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Wind impact on sea ice motion in the Arctic

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Abstract

In order to examine how the wind at 10 m above the surface influences the sea ice motion in the Arctic Ocean, a correlation coefficient between wind and ice drift, an angle between wind direction and ice velocity and a reduction factor of the ice speed relative to the wind speed were calculated, using statistical methods. This was done on a 10 km by 10 km grid, for both winter, January to March, and summer, July to September, with data from 2014 and 2015. The ice displacement data originated from satellite measurements and the wind velocity data were obtained from a reanalysis made by the European Centre for Medium-Range Weather Forecasts.

It was found that the correlation coefficient, that is the fraction of the ice motion that is caused by the wind, was higher in the winter (up to 90 %) than in the summer (up to 70 %). The correlation coefficient, as well as the speed reduction factor, was larger in areas not near any coasts, and where the sea ice concentration is not 100 %. The ice movement was directed to the right of the wind velocity in most parts of the Arctic Ocean.

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1 Introduction

1.1 Role of sea ice in the climate system and society

The global climate system and the way it is changing are international issues of great importance for every part of society, from individuals to industry. A key part of understanding the climate system is the variation of ice cover in the polar regions and how this influences the interaction between the ocean and the atmosphere. The amount of ocean surface covered with ice determines the heat exchange rate between the ocean and the air (Leppäranta 2005). The heat exchange, in turn, plays an important role in the global climate, and the movement of the ice influences the heat exchange.

Drifting ice may be transported large distances, from the ice-covered area where it was formed to southerly located areas without the right environment for ice sheets to form. The latent heat and the amount of fresh water, locally changing the salinity, that the drifting and melting ice contributes with is comparable to heavy precipitation (Leppäranta 2005). Thus, the drifting ice has to be considered in the field of Arctic Oceanography and weather forecasting. Additionally, while being transported, the ice may carry pollutants far away from the source. Atmospheric fallouts from the air as well as pollutants from the ocean and the sea bottom accumulate within the ice as it is formed and are then transported with the ice (Leppäranta 2005). Drifting ice may also exacerbate the effect of an oil spill accident, as the oil is both pulled by the ice and transported with it (Leppäranta 2005).

Ships travelling in the Arctic region have always encountered difficulties with ice, especially in the winter. The drift of sea ice does not only influence the extent of the stationary ice, but also the leads, that is, the channels of open water through ice covered areas (Leppäranta 2005). Knowledge about the current ice extent and expected paths of drifting ice is therefore essential for shipping in this region. The configuration of the ice may change very fast, and therefore forecasts for the ice cover and ice drift are made every day based on models (Leppäranta 2005). Further knowledge about how wind and ice drift are related enables the improvement of these models.

1.2 Previous studies on sea ice and wind

Previous studies on the impact of wind on ice drift include Hibler (1979), McPhee (1980), Thorndike and Colony (1982), Steele et al. (1997) and Kimura and Wakatsuchi (2000). Two of the, for this work, most relevant studies are described below.

In the light of a rule of thumb that the ice moves with a certain angle to the right of the wind, and that the ice speed is a certain fraction of the wind speed, Thorndike and Colony (1982) studied the relationship between ice motion and the geostrophic wind at 10 m above the surface with ice drift data and pressure data from buoys and wind data calculated from the pressure gradient. The 10 m geostrophic wind consists of the component of the actual 10 m wind that is parallel to the isobars, and is thus easy to derive from the pressure field. Thorndike and Colony (1982) found that, on the long term scale, when calculating the mean of several months, about half of the ice motion is influenced by the geostrophic wind while the other half is controlled by the ocean currents. On shorter time scales however, at least 70% of the motion was explained by the geostrophic wind. Thorndike and Colony (1982) also state that the geostrophic wind is less influential in coastal regions, up to 400 km from the coast. They also discovered a seasonal variation in the relationship. In the summer there was a higher correlation between ice drift and geostrophic wind than in the winter, 80 % in summer compared to 75 % in winter (at more than 400 km from the coast).

In another study, Kimura and Wakatsuchi (2000) studied the ice motion-wind correlation with data from 1991 to 1998, December to April, using satellite-derived ice drift data instead of buoys. They obtained the ice motion data from the Defence Meteorological Sensor Satellite Program (DMSP) Special Sensor Microwave Imager (SSM/I), which is satellite data that is independent of weather conditions. Kimura and Wakatsuchi confirmed that ice drift and geostrophic wind are correlated to a large extent, except in areas near the coast. Additionally, they found that the speed reduction factor, which corresponds to the ratio between wind and ice speed, is smaller (about 0.8 %) in the interior of the Arctic than in the seasonal ice zones (about 2 %). The results by Kimura and Wakatsuchi could have been more accurate if satellite images with a higher resolution than what was available at that time had been studied.

1.3 Aim

The purpose of this Bachelor thesis is to investigate how ice motion and 10 m wind are related in the Arctic sea, taking spatial variations into account. This includes finding the following information for different positions in the Arctic:

1. The correlation coefficient, describing the fraction of the ice motion that is caused by the wind
2. The turning angle, the angle between the direction of ice motion and the direction of the wind
3. The speed reduction factor, the ratio between the ice speed and the wind speed

A comparison between winter and summer, with respect to the parameters above, is done. The model used is the same as the one both Thorndike and Colony (1982) and Kimura and Wakatsuchi (2000) used, enabling more detailed comparisons. Since the satellite data in this work is of higher quality than the data that Kimura and Wakatsuchi used, there is a possibility to obtain improved and more accurate results. A statistical analysis is made and the relationship is examined for the first and third quarter of the year (summer and winter). The result is presented on maps.

2 Theory

2.1 Ice dynamics

Leppäranta (2005) describes the momentum equation of sea ice. From Newton's second law, a three-dimensional momentum equation can be directly derived. The equation of motion of sea ice on a sea surface is obtained by integrating the three-dimensional momentum equation through the vertical thickness of the ice. Hibler (1979) uses the form:

$$m\frac{D\mathbf{U}}{Dt} = \nabla \cdot \boldsymbol{\sigma} + \boldsymbol{\tau_a} + \boldsymbol{\tau_w} - \mathbf{k} \times mf\mathbf{U} - mg\nabla H_0 \tag{1}$$

where m is the ice mass per unit area, $\mathbf{U}$ is the ice velocity, $\boldsymbol{\sigma}$ the internal stress tensor, $\boldsymbol{\tau_a}$ is the air stress, $\boldsymbol{\tau_w}$ is the water stress, $\mathbf{k}$ is the unit vector that is perpendicular to the surface, f is the Coriolis parameter, g is the gravitational acceleration and H_0 the sea surface dynamic height.

If constant turning angles are assumed, the air and water stress can be written:

$$\boldsymbol{\tau_a} = \boldsymbol{\rho_a C_a} \left|\boldsymbol{u_a}\right| (\boldsymbol{u_a} cos\theta + \boldsymbol{k} \times \boldsymbol{u_a} sin\theta) \tag{2}$$

$$\boldsymbol{\tau_w} = \boldsymbol{\rho_w C_w} \left|\boldsymbol{u_w} - \boldsymbol{U}\right| [(\boldsymbol{u_w} - \boldsymbol{U}) cos\phi + \boldsymbol{k} \times (\boldsymbol{u_w} - \boldsymbol{U}) sin\phi] \tag{3}$$

where $\boldsymbol{\rho_a}$ and $\boldsymbol{\rho_w}$ are air and water densities, $\boldsymbol{C_a}$ and $\boldsymbol{C_w}$ air and water drag coefficients, $\boldsymbol{u_a}$ and $\boldsymbol{u_w}$ are the wind velocity and the ocean current and $\boldsymbol{\theta}$ and $\boldsymbol{\phi}$ are the air and water turning angles.

The internal stress is caused by interaction between ice floes and has a damping effect on the ice momentum. Internal stress is dependent on rheology, the material properties of the ice that determine how it reacts to stress forces, and the strength of the ice (Wadhams 2000). The larger the ice strength, the larger the internal stress. The strength of the ice, in turn, is a function of ice thickness and concentration. An empirical formula for the ice strength is used by Hunke et al. (2015):

$$P = P' h_{ice} e^{-C(1-A)} \tag{4}$$

with the empirical constants $P' = 27500 N/m$ and $C = 20$, and where h_{ice} is the thickness of the ice and A is the ice concentration. Thus, an increase in ice concentration, as well as an increase in thickness, increase the internal stress.

2.2 Model and calculations

The model that was used is the same as Thorndike and Colony (1982) and Kimura and Wakatsuchi (2000) used. This model relates the ice velocity to the wind velocity via a turning angle and a speed reduction factor. All remaining factors that influence the sea ice motion, such as ocean current, internal stress, the Coriolis force and sea surface tilt, are included in a separate term, which in the following sections is called calculated current.

$$\begin{bmatrix} U \\ V \end{bmatrix} = F \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} u \\ v \end{bmatrix} + \begin{bmatrix} c_u \\ c_v \end{bmatrix} \tag{5}$$

Here, (U, V) denotes the ice velocity, F the speed reduction factor, θ the turning angle, (u, v) the wind velocity and (c_u, c_v) the ocean current. F is a measure of the proportion between the wind speed and the ice speed. F, θ and (c_u, c_v) are assumed to be constant during a period of three months, in a grid box of the size 10 by 10 km. They are calculated with the following equations, which are directly adapted from Kimura and Wakatsuchi (2000) and are based on a least squares technique.

$$\theta = arctan\left[\frac{\Sigma u_{di} V_{di} - \Sigma v_{di} U_{di}}{\Sigma u_{di} U_{di} - \Sigma v_{di} V_{di}}\right] \tag{6}$$

$$F = \frac{c_1 + c_2 - c_3 + c_4}{\Sigma u_{di}^2 + \Sigma v_{di}^2} \quad (7)$$

where

$$c_1 = cos\theta \Sigma u_{di} U_{di}, \qquad c_2 = sin\theta \Sigma v_{di} U_{di},$$
$$c_3 = sin\theta \Sigma u_{di} V_{di}, \qquad c_4 = cos\theta \Sigma v_{di} V_{di},$$

$u_{di} = u_i - \overline{u}$, $v_{di} = v_i - \overline{v}$, $U_{di} = U_i - \overline{U}$ and $V_{di} = V_i - \overline{V}$. The sums are calculated over all measurements made in one grid box (10 by 10 km) during either winter or summer, in both 2014 and 2015. The current is calculated by

$$\begin{bmatrix} c_u \\ c_v \end{bmatrix} = \begin{bmatrix} \overline{U} \\ \overline{V} \end{bmatrix} - F \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} \overline{u} \\ \overline{v} \end{bmatrix} \quad (8)$$

Also, a correlation coefficient r is given by

$$r = \frac{c_1 + c_2 - c_3 + c_4}{\sqrt{\Sigma u_{di}^2 + \Sigma v_{di}^2}\sqrt{\Sigma U_{di}^2 + \Sigma V_{di}^2}} \quad (9)$$

A high correlation coefficient means that the influence of the wind on the ice is large compared to the influence from other factors.

