounded icebergs. When an iceberg is in a transition mode, moving from a deep region to a region shallower than its immersed part, we used a friction coefficient of 0.35.
The icebergs are allowed to roll over, following the Weeks and Mellor (1978) stability criterion. Note that an iceberg is removed if any of its dimensions above the sea surface are less than 1 m.

Melting parameterizations

Among the mechanisms involved in the deterioration of icebergs, we consider only the most important ones: wave erosion, which is the primary source of melting (White et al. (1980) and Bigg et al. (1997)), lateral melting, and basal melting.
Wave erosion V_{wave} parameterization is taken from Gladstone and Bigg (2001), who incorporated a dependency on the sea-surface temperature (SST) and the sea-ice concentration (m/day):

$$V_{wave} = [\frac{1}{6}(T_{\mathrm{w}}(1) + 2)]S_s[\frac{1}{2}(1 + cos(f^3\pi))], \tag{8}$$

where $T_{\mathrm{w}}(1)$ is the SST, f is the sea-ice concentration, and S_s is the sea state derived from the wind speed. Thus, the wave erosion is damped in presence of sea ice.

Lateral melting $V_{lateral}$ is based on the parameterization of Kubat et al. (2007) over the iceberg draft. The empirical estimate of lateral melt rate (m/day) is:

$$V_{lateral} = \sum_{k=1}^{n} \left[7.62 \times 10^{-3}(\Delta T(k)) + 1.29 \times 10^{-3}(\Delta T(k))^2\right], \tag{9}$$

where $\Delta T(k)$ is the difference between the sea-water temperature and the freezing-point temperature at the k^{th} layer interface. The iceberg draft crosses the layers 1 to n of the ocean model. The estimation of the basal turbulent melting rate V_{basal} (in m/day) follows Weeks and Campbell (1973):

$$V_{basal} = 0.58|\mathbf{v}_{\mathrm{w}}(n) - \mathbf{u}|^{0.8} \times \frac{T_{\mathrm{w}}(n) - T(n)}{L^{0.2}} \tag{10}$$

where $\mathbf{v}_{\mathrm{w}}(n)$ is the water velocity at the iceberg base and $\mathbf{u}$, the iceberg velocity. L is the iceberg length, and $T(n)$ is the iceberg basal temperature. Similar to what it is done for sea-ice model basal-melting parameterizations, $T(n)$ is the local freezing-point temperature at the iceberg base and $T_{\mathrm{w}}(n)$ is the local water temperature at the iceberg base.
Note that thermodynamics are considered only in in Paper II and Paper III.

Wind forcing

The iceberg-ice-ocean system is forced by wind fields from the 40-year European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40) data (Uppala et al., 2005) for Paper I and Paper II with 1.125° grid cell resolution. For Paper III, the atmospheric parameters were taken from ERA-Interim, given on a 0.5° grid-cell resolution (Simmons et al., 2007).

Ocean and sea ice forcing

During the Global Ocean Data Assimilation Experiment (Dombrowsky et al., 2009, GODAE), ocean and sea ice forecasts over the North Atlantic and the Arctic Ocean were produced by the TOPAZ system (Bertino and Lisæter, 2008). Hence, the approach used here was to set-up a nested configuration of the Nansen/Mohn Sverdrup Center version of the Hybrid Coordinate Ocean Model (Bleck, 2002, HYCOM), where TOPAZ gives boundary conditions to a high resolution model (Barents model) covering the Barents and Kara Seas. The sea ice dynamics are based on the elastic-viscous-plastic rheology from Hunke and Dukowicz (1997). Thermodynamic fluxes over open water, ice-covered water and snow-covered ice are given in Drange and Simonsen (1996).
HYCOM has been tested on coastal and shelf ocean areas and found to reproduce the currents, salinities and temperatures well (Winther and Evensen, 2006). The Barents model has a 5 km horizontal grid cell resolution, 22 vertical hybrid layers and includes tides. The local Rossby radius of deformation is about 3 km (Løyning, 2001). As the model resolution is not sufficient to resolve mesoscale activity in the region, residual currents are underestimated. Nevertheless, the model has encouraging skills as shown in the KARBIAC project with a similar version (Bertino et al., 2007). For each study, the ocean sea ice model is forced by the same wind forcing as the iceberg model.

Validation data

For calibration and validation of iceberg drift, we used a dataset deployed during IDAP experiment (Spring, 1994). Icebergs from which information on their initial size was missing as well as those grounded during most of their recorded drift were excluded. Finally, we focused on data from 1990 where the time-averaged influence of the atmosphere and the ocean currents seemed to be the strongest, and thus most appropriate for model parameterization.

Data assimilation method

The data assimilation method used in this thesis is the Ensemble Kalman Filter (Evensen, 2009, EnKF). It is based on a Monte Carlo technique where error statistics are calculated from an ensemble of model states. It provides a spatial and temporal varying error covariance matrix which evolves according to model dynamics. It also allows for multivariate updates, and thus for the estimation of non-observed model parameters.

Summaries of papers

Paper I: Parameterization of an iceberg drift model in the Barents Sea

Paper I addresses the problem of parameter estimation to limit the errors in an ice-ocean-iceberg drift model for the Barents Sea. The system is forced by the ERA40 atmospheric reanalysis data from ECMWF and ocean and sea ice variables are from a nested configuration of HYCOM described in the previous section. The parameterization is tested and validated using four observed iceberg trajectories northwest of the Barents Sea from April to July 1990 (Spring, 1994). The model accuracy relies mainly on the quality of its forcing and the knowledge of the initial iceberg form and mass.

In the first part of the study, a measure of the sensitivity of the model to uncertainties in the mass of the iceberg and the forcing is given by jointly varying the iceberg mass and the form drag coefficients. As the iceberg mass increases, the optimal form drag coefficients increase linearly. A balance between the drag forces and the Coriolis force explains this behavior. It suggest that an optimal trajectory can be obtained by perturbing only the ocean and atmospheric form drags. The ratio between the optimal oceanic and atmospheric form drag coefficients is similar in all experiments, although there are large uncertainties on the iceberg geometries and errors in the forcing.

The second part of the study focuses on the impact of sea ice parameterization for the iceberg drift. Following Lichey and Hellmer (2001), there is a threshold value for the sea ice concentration and the sea ice strength from which the iceberg is moving entirely with the sea ice. We perturbed the threshold value of the sea ice strength, but the sea ice conditions East of Svalbard in winter 1990 were such that they exhibit no sensitivity.

Using optimal parameter values, the average distance from observation is: less than 20 km after two months of drift for the northernmost icebergs and less than 25 km after the first month and increasing rapidly to over 70 km thereafter for the two southernmost icebergs.

ERRATUM on Paper I publication

The Equation 6 presents a typographic error. The atmospheric force is written as $\mathbf{F}_{\mathrm{A}}$ while it should be $\mathbf{F}_{\mathrm{AT}}$.
The estimated iceberg masses are 10 times bigger than the values specified in the Table 1.

Paper II: Modeling dynamics and thermodynamics of icebergs in the Barents Sea from 1987 to 2005