2.3 Ice amounts and geographical circumstances

The data that is studied in this Bachelor project mainly covers the Arctic Ocean north of Greenland and north of Svalbard. For the winter, a larger area, including the sea outside the east coast of Greenland and the Kara Sea, is studied. The topography and bathymetry of the Arctic is shown in Appendix A. The Arctic Ocean is surrounded by land masses and has few passages to other seas. The large shelves north of Russia contribute to the Arctic Ocean having a small mean depth compared to other oceans (Wadhams 2000).

The general circulation, averaged over a long time, of the surface water in the Arctic Ocean is characterized by the strong Transpolar Drift Stream, which runs from the Eurasian shelves to the Fram Strait, where the current is called East Greenland current (Wadhams 2000) (see Figure 1). Most of the ice that leaves the Arctic basin goes through the Fram Strait. The Beaufort Gyre is a large circular current in the Canada Basin that turns anticyclonic, clockwise.

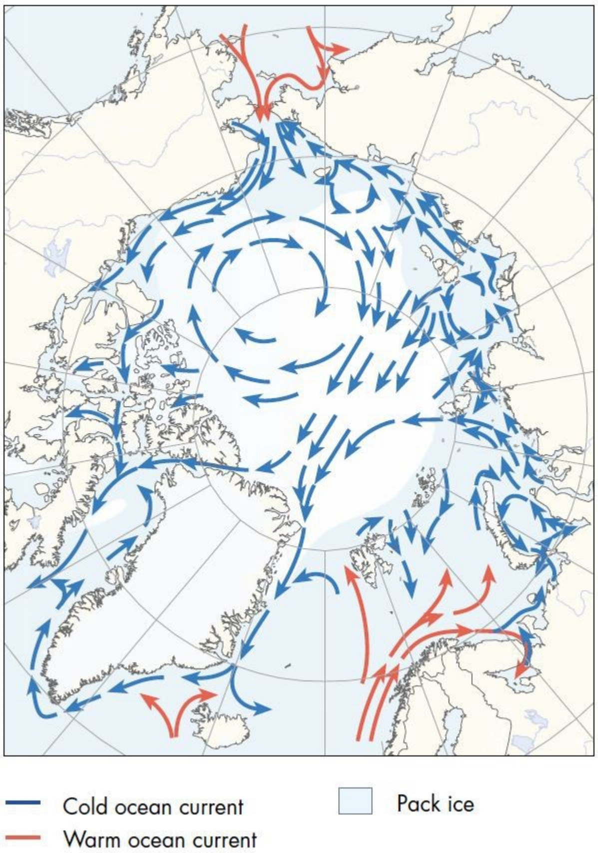

Figure 1: Currents in the Arctic region. (Arctic Council 2001)

The monthly sea ice extent for many years, in the Arctic region, has been compiled from satellite measurements by NSDIC (2016). They define "sea ice extent" as the area which is at least 15 % covered by ice. The largest sea ice extent occurs in March for both 2014 and 2015. In this month, there is ice present in the Arctic Ocean, Hudson Bay, the Baffin Bay, the Canadian archipelago, the Kara Sea and the Bering Straight as well as along the east coast of Russia and the east coast of Greenland. The month with the smallest sea ice extent is, for 2014 and 2015, September. The ice covers a large part of the Arctic Sea, some parts of the Canadian archipelago and the north coast of Greenland.

NSDIC (2016) also measured the monthly concentration, which is the percentage of an area that is covered by sea ice. In the winter, January to March, in 2014 and 2015, a large part of the area within the sea ice extent has a sea ice concentration near 100 %. Areas which do not have a concentration near 100 % include north-east of Greenland, around Svalbard and Franz Josef Land and east of Greenland. In the summer, from July to September, there is no area entirely covered with sea ice. The least concentration is found in the southern parts of the ice extent.

The thickness distribution in the Arctic has been measured by the satellite CryoSat and presented by CPOM (2016). They provide thickness maps for spring (March and April) and autumn (October and November) for each year from 2011 to 2014. Due to high uncertainty in absolute thickness, only a relative thickness distribution is presented here.

Although the thickness distribution varies significantly from year to year, there are some features that occur in each of the years presented by CPOM. These features are likely to apply for 2015 as well. Something that applies for every year is that, during spring, the thickest ice was found north of the Canadian archipelago and north-west of Greenland. The same area contains thick ice in the autumn as well, but to a smaller extent, and it is only in 2013 and 2014 that some of the ice reaches about the same thickness as in spring. The area north-east of Greenland and north of Svalbard contained sea ice of varying thickness in both seasons, but the ice is thinner than north-west of Greenland. The area between Svalbard and Franz Josef Land is, in spring, near the edge of the ice extent and contains ice that is relatively thin, compared to previous mentioned areas. In the autumn, this area is, in most years, free from ice.

Overall, the ice is thicker during spring than during autumn. The ice in the Kara Sea, in spring, was on the whole thicker than between Svalbard and Franz Josef Land, but significantly thinner than north-west of Greenland. The sea ice thickness along the east coast of Greenland had a larger variation from year to year during autumn than during spring, and was generally slightly thinner during autumn.

3 Data

Ice data

The ice movement was derived from satellite measurements from a Synthetic aperture radar (SAR). Until December 15th 2014, the measurements were made by the Radarsat2 satellite. After that, the Sentinel 1A satellite was used (Saldo 2015). The measurements were made about once a day during 2014 and 2015. From these measurements a start and an end position of the ice were derived, with algorithms that use area-based tracking of the ice. This means that the pattern in the first image is searched for in the subsequent image, using 2-dimensional digital cross correlation of the image intensities. Data is only created when an area can be recognized with sufficient certainty. These algorithms are described in Kwok et al. (1990).

The number of measurements from the satellite data varies over the Arctic. Many measurements are made north of Greenland. This area contains ice during the whole year, and is therefore suitable for comparison between different seasons. In February 2015, for example, there is a large area north of Greenland where there are 200-350 data points per 100 km^2 while in other areas there are less than 50 or no data points at all. The orbit of the satellites causes fewer measurements in southern regions than in northern. An ice displacement was calculated for approximately every 10 km.

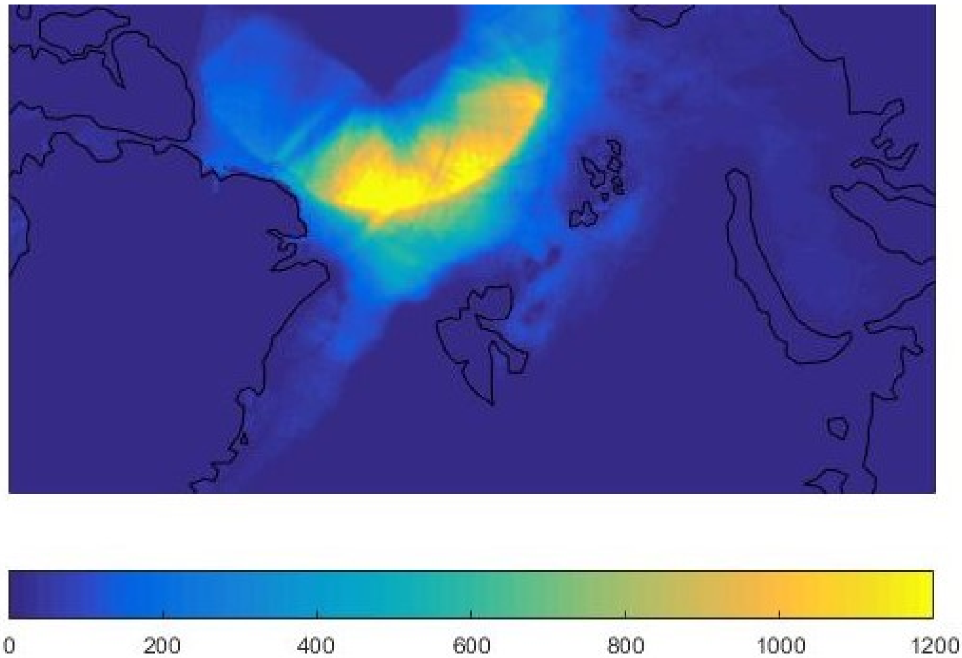

Figure 2: The total number of data points during the winters (January to March) 2014 and 2015

DTU (2016) has made a validation of the data by analysing the correlation between the satellite ice data and measurements from drifting buoys, which can be considered as reference data points. For most quarters in 2014 and 2015 the correlation coefficient is 0.99 or 1.00. In the first quarter of 2014 however, the buoy "itp48" has correlation coefficient 0.69, and in the third quarter of 2015, another buoy, "itp74", has correlation coefficient -0.57. The large difference between these correlation values and those from the rest of the buoys suggests that the later values have been disturbed by external factors, so that the ice and buoy motions are not comparable. An additional quality evaluation is made in the present work and presented together with the results in Section 5.2.

The ice drift data that was used in this project contains start time, start position in latitude and longitude, end time and end position.

Wind data

The wind data was obtained from the ERA-Interim reanalysis from ECMWF (2016). In a reanalysis, measurements from many different sources are combined. Measurements in the Arctic include ship synoptic observations, drifting buoys and satellite measurements (ECMWF 2010). To create the datasets, the wind is calculated every 12th hour from measurements of other parameters. A model is run to obtain wind data every third hour. The data has a spatial resolution of about 80 km, which is eight times larger than the ice data. For weather situations with weak wind gradients, the wind data resolves the actual wind pattern well, but phenomena on smaller scale, with large wind gradients, may not be resolved by the data. Such phenomena are for example deep low pressures. The wind velocity is the wind at 10 m above the surface.

4 Method

In order to relate wind to ice drift, a mean wind velocity for the period during which the ice displacement was measured, in the area where the ice was moving, had to be calculated for each ice data point. This was done by first finding the wind measurement that was spatially nearest the mid point of the ice path, and for that wind measurement calculating the mean velocity by linear interpolation in time. Also, the average ice velocity for each ice measurement was calculated from the starting and ending position together with the time difference.

After this, each ice data point was related to a box in a spatial grid. The grid was made on a polar stereographic projection and each grid box was 10 by 10 km. The coordinates, x and y, in the projection were transformed from latitude and longitude using Equations 10 and 11, adopted from Snyder (1984). The approximation that the Earth is spherical is used. However, this approximation only impacts the size of the grid boxes.

$$x = 2Rk_0 tan(\pi/4 - \phi/2) sin(\lambda - \lambda_0) \tag{10}$$

$$y = -2Rk_0 tan(\pi/4 - \phi/2) cos(\lambda - \lambda_0) \tag{11}$$

where R is the earth radius, k_0 is a scale factor, ϕ is the latitude, λ is the longitude and λ_0 is the central meridian, used to set the middle of the projection. λ_0 was set to 90°.

For every grid box the turning angle θ, the speed reduction factor F, the mean ocean current and the correlation coefficient r were calculated using Equations 6 to 9. At first, the variables were calculated for one month, but, since many grid boxes had too few data points, a pattern was difficult to detect in all regions except north of Greenland, where there are many measurements. To obtain more accurate results in a larger region, and to enable a better comparison with the study by Kimura and Wakatsuchi (2000), the variables were instead calculated for every quarter of the year.

In order to plot the calculated variables on a map, the x- and y-coordinates had to be transformed back into latitude and longitude. This was done by the following equations, which are also adopted from Snyder (1984).

$$\phi = arcsin(cos\, c\, sin\phi_1 + (y\, sin\, c\, cos\, \phi_1/\rho)) \tag{12}$$

$$\begin{cases} \lambda = \lambda_0 + arctan(x/-y) & y < 0 \\ \lambda = \lambda_0 + arctan(x/-y) + 180° & y \geq 0 \end{cases} \tag{13}$$

Here, $c = 2\, arctan(\rho/(2R))$ and $\rho = \sqrt{x^2 + y^2}$.

To obtain a high-quality result, grid boxes with less than 10 observations were not plotted. The limit of 10 data points was set using visual argumentation; a lower limit gives rise to discontinuity in the plotted values, while a higher limit reduces the area that is evaluated. Moreover, in order to obtain a comprehensive result, each box has to contain wind velocities with different directions. This is because the impact from the wind may be influenced by the wind direction. The essential parts of the MATLAB-code that was written for this work can be found in Appendices B to E.

5 Results

This section presents the mean winds and ice motions as well as the obtained turning angle, correlation, speed reduction factor and calculated current. An analysis and discussion of the result follows in the next section. Due to the orbit of the satellites, there is a circular area at the North Pole where no measurements were made, and that is not analysed in this study. The geographical names of the different parts of the Arctic Ocean are presented in Appendix A.

5.1 Wind

In the winter, typical values for the wind speed north of Greenland are 4 to 6 m/s (see Figure 3). Stronger mean winds are found east of Franz Josef Land, between 5 and 7 m/s. The average wind direction in the Arctic Ocean is from the east. In the northern parts of the Kara Sea, the winds are generally also between 5 and 7 m/s, while the winds in the southern part are weaker.

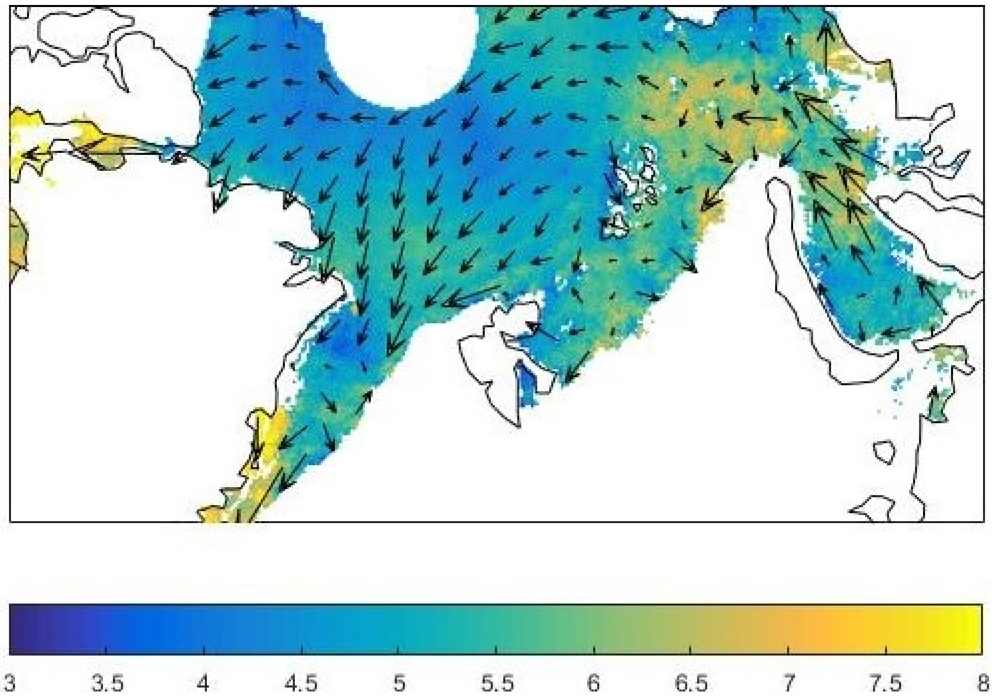

Figure 3: The winter (January to March) mean wind in m/s

In the summer, the mean wind speed in the area that was studied is between 3 and 5 m/s (see Figure 4). North of Greenland, it is between 3 and 4 m/s. The average direction of the wind is southwards, from the North Pole, towards Greenland, Svalbard or Franz Josef Land.

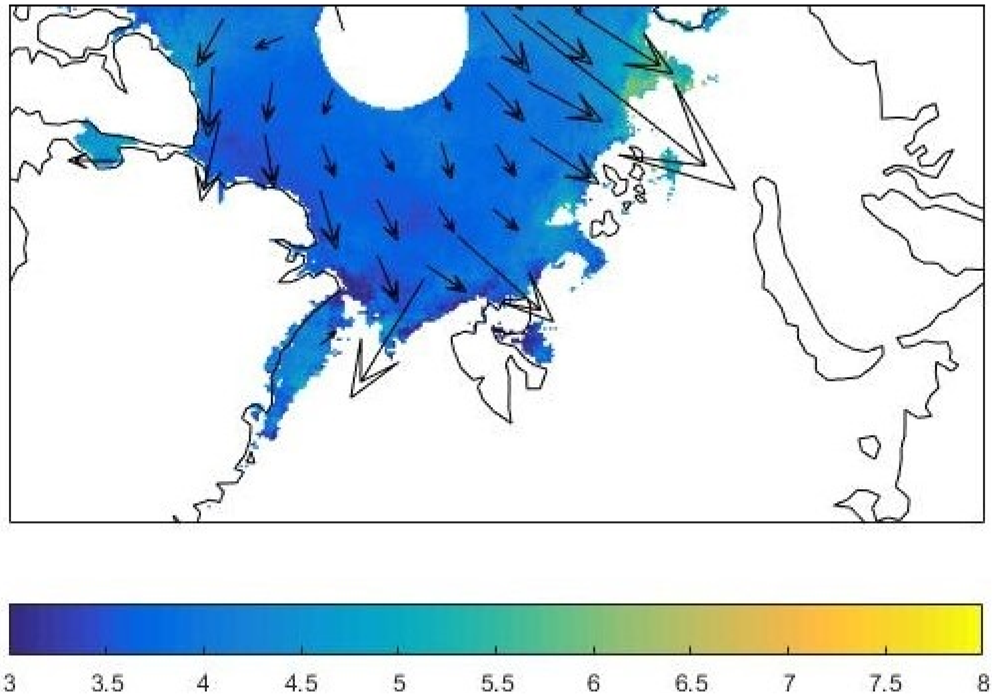

Figure 4: The summer (July to September) mean wind in m/s

5.2 Ice motion

In the first quarter of the year, an area close to the east coast of Greenland with coordinates 79N-80N and 13W-17W is entirely covered by stationary ice. Thus, the true ice movement is zero and the standard deviation, that was calculated to be 0.23 cm/s, of the observed ice speeds in this region is a measurement of the error in the ice data. With ice speeds ranging from 0 to above 20 cm/s, this error is considered small.

In the winter, a typical average ice speed in the middle of the Arctic Ocean is 10-12 cm/s. As can be seen in Figure 5 the speed is rather uniform in a large part of the central Arctic Ocean. In this area, the ice moves primarily westwards but turns southwards to enter the Fram Strait. However, the ice speed is much lower north-west of Greenland than north-east of the island. Here, the direction of the movement is overall also towards the Fram Strait, although near the Nares Strait between Ellesmere Island and Greenland, the ice moves towards the Nares Strait.

The ice velocity east of Greenland is generally high, 15-20 cm/s, and directed southwards. Close to the coast though, the speeds are very low. At the southernmost edge of the observed area east of Greenland, there are ice speeds up to 35 cm/s. In the area around Svalbard and Franz Josef Land, as well as in the Kara sea, the ice speed follows the pattern with low speed near land and high speed away from land.

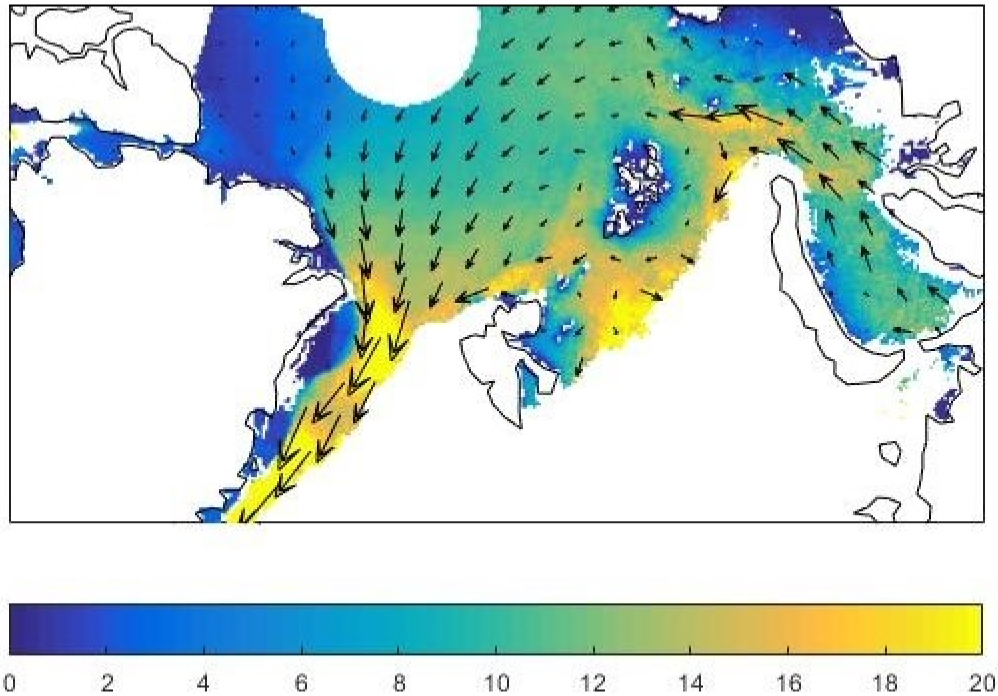

Figure 5: The winter (January to March) ice velocity in cm/s

In the summer, the ice speed in the middle of the Arctic Ocean is lower than in the winter. The ice speed during the third quarter of the year is shown in Figure 6. Typical values are 8-10 cm/s north-east of Greenland and 4-8 cm/s north-west of Greenland. Ice has been observed east of Greenland with speeds between 0 and 6 cm/s. Between Svalbard and Franz Josef Land there is an area with ice speeds up to 16 cm/s. The direction of the ice movement is similar in the summer to that in the winter.