A modeling study of iceberg drift characteristics in the Barents and Kara Seas based on a 19-year simulation is presented. In addition to the dynamics presented in Paper I, the effects of wave erosion, basal melting and lateral melting are included. An additional frictional term is also introduced in order to better simulate iceberg grounding, and the iceberg is allowed to roll over if it becomes unstable. Based on the estimates of iceberg production given by Dowdeswell et al. (2002), Hagen et al. (2003), Kubyshkin et al. (2006) and Dowdeswell et al. (2008), we define 11 calving sites representing the iceberg production per region. Initial iceberg sizes are generated randomly with a log-normal distribution following statistics on iceberg length width and height obtained during the 1988-1993 IDAP campaign (Spring, 1994). Seasonal variability of the calving rate is neglected despite indications of increased release from June through September (Kubyshkin et al., 2006), allowing an independent evaluation of the seasonal influence of the ocean currents, wind and sea ice on the iceberg characteristics and drift. Every day, icebergs are released according to a Poisson process, guarantying the independence of each calving event and a control on the average rate. The simulation starts in July 1985 and ends in December 2005. The first 1.5 years of the simulation are not used to allow sufficient time for the model to spin up.
Satistics of iceberg characteristics as a function of their origin are investigated. Maps of iceberg density and grounding locations complement sparse existing oceanographic and aerial field survey campaigns. Model results compare qualitatively well to the observations (Abramov and Tunik, 1996) and suggest preferential pathways and extensions from simulated calving sources. For example, icebergs originating from Franz Josef Land have the largest spread over the domain.
Moreover the simulations show a seasonal cycle of the southernmost extent of the icebergs, even though the seasonality of the calving was not considered. Icebergs released in summer have the largest spreading. Hence, we suspect that introducing seasonal variability in the calving rate would intensify this latter pattern.
The interannual variability of the iceberg spread is analysed jointly with the iceberg extent. The latter shows a strong interannual variability. It is found that atmospheric forcing drives the extension of iceberg similarly to the sea ice extent (Sorteberg and Kvingedal, 2006). Anomalous northerly winds enhance the southward iceberg extension. They also produce a positive but delayed impact on the iceberg extent by limiting the inflow of Atlantic Water into the Barents Sea therefore reducing the heat content the following year and increasing the mean age of icebergs and thus their potential extension. This demonstrates that the thermodynamics also play an important role.
Finally, confidence in the system is reinforced as the model reproduces the observed extreme iceberg extension event, southeast of the Barents Sea in May 2003.

Paper III: Adaptive estimation of iceberg parameters using the Ensemble Kalman Filter

Paper I showed the ability of the model to reproduce iceberg drifts successfully, using optimal form drag coefficients. However, the model error grows in time due to inherent errors in the forcing, initial conditions and model parameterization. In this paper, we attempt to limit the error growth by correcting the icebergs position once per day using data assimilation. Such problem is non linear and requires advanced statistical methods.
In addition we intend to improve on the limitations regarding the estimate of the form drag coefficients in Paper I. First, the optimal values were estimated by minimizing the distance over the whole trajectory, although these parameters are expected to evolve with time due to the change in the shape of the iceberg. Second, the method employed was a classical Monte-Carlo approach with a regular sampling of initial parameters, which is computationally costly. The Ensemble Kalman Filter is an efficient data assimilation method based on Monte-Carlo that allows for multivariate update. Thus, the method corrects the position and gives the possibility to estimate non-observed parameters at a given time.
The system is composed of the iceberg drift model used in Paper II but the atmospheric forcing is updated to ERA-interim, the latest reanalysis product from ECMWF with 0.5° resolution. Observed trajectories of four icebergs from 1990, registered during the IDAP campaign (Spring, 1994), were assimilated in the model. The two northernmost simulated trajectories have a precision of 15 km and the two southernmost ones have a precision better than 25 km over the two months of drift. An analysis of the estimated form drag coefficients allows us to identify whether the shape was correct and when the forcing fields were failing.

Conclusions

This thesis has shown that a coupled ocean-sea ice-iceberg drift model system is able to describe physical processes, icebergs characteristics and trajectories in the Barents Sea. Its limitations were emphasized and the following conclusions are obtained:

- The proposed nested configuration has reasonably good prediction skills through the optimization of the iceberg mass and the ocean and atmospheric form drag coefficients. The best members reproduce observed iceberg trajectories for at least one month of drift with a precision better than 25 km.

- A 19 years simulation of iceberg trajectories in the Barents Sea complement and extend iceberg information from satellites and oceanographic and aerial field campaigns. Potential grounding location and preferential pathways from each of the principal calving sources are suggested.