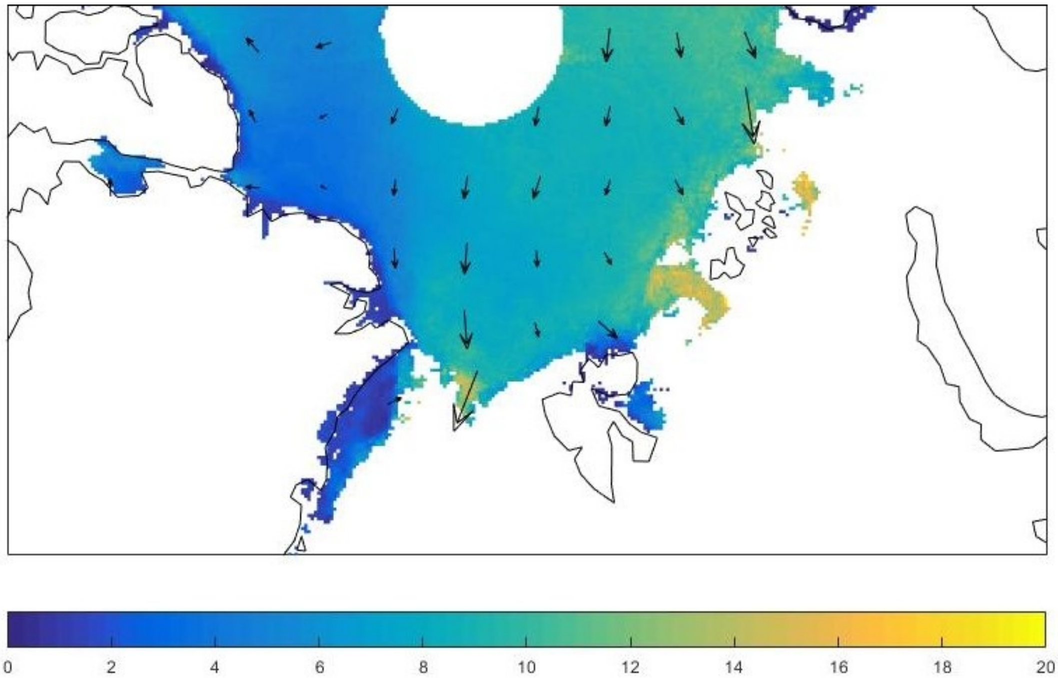

Figure 6: The summer (July to September) ice velocity in cm/s

5.3 Turning angle

In the winter, north-east of Greenland the turning angle is between 0° and 25° to the right (see Figure 7). The corresponding angle in the summer is between 0° and 40° (see Figure 8). In both seasons, the angle is negative in a large part of the Arctic Ocean. This means that the ice movement is directed to the right of the wind velocity.

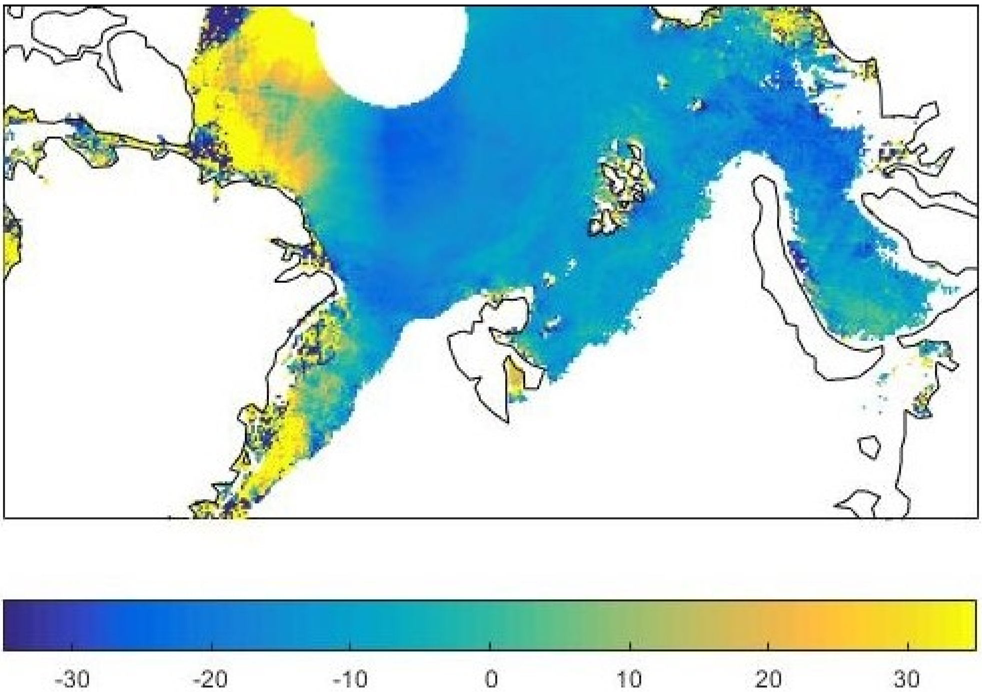

Figure 7: The winter (January to March) turning angle in degrees

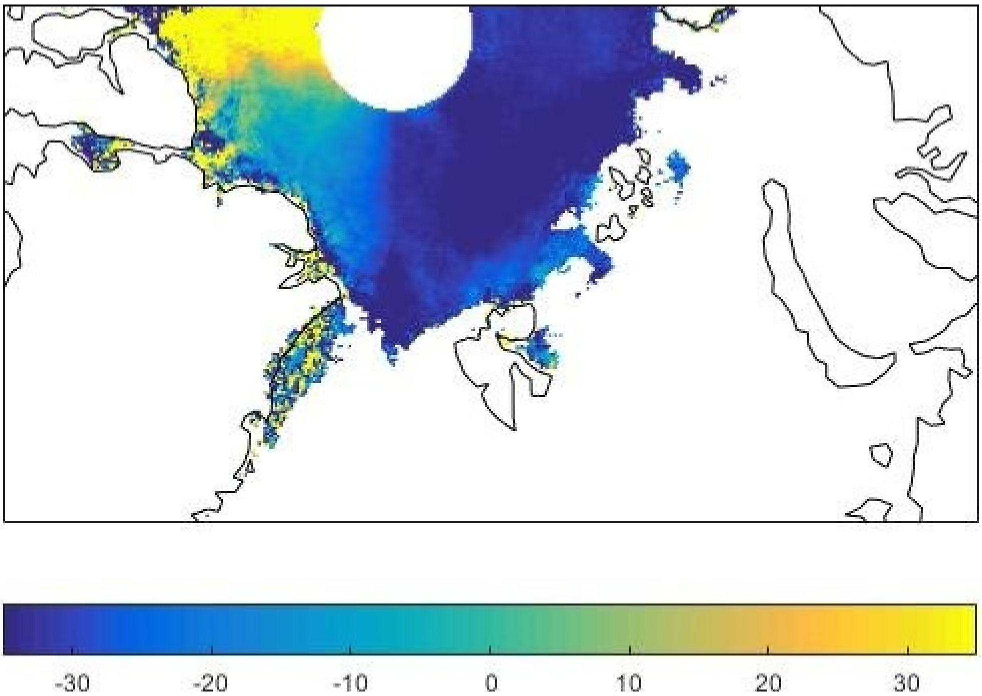

Figure 8: The summer (July to September) turning angle in degrees

5.4 Correlation

In the winter, the squared correlation coefficient between ice and wind velocity is very high in the area north-east of Greenland and between Svalbard and Franz Josef Land, typically around 80 %, but up to 90 % in a small area (see Figure 9). North and north-east of Franz Josef Land the correlation is between 50 and 70 %. North-west of Greenland, on the other hand, the correlation is much lower. Near land the correlation is low or even zero. In the Kara sea the squared correlation coefficient ranges from below 20 % near the coast to about 75 % on the middle of the sea. Right between Greenland and Svalbard there is an area with about 60 % correlation, although generally, east of Greenland, the correlation is between 0 and 40 %.

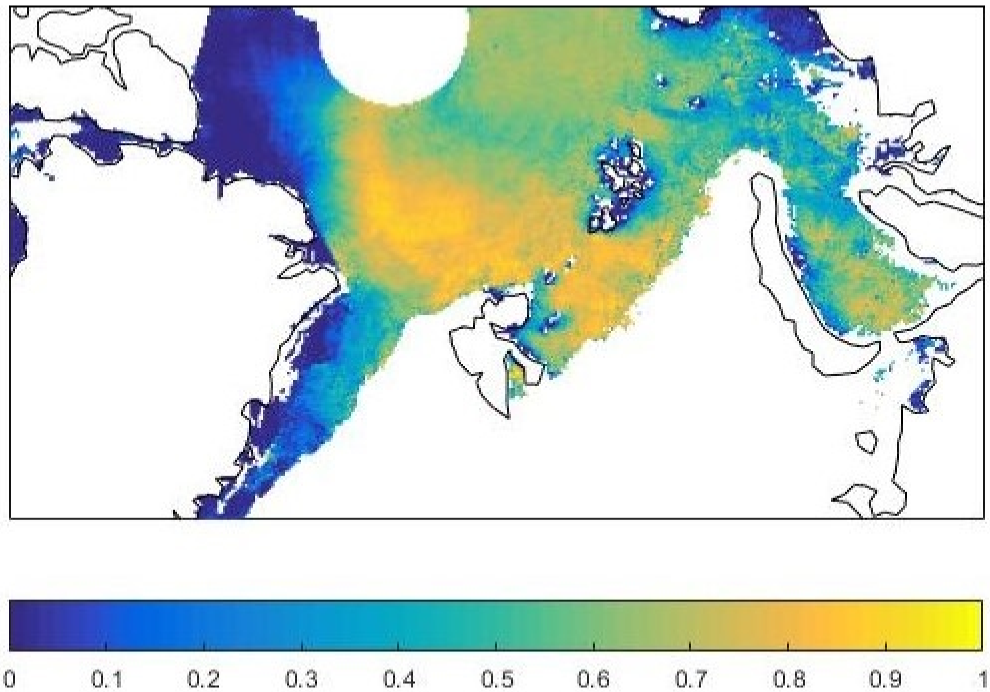

Figure 9: The winter (January to March) squared correlation coefficient

In the summer, the correlation is lower (see Figure 10). Typical values for the area north-east of Greenland are 20 to 50 %. The correlation is slightly higher between Svalbard and Franz Josef Land as well as near the North Pole, up to 70%. North-west of Greenland, the correlation is low. Along the east coast of Greenland the squared correlation is below 20 %.

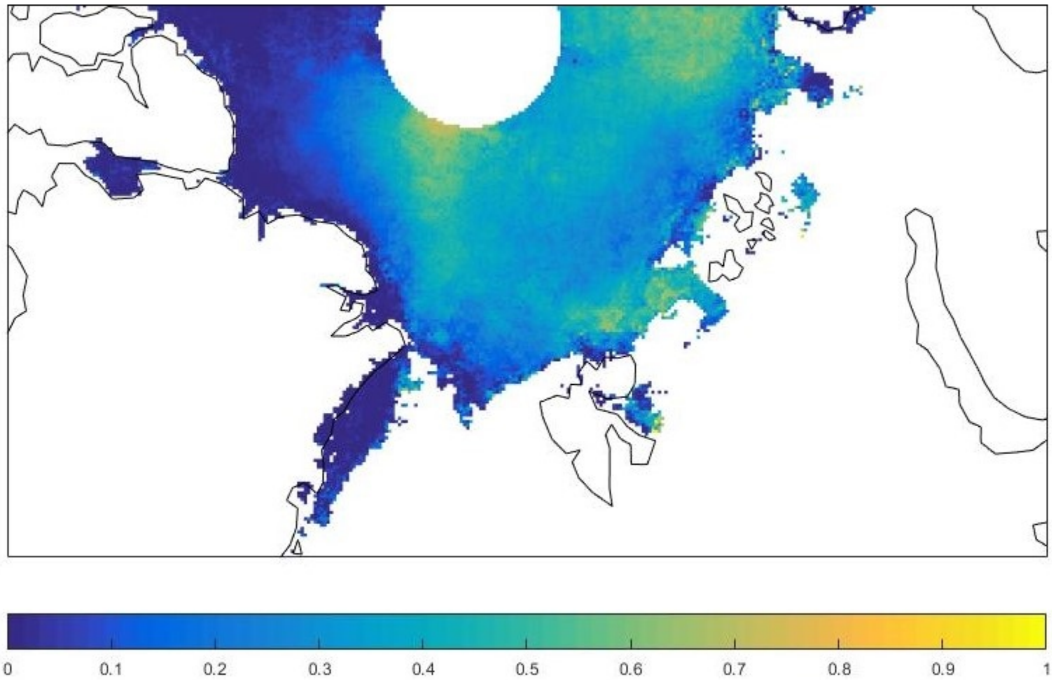

Figure 10: The summer (July to September) squared correlation coefficient

5.5 Speed reduction factor

The speed reduction factor, F, shows a similar pattern to the correlation coefficient. During winter, there are very low values of F north-west of Greenland and close to land, as shown in Figure 11. The highest values in the region though, is not north-east of Greenland (typically 1 to 2.5 %) but between Svalbard and Franz Josef Land (up to 3.5 %). In the Kara Sea, the speed reduction factor ranges from about 0 % close to the coast, up to 2 % at the middle of the sea.

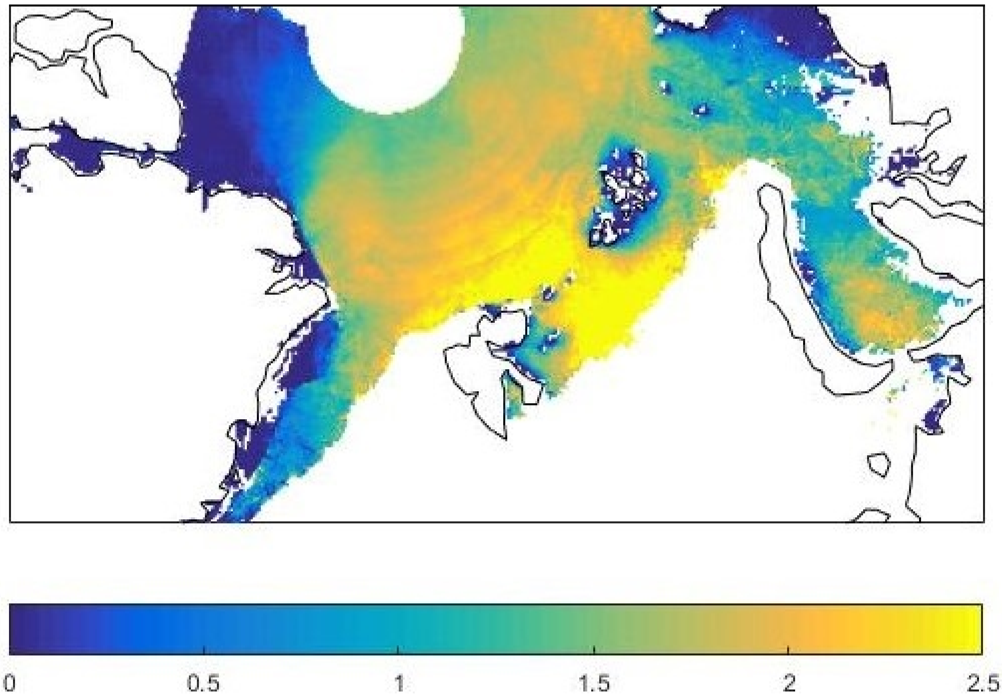

Figure 11: The winter (January to March) speed reduction factor in percent

Just like the correlation coefficient, the speed reduction factor is lower in summer than in winter (see Figure 12). Typical values for north-east of Greenland are 1 to 1.5 %, with slightly higher reduction factor in an area near the north pole. Values up to 2.5 % are found between Svalbard and Franz Josef Land.

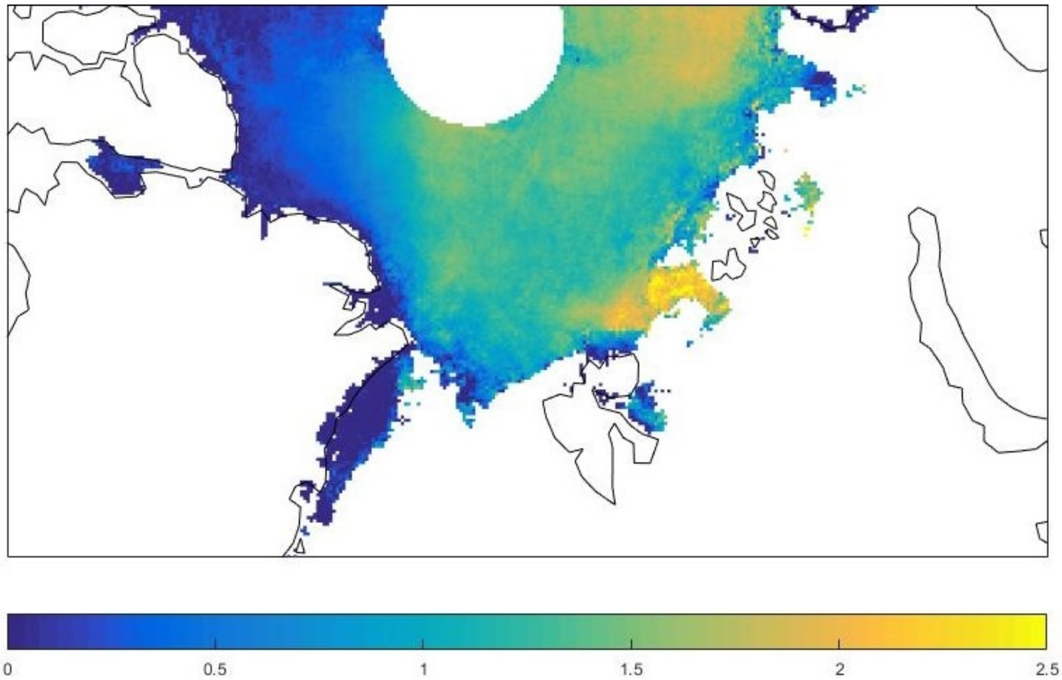

Figure 12: The summer (July to September) speed reduction factor in percent

5.6 Ocean current

What is here denoted "calculated ocean current" actually includes all driving forces that act on the ice, except for the wind stress. Thus, the "ocean current" also includes the internal stress.

As can be seen in Figure 13, the winter currents that were obtained in this study coincide to a large extent with the general ocean circulation in the Arctic region, which is shown in Figure 1. A current that is directed from the North Pole towards the Fram Strait flows with a speed of 2 to 10 cm/s. The closer to Fram Strait, the higher is the speed. The current with the highest speed is found along the east coast of Greenland. This current is especially high in the south, up to 30 cm/s. Near the coast, the current speed is close to zero. North-west of Greenland, the magnitude of the current is small. Just like the ice, the current in this region flows generally towards the Fram Strait, but it also flows towards Nares Strait. The currents in the northern Barents Sea seem irregular, but not without magnitude (up to 4 cm/s). The current velocity in the Kara sea is up to 7 cm/s and directed northwards. There is a fairly strong (4-12 cm/s) current that exits the Kara Sea to pass east of Franz Josef Land.

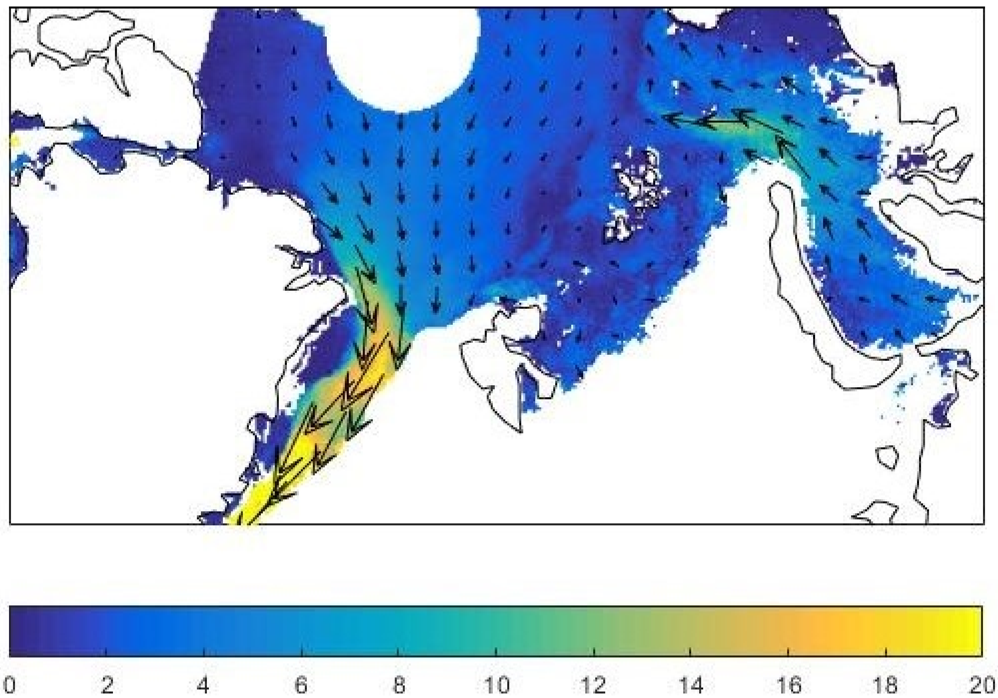

Figure 13: The winter (January to March) calculated ocean current in cm/s

The ocean current shows approximately the same pattern in the summer as in the winter. The current speed north-east of Greenland is generally lower than in the winter, 1 to 7 cm/s. The speed of the current east of Greenland, close to the coast, is up to 4 cm/s.

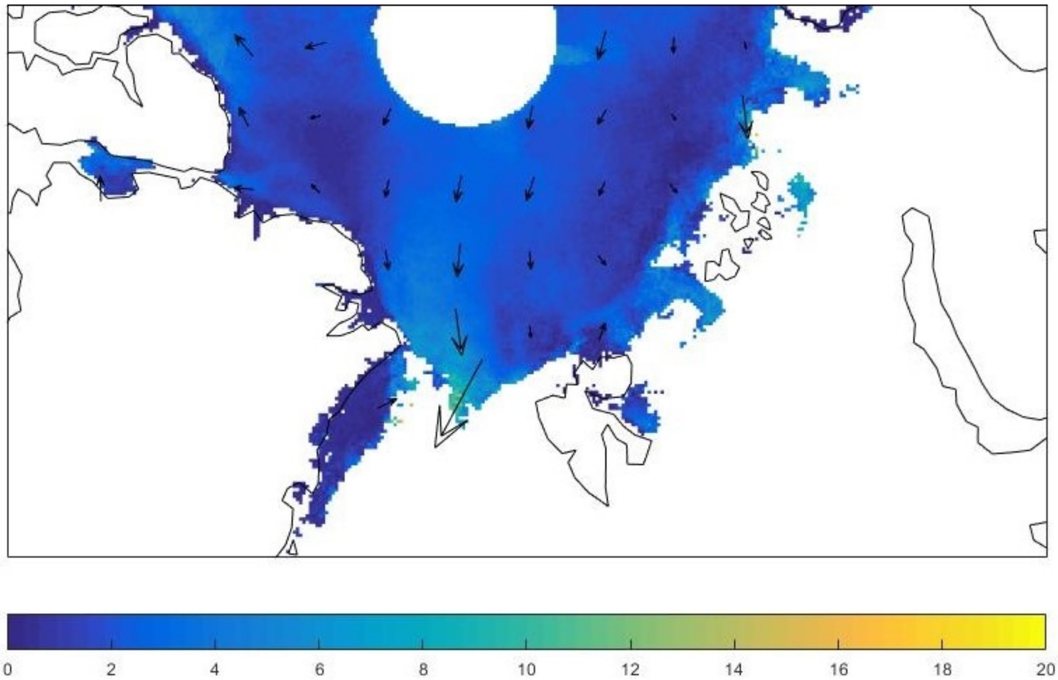

Figure 14: The summer (July to September) calculated ocean current in cm/s

6 Discussion and conclusion

6.1 Correlation

North-east of Greenland

The area north-east of Greenland, which in the winter has a high correlation between wind and ice drift, is not close to any coast. The average wind blows in approximately the same direction as the general ocean current. The thickness of the ice in this area can vary a lot but is not the thickest in the Arctic Sea. Thinner ice, along with the relatively low ice concentration that is found in this area, lead to a low internal stress, according to Equation 4. If the internal stress is low, the influence of the wind stress term in the momentum equation (Equation 1) increases. This leads to a higher correlation. In this area, the ice concentration does not reach 100 %. Thus, the ice floes are not entirely blocked by surrounding ice and it is possible for the wind to affect the ice motion.

In the summer, the thickness of the ice north-east of Greenland has probably more similarities with the autumn (October and November) ice than the spring (March and April) ice, since the autumn months are closer in time. From this point of view, the ice in this area is likely to be thinner in the summer than in the winter. In spite of this, and even though the sea ice concentration is lower in the summer, the correlation coefficient is significantly lower in the summer than in the winter. One explanation for this could be the weaker summer winds. Equation 2 tells that the air stress is proportional to the squared wind speed.

Between Svalbard and Franz Josef Land

High correlation is also found between Svalbard and Franz Josef Land. An part of the explanation for this may be the high mean wind speed in this area. The direction of the calculated current is varying in this area, and some arrows are in the opposite way from the mean ocean current. This can indicate that the current actually was flowing in opposite direction from the average during these months. A calculated current in summer could help determine whether this is the case or not, but there are too few data points for this region in the summer to be able calculate a current. The opposite directions can also indicate that other factors than the actual current have a major influence on the ice movement. One such factor could be the internal stress. However, the ice concentration in this area was not very high, and the thickness was most likely relatively low, implying low internal stress. Even a low internal stress can play a large role in the equation of motion, if the ocean current velocity, and thereby the water stress, is low. A low water stress would also contribute to a high correlation between the wind velocity and ice movement, which is here the case.

Lincoln Sea

The low correlation in Lincoln Sea in the winter corresponds well with the thick ice that is common in this region, and with the concentration of near 100 %. The correlation in summer in this region is very low, about the same as in winter, even though the ice is thinner and the ice concentration is slightly lower in summer. This low internal stress should indicate a high correlation, and the fact that this is not the case may be due to weaker winds in summer.

The calculated ocean current in this area differs between winter and summer. The weak calculated current in winter is likely to have the same origin as the low correlation, namely high ice concentration and high internal stress. This is supported by the low ice speed; both the wind and the current have difficulties moving the thick, concentrated ice masses. In summer, however, the calculated current is similar to the average ocean current, which in this region splits into two parts, one that flows east towards the Fram Strait and one which flows west and enters the Beaufort Gyre. This was expected, since the relatively low ice concentration and thin ice enables the ocean current to set the ice in motion.

Kara Sea

The Kara Sea is an example of a region where the correlation is notably higher away from the coasts than close to them. Thicker and more concentrated ice, as well as the, in all directions, vicinity to land, are likely explanations of the lower correlation in the Kara Sea than between Svalbard and Franz Josef Land. The wind speeds in these two regions are approximately of the same size. The average wind direction in the Kara Sea is along the coast rather than towards it. This enables a high correlation.

Along the east coast of Greenland

The very low correlation close to the Greenland coast is most likely because the ice is attached to land or the bottom of the sea and therefore is not put in motion. As the ocean current is to a large extent driven by the wind, one can expect a higher wind ice correlation than is actually the case in areas where the mean wind coincides with the average ocean current. In such areas, the wind both influences the current, which in turn influences the ice, and the ice drift directly. The calculated ocean current would then be weaker than the actual ocean current, since some of the effects of the current are taken to be originating from the wind. In the East Greenland current, which is largely influenced by the wind, this enhanced correlation could be the case. However, the result shows a rather low correlation also in areas which are not very close to the coast, and a strong calculated current. The mean wind direction is uniform and coincides with the East Greenland current in the northern part of the Fram Strait, and this is also where the correlation is relatively high. Along the rest of the Greenland east coast, the wind is varying in speed and direction. This suggests that it is the wind in the north that drives the ocean current, and that the ice that has been measured east of Greenland is too near the coast, and thus is pushed by winds of too random velocities, for a high correlation to occur. The narrow of higher correlation further from the coast in the north is probably situated far enough from land to experience a more steady wind stress, and to avoid attaching to the bottom of the shallow water that is found closer to land.

6.2 Turning angle and speed reduction factor

The turning angle is generally larger in the summer than in the winter. The low correlation between wind and ice motion in summer means that the turning angle to a large extent corresponds to the angle between the wind and the ocean current.

Although the patterns of the correlation coefficient and the speed reduction factor are very similar, the area with the largest speed reduction factor, between Svalbard and Franz Josef Land, does not coincide with the area with the highest correlation, which is north-east of Greenland. This holds for both summer and winter. This means that, even though the correlation of the movement is high north-east of Greenland, the ice moves relatively slow. An explanation for the differing speed reduction factor can be varying theta, since F only depends on the speed, not the velocity.

6.3 Comparison with previous studies

The winter ice motion field that was used in this study corresponds well with the ice velocities obtained by Kimura and Wakatsuchi (2000). The same applies, on the whole, for the correlation coefficient, but there are some differences. For instance, the present study obtained higher correlation in the Kara Sea. This region is a seasonal ice zone, in which the ice concentration may vary between different years. This could be one reason for differing results. The present study also obtains higher correlation north of Svalbard.

Kimura and Wakatsuchi (2000) use measurements from seven years, compared to two years in the present work. The result from the longer time period should represent the average case more accurately, but, due climatological variations, the situation in the Arctic has probably changed since the time period studied by Kimura and Wakatsuchi (2000), so that the results in the current work represent the present state better. Additionally, differences in the result may also originate from the number of months that were studied. Kimura and Wakatsuchi (2000) studied December to April, while this work studies January to March. For example, both December and April will contribute to a smaller mean sea ice extent for the studied period. Another difference between Kimura and Wakatsuchi (2000) and the present study is that higher values for the speed reduction factor in the interior of the Arctic were found in the latter. Large speed reduction factor is generally associated with lower ice concentration and thinner ice. This could be the case.

With the results from Thorndike and Colony (1982) in mind, who measure a higher correlation in summer than in winter, the present results, indicating the opposite, are surprising. A possible explanation for this would be that Thorndike and Colony (1982) analysed buoys in regions that are not covered by the present study. Another explanation could be that the correlation actually differs between the different time periods.

Differences between the, in the current study, obtained turning angle and the turning angles calculated by both Kimura and Wakatsuchi (2000) and Thorndike and Colony (1982) are expected, since the two later works put the ice motion in relation to geostrophic wind, while in the present work, the same is done with the 10 m wind. If the turning angle between the ice drift and the 10 m geostrophic wind is close to zero , which the result by Kimura and Wakatsuchi (2000) indicate(-10° to 10°), then the angle between the ice drift and the 10 m wind should be of the same size as the angle between the 10 m wind and the 10 m geostrophic wind. This angle must be smaller than the angle between the surface wind and the 10 m geostrophic wind, which has been observed to be approximately 25° (Wadhams 2000). Thus, and since the 10 m wind is directed to the left of the 10 m geostrophic wind, the turning angle θ that was calculated in this study, should be negative (to the right) and smaller than 35°, in order to coincide with the results from Kimura and Wakatsuchi (2000). In the winter, this is the case in a large part of the examined area.

6.4 Conclusion

On the time scale of three months, wind is responsible for a large fraction, up to 90 % in the winter and up to 70 % in the summer, of the ice movement in areas that are not near any coast and where the ice concentration is not 100 %. It is very likely that strong winds contribute to a higher correlation. Very low correlation can be expected close to coasts, in shallow water and where the ice is very thick. The correlation reducing effect of coasts decline at different rates. This may be connected to the depth of the ocean, or the size of the Islands.

The speed reduction factor is generally large where the correlation is high, and small where the correlation is low. There exists a turning angle theta between the 10 m wind and the ice motion, which is negative in most parts of the Arctic ocean.

Differences in the influence of wind in summer and in winter are significant. Both the correlation and the speed reduction are lower in summer than in winter, which most likely is explained by weak winds. The turning angle is larger in summer than in the winter. This can be explained by the low correlation between wind and ice drift, allowing the ocean current to determine the path of the ice floes.

The results from the present study confirms the results by Kimura and Wakatsuchi (2000) regarding both correlation, speed reduction factor and turning angle. However, the present study received opposed results to those from Thorndike and

Colony (1982) when it comes to seasonal variations in correlation. Thorndike and Colony (1982) found higher correlation in the summer while the present work found the correlation to be higher in the winter.

7 Outlook

It would be interesting to study the effect of winds from different directions and their relation to the ice drift, since this might give a higher correlation in some areas. Another aspect that could be included in a study is how much the wind velocity changes during the period of ice measurement. This could have an impact on the averaged ice motion.

A more precise result may be obtained by studying the years 2014 and 2015 separately, as the relationship may differ between the years due to different ice, ocean and weather conditions. Analysing each month separately, as well as studying the second and fourth quarter of the year may also enable more detailed results. The conclusions from the current work may be confirmed by investigating the relationship in the whole Arctic region, including the Canada Basin, East Siberian Sea, Laptev Sea and Bering Strait.

Wind data with higher resolution would probably improve the accuracy, especially in regions near coasts, where the wind varies a lot, and in seasons and regions with frequent storms and low pressures.

The results concerning the relation during summer need to be confirmed by further studies, for example by looking at a larger area and other years. A deeper understanding of the summer relation may be reached by investigating the relation in the second and forth quarter of the year as well.

References

Arctic Council (2001). *CAFF Map No.43 - Surface ocean currents and the minimum extent of sea ice in the Arctic.* Conservation of Arctic Flora and Fauna Working Group. URL: `http://library.arcticportal.org/1375/`.

CPOM (2016). *Arctic Sea Ice Thicknes Map.* Centre for Polar Observation and Modelling. URL: `http://www.cpom.ucl.ac.uk/csopr/seaice.html`.

DTU (2016). *Index of /myocean/validation.* Technical University of Denmark. URL: `http://www.seaice.dk/myocean/validation/`.

ECMWF (2010). "Part II: Data Assimilation". In: *IFS Documentation CY36R1.* IFS Documentation. Operational implementation 26 January 2010. The European Centre for Medium-Range Weather Forecasts.

— (2016). *ERA-Interim.* The European Centre for Medium-Range Weather Forecasts. URL: `http://www.ecmwf.int/en/research/climate-reanalysis/era-interim`.

Hibler, W.D. (1979). "A Dynamic Thermodynamic Sea Ice Model". In: *Journal of Physical Oceanography* 9, pp. 815–846.

Hunke, E. C. et al. (2015). *CICE: the Los Alamos Sea Ice Model. Documentation and Software User's Manual.* Version 5.1. Los Alamos National Laboratory.

Kimura, N. and M. Wakatsuchi (2000). "Relationship between sea-ice motion and geostrophic wind in the Northern Hemisphere". In: *Geophysical Research Letters* 27.22, pp. 3735–3738.

Kwok, R. et al. (1990). "Ice-Motion Tracking System at the Alaska SAR Facility". In: *IEEE Journal of Oceanic Engineering* 15.1, pp. 44–54.

Leppäranta, M. (2005). *The drift of sea ice.* Chichester: Praxis Publishing Ltd.

McPhee, M. G. (1980). "An Analysis of Pack Ice Drift in Summer". In: *Sea Ice Processes and Models.* Ed. by R. S. Pritchard. Seattle and London: University of Washington Press, pp. 62–75.

NSDIC (2016). *Sea Ice Index.* National Snow and Ice Data Center. URL: http://nsidc.org/data/seaice_index/archives.html.

Saldo R., Hacket B. (2015). *PRODUCT USER MANUAL For Global high resolution SAR sea ice drift.* Copernicus Marine Environment Monitoring Service.

Snyder, J. P. (1984). *Map projections used by the U.S Geological Survey.* 2nd ed. U.S. Government Printing Office.

Steele, M. et al. (1997). "The force balance of sea ice in a numerical model of the Arctic Ocean". In: *Journal of Geophysical Research* 102.C9, pp. 21061–21079.

Thorndike, A. S. and R. Colony (1982). "Sea Ice Motion in Response to Geostrophic Winds". In: *Journal of GeoPhysical Research* 87.C8, pp. 5845–5852.

Wadhams, P. (2000). *Ice in the Ocean.* Taylor & Francis.

Appendix A: Map of the Arctic Region

Figure A.1: Topography and bathymetry of the Arctic region. (Ahlenius, H. (2016). *Arctic topographic map, with bathymetry.* Nordpil. URL: https://nordpil.com/portfolio/mapsgraphics/arctic-topography/) The sea north-west of Greenland and north-east of Ellesmere Island is called Lincoln Sea.

Appendix B: SortWindData.m

```
%{
This program takes the wind data files and sorts the data in
chronological order.
%}

% Convert the wind-time into matlab-date
windTime  = double(windTime)/24 + datenum('1900-01-01 00:00:00');

% Sort the time, u and v
c1=1;
c2=1461;
windTimeOld = windTime;
u10Old = u10;
v10Old = v10;

for i=1:length(windTime)/4
    windTime(4*i-3)=windTimeOld(c1);
    u10 (:,:,4*i-3)=u10    (:,:,c1);
    v10 (:,:,4*i-3)=v10    (:,:,c1);
    c1 = c1+1;

    windTime(4*i-2)=windTimeOld(c2);
    u10 (:,:,4*i-2)=u10    (:,:,c2);
    v10 (:,:,4*i-2)=v10    (:,:,c2);
    c2 = c2+1;

    windTime(4*i-1)=windTimeOld(c2);
    u10 (:,:,4*i-1)=u10    (:,:,c2);
    v10 (:,:,4*i-1)=v10    (:,:,c2);
    c2 = c2+1;

    windTime(4*i)=windTimeOld(c2);
    u10 (:,:,4*i)=u10    (:,:,c2);
    v10 (:,:,4*i)=v10    (:,:,c2);
    c2 = c2+1;
end
```

Appendix C: Interpolate2015.m

```
%{

This program imports the wind data from both 2014 and 2015 and the ice data
month by month from 2015. For every ice measurement, the start and end
position of the ice is calculated in x and y coordinates in a
polarstereographic projection. A mean wind for each ice measurement is
calculated. For each month, a matrix, containing the starting time, the
starting latitude, the starting longitude, the starting x-coordinate, the
starting y-coordinate, the end time, the end latitude, the end longitude,
the end x-coordinate, the end y-coordinate, the mean zonal wind and the
mean meridional wind, is saved.

Another, very similar, program does the same for 2014, as the data files
from 2014 are slightly different. The output data that is saved has the
same format for both years.

%}

%% Import the wind data
windTime=importdata('windTime.mat');
u10=importdata('u10.mat');
v10=importdata('v10.mat');
windLat = ncread('wind_2014+15.nc','latitude');
windLong = ncread('wind_2014+15.nc','longitude');
%% Loop through every month of the year
for month=1:12
   month
    %% load ice data
    if month<10
        iceData=importdata(strcat('2015.0',num2str(month),'.txt'));
    else
        iceData=importdata(strcat('2015.',num2str(month),'.txt'));
    end
    iceData=iceData.textdata;
    'Loaded!'
    %% Tidy up the ice data

    % Delete the columns which do not contain numbers
    iceData(:,9) = [];
    iceData(:,18)= [];

    % Turn the cell array "iceData" into a double matrix
    iceData=str2double(iceData);

    % Extract the starting and ending time from the ice data
    startTime =
datenum(iceData(:,1),iceData(:,2),iceData(:,3),iceData(:,4),iceData(:,5),ic
eData(:,6));
```

```
    endTime   =
datenum(iceData(:,9),iceData(:,10),iceData(:,11),iceData(:,12),iceData(:,13
),iceData(:,14));

    % Calculate x and y, in the polarstereographic projection (see Theory)
    % input: latitude, longitude, lambda0, k0, R
    % output: x, y in km
    lambda0 = 0; %central meridian
    k0 = 1; % scale factor
    R = 6371.0; % radius of the earth in km
    xStart  =  2*R*k0*tan(pi/4-
deg2rad(iceData(:,2))/2).*sin(deg2rad(iceData(:,3))-lambda0);
    yStart  = -2*R*k0*tan(pi/4-
deg2rad(iceData(:,2))/2).*cos(deg2rad(iceData(:,3))-lambda0);
    xEnd    =  2*R*k0*tan(pi/4-
deg2rad(iceData(:,7))/2).*sin(deg2rad(iceData(:,8))-lambda0);
    yEnd    = -2*R*k0*tan(pi/4-
deg2rad(iceData(:,7))/2).*cos(deg2rad(iceData(:,8))-lambda0);

    % Put it all together in an new iceData matrix
    iceData = [startTime iceData(:,7) iceData(:,8) xStart yStart endTime
iceData(:,15) iceData(:,16) xEnd yEnd zeros(length(iceData),1)
zeros(length(iceData),1)];
    clear startTime
    clear endTime
    clear xStart
    clear yStart
    clear xEnd
    clear yEnd
    'Fixed iceData!'
    %% Loop through iceData, that is every ice measurement
    % Many ice measurements were done simultaneously, and thus can use the
    % same time information. To determine whether two ice measurements were
    % made simultaneously, the last starting and ending ice time are stored
    % in the following variables.
    lastStartTime = 0;
    lastEndTime = 0;
    for j=1:length(iceData)
        %% Make a vector containing the windTime-indexes for the wind
measurements that are within the ice measurement interval
        startIceTime=iceData(j,1);
        endIceTime=iceData(j,6);
        if lastStartTime~=startIceTime && lastEndTime~=endIceTime
            withinIceTime = windTime(windTime<endIceTime &
windTime>startIceTime);
            IValues = ismember(windTime,withinIceTime); %The values of the
wind measurements that are withing the ice measurement interval
            IIndex= zeros(length(withinIceTime),1); %The time indexes of
the wind measurements that are within the ice measurement interval
            n = 1; % where in IIndex to put the new index of the ice-time
that is within the interval and is discovered in the loop below
            for i=1:length(IValues)
                if IValues(i)==1
                    IIndex(n)=i;
```

```
                n = n+1;
            end
        end

        % The indexes just before and after the interval
        beforeIceTime = IIndex(1)-1;
        afterIceTime  = IIndex(length(IIndex))+1;
    end
    %% Find the spacially nearest wind measurement
    % First, find the point on the middle of the ice path, that is the
point that will be compared.
    startLat = iceData(j,2);
    startLong = iceData(j,3);
    endLat = iceData(j,7);
    endLong = iceData(j,8);
    midLat = (startLat+endLat)/2;
    midLong = (startLong+endLong)/2;
    % Find the closest long- and lat-value of the wind measurements
    [c latNearestIndex] = min(abs(windLat-midLat));
    latNearestValue = windLat(latNearestIndex);
    [c longNearestIndex] = min(abs(windLong-midLong));
    longNearestValue = windLong(longNearestIndex);
    % Make vectors containing the u- and v-velocities at the nearest
point for
    % the times that are within the time-interval of ice-measurement,
and variables with velocities just
    % before and just after
    uNearestB = u10(longNearestIndex,latNearestIndex,beforeIceTime);
%before
    uNearestA  = u10(longNearestIndex,latNearestIndex,afterIceTime);
%after
    uNearest = u10(longNearestIndex,latNearestIndex,IIndex);
    uNearest = squeeze(uNearest);

    vNearestB = v10(longNearestIndex,latNearestIndex,beforeIceTime);
%before
    vNearestA  = v10(longNearestIndex,latNearestIndex,afterIceTime);
%after
    vNearest = v10(longNearestIndex,latNearestIndex,IIndex);
    vNearest = squeeze(vNearest);

    %% Interpolate the wind in time
    windDT = 0.125; % the time step in windTime

    % u-component
    k = (uNearest(1)-uNearestB)/(windDT);
    m = uNearest(1)-k*windTime(IIndex(1));
    u = k*startIceTime+m;
    dM = (u+uNearest(1))/2;
    M = dM*(windTime(IIndex(1))-startIceTime);
    for i=1:length(IIndex)-1
        dM = (uNearest(i)+uNearest(i+1))/2;
        M  = M + dM*windDT;
    end
```

```
        k = (uNearestA-uNearest(length(IIndex)))/(windDT);
        m = uNearestA-k*windTime(afterIceTime);
        u = k*endIceTime+m;
        dM = (u+uNearest(length(IIndex)))/2;
        M = M + dM*(endIceTime-windTime(IIndex(length(IIndex))));
        % Mean u wind:
        iceData(j,11) = M/(iceData(j,6)-iceData(j,1));

        % v-component
        k = (vNearest(1)-vNearestB)/(windDT);
        m = vNearest(1)-k*windTime(IIndex(1));
        v = k*startIceTime+m;
        dM = (v+vNearest(1))/2;
        M = dM*(windTime(IIndex(1))-startIceTime);
        for i=1:length(IIndex)-1
            dM = (vNearest(i)+vNearest(i+1))/2;
            M  = M + dM*windDT;
        end
        k = (vNearestA-vNearest(length(IIndex)))/(windDT);
        m = vNearestA-k*windTime(afterIceTime);
        v = k*endIceTime+m;
        dM = (v+vNearest(length(IIndex)))/2;
        M = M + dM*(endIceTime-windTime(IIndex(length(IIndex))));
        % Mean v wind:
        iceData(j,12) = M/(iceData(j,6)-iceData(j,1));

        %% prepare next iteration and tell what's happening
        lastStartTime = startIceTime;
        lastEndTime = endIceTime;

        if mod(j,100000)==0
            j
        end
    end %iceData
end %month
clear IValues
%% Save
save(strcat('NewIceData15-',num2str(month)),'iceData','-v7.3')
```

Appendix D: CalculateFaster1Month.m

```
%{

ThisProgram creates, for each motnh, a grid in a polar stereographic
projection, with a given grid size. It takes the ice data file for every
month and calculates, for every month and for every grid box, the number of
data points, the turning angle theta, the speed reduction factor F, the ocean
current components cu and cv as well as the correlation coefficient r. These
variables are saved month by month.

There is a similar program that does the same as this, but for three months
instead of one month. That program makes use of some of the output from this
program, for example the number of data points. It also calculates the mean
wind, ice and current speed for each box and quarter of the year. This in
order to be able to plot arrows on the maps, which is done in PlotMap.m.

%}

%% Check how long time it takes
tic
%% Loop through all months.
for year =14:15
    for month=1:12
iceData = importdata(strcat('IceData',num2str(year),'-
',num2str(month),'.mat'));
%% How many data points to loop through
% This will of course be all when I am finished testing
loopStop = length(iceData);

%% Create the grid
gridSize = 10; %km
% Check how large the grid has to be
xMin = min(min(iceData(:,4)), min(iceData(:,9)));
xMax = max(max(iceData(:,4)), max(iceData(:,9)));
yMin = min(min(iceData(:,5)), min(iceData(:,10)));
yMax = max(max(iceData(:,5)), max(iceData(:,10)));
xWidth = xMax-xMin;
yWidth = yMax-yMin;
% Calculate how many boxes there shall be
xN = xWidth/gridSize;
yN = yWidth/gridSize;
xN = ceil(xN); %rounds up to nearest integer
yN = ceil(yN);
% The vectors X and Y will contain the mid point of every box
X = zeros(xN,1);
Y = zeros(yN,1);
for i=1:xN
    X(i) = xMin - gridSize/2 + i*gridSize;
end
for i=1:yN
    Y(i) = yMin - gridSize/2 + i*gridSize;
end
```

```
%% Prepare the matrices that will be filled with values

% uMean and vMean will contain the monthly mean wind in each box
uMean = zeros(xN,yN);
vMean = zeros(xN,yN);

% Mean ice velocity
UMean = zeros(xN,yN);
VMean = zeros(xN,yN);

% Count the number of data points in each box
nDataPoints = zeros(xN,yN);

% These sums are used in future calculations (see Kimura and Wakatsuchi)
sumC1 = zeros(xN,yN);
sumC2 = zeros(xN,yN);
sumC3 = zeros(xN,yN);
sumC4 = zeros(xN,yN);
sumu2 = zeros(xN,yN);
sumv2 = zeros(xN,yN);
sumU2 = zeros(xN,yN);
sumV2 = zeros(xN,yN);

iceBox = zeros(length(iceData),2);

%% Calculate U and V for every row in iceData
% Independent of grid
U = zeros(length(iceData),1);
V = zeros(length(iceData),1);
'U and V'
for k=1:loopStop
    t = ((iceData(k,6)-iceData(k,1))*24*60*60); % the time for the ice to
move, in seconds
    U(k) =
distance('gc',iceData(k,2),iceData(k,3),iceData(k,2),iceData(k,8)); %(great
circle, startLat, startLong, startLat, endLong) Change position in x-
direction but not in y-direction
    V(k) =
distance('gc',iceData(k,2),iceData(k,3),iceData(k,7),iceData(k,3)); %(great
circle, startLat, startLong, endLat, startLong) Change position in y-
direction but not in x-direction
    U(k) = distdim(U(k),'deg','m'); % convert from degrees of arc to meter
    V(k) = distdim(V(k),'deg','m'); % convert from degrees of arc to meter
    U(k) = U(k) / t;
    V(k) = V(k) / t;
    % Check if the U ice velocity is positive or negative
    if iceData(k,3)>iceData(k,8)
       U(k) = -U(k);
    end
    % Check if the V ice velocity is positive or negative
    if iceData(k,2)>iceData(k,7)
       V(k) = -V(k);
```

```matlab
    end
    if mod(k,100000)==0
        k
    end
end

%% Determine what box each data point belongs to
% dependent of correct grid, dependent of grid size
'iceBox'
for k=1:loopStop
    x = (iceData(k,9) +iceData(k,4))/2;
    y = (iceData(k,10)+iceData(k,5))/2;
    iceBox(k,1) = round((x-xMin)/gridSize + 0.5); % With +0.5, if x-xMin=0,
it will indicate the first box-column
    iceBox(k,2) = round((y-yMin)/gridSize + 0.5);
    if mod(k,100000)==0
        k
    end
end


%% Calculate uMean, vMean, UMean, VMean, nDataPoints
'*Mean'
for k=1:loopStop

    uMean(iceBox(k,1),iceBox(k,2))= uMean(iceBox(k,1),iceBox(k,2)) +
iceData(k,11);
    vMean(iceBox(k,1),iceBox(k,2))= vMean(iceBox(k,1),iceBox(k,2)) +
iceData(k,12);
    UMean(iceBox(k,1),iceBox(k,2))= UMean(iceBox(k,1),iceBox(k,2)) + U(k);
    VMean(iceBox(k,1),iceBox(k,2))= VMean(iceBox(k,1),iceBox(k,2)) + V(k);
    nDataPoints(iceBox(k,1),iceBox(k,2))=
nDataPoints(iceBox(k,1),iceBox(k,2)) + 1;
    if mod(k,100000)==0
        k
    end
end
uMean = uMean./nDataPoints;
vMean = vMean./nDataPoints;
UMean = UMean./nDataPoints;
VMean = VMean./nDataPoints;

%% Calculate the sums
'sums'
for k=1:loopStop
    Udi = U(k) - UMean(iceBox(k,1),iceBox(k,2));
    Vdi = V(k) - VMean(iceBox(k,1),iceBox(k,2));
    udi = iceData(k,11) - uMean(iceBox(k,1),iceBox(k,2));
    vdi = iceData(k,12) - vMean(iceBox(k,1),iceBox(k,2));

    sumC1(iceBox(k,1),iceBox(k,2)) = sumC1(iceBox(k,1),iceBox(k,2)) +
udi*Udi;
```

```
    sumC2(iceBox(k,1),iceBox(k,2)) = sumC2(iceBox(k,1),iceBox(k,2)) +
vdi*Udi;
    sumC3(iceBox(k,1),iceBox(k,2)) = sumC3(iceBox(k,1),iceBox(k,2)) +
udi*Vdi;
    sumC4(iceBox(k,1),iceBox(k,2)) = sumC4(iceBox(k,1),iceBox(k,2)) +
vdi*Vdi;

    sumu2(iceBox(k,1),iceBox(k,2)) = sumu2(iceBox(k,1),iceBox(k,2)) + udi^2;
    sumv2(iceBox(k,1),iceBox(k,2)) = sumv2(iceBox(k,1),iceBox(k,2)) + vdi^2;
    sumU2(iceBox(k,1),iceBox(k,2)) = sumU2(iceBox(k,1),iceBox(k,2)) + Udi^2;
    sumV2(iceBox(k,1),iceBox(k,2)) = sumV2(iceBox(k,1),iceBox(k,2)) + Vdi^2;
    if mod(k,100000)==0
        k
    end
end

%% Then theta, c1, c2, c3, c4, F, cu, cv and r can be calculated without
% loops.

theta = atan((sumC