- There is a seasonal variation of iceberg density in the Barents Sea, although the calving rate was set to be constant throughout the year.

- The interannual variability of the iceberg extent is strong and highly correlated with the sea ice area. This variability can be explained by two main mechanisms:

  - Northerly winds are the principal factor enhancing iceberg extent: higher than normal atmospheric mean sea level pressure over Svalbard region favors large iceberg extent.
  - Northerly winds also have a positive but delayed impact on the iceberg extent that shows the importance of the thermodynamics. They limit the inflow of Atlantic Water into the Barents Sea and therefore reduces the heat content during the following year, increasing the mean age of icebergs and thus their potential extension.

- The model is able to reproduce the extreme southernmost coverage of icebergs south east of the Barents Sea observed in May 2003.

- Part of the model errors can be compensated for by using the Ensemble Kalman Filter towards a pre-operational system for the region. It is shown that data assimilation clearly improves the prediction and has the advantage to give an estimation unknown model parameters.

- From the latter, we can also deduct information on the error in the iceberg mass and the forcing fields.

Outlook

The primary results have shown encouraging skills for the prediction of iceberg drift in the Barents Sea. The Barents Sea model is part of the operational TOPAZ system. The latter has undergone a significant upgrade in 2010, especially in the sea ice model formulation and in the data assimilation setup. It led to improvements both in the North Atlantic and in the high resolution Fram Strait model. In particular, the sea ice front is better described, and the heat balance is better represented. One can expect a better prediction in the Barents Sea model with a similar upgrade. Hence, those improvements are expected to be significant, especially for the thermodynamic part of the iceberg model.
In addition the latest version of the HYCOM model performs approximately twice as fast as the former one. It implies that running the model configuration with double resolution (~2.5 km, i.e. eddy permitting) can be achieved at a four times the computational cost of the current model version. This model upgrade would impact the iceberg dynamics. Running an eddy resolving model operationally (~ 750 m horizontal grid cell resolution) is today still out of reach for such a large domain.
Forecasting capabilities can be improved by including data assimilation in the ocean model. EnKF is advised for assimilation of sea ice concentration (Lisæter et al., 2003), but too costly to be applied in a regional model. Nevertheless, sea surface temperature could be assimilated using Ensemble Optimal Interpolation, a method that has yielded good results in regional models (Evensen, 2003), and is computationally less expensive.
The effect of waves can be important on icebergs. In the current model implementation, the wave drag is included implicitly through the atmospheric drag force. The Barents Sea is a small and relatively closed basin. It is unclear how important swells are compared to the wind sea. Nevertheless, separating wave drag from atmospheric form drag may give more precision in the sources of errors and would help to give a more precise parameterization. Some icebergs are large enough to feel ocean swell since the swell wavelength is on the order of the iceberg

lateral dimensions (~100-300 m). It is a point to consider in future studies, which would involve wave input from a wave model. With realistic wave information, the wave erosion could include calving process as suggested by Kubat et al. (2007).
Despite the model improvement, the forcing fields are not perfect. An approach to complement information from the forcing fields is to perturb them randomly. Such a perturbation would account for errors in the wind and ocean current direction as well as intensity. It would be easier to relate the evolution of the form drag parameters to the change in the iceberg shape.
A more advanced but computationally more costly approach is to use forcing from an ensemble run: for example, ensemble runs from the TOPAZ and ECMWF systems into a high resolution Ensemble Barents Sea system. The TOPAZ system provides a 10 days forecast of ocean and sea ice parameters using ECMWF 10 days forecast of atmospheric fields for the North Atlantic and Arctic Ocean. Hence, based on the approach described in Paper III, it is possible to provide a forecasting system of iceberg trajectory 10 days ahead.

Figure 3: Iceberg north of Kangerlussuaq fjord. Håkon Mosby cruise, September 2007.

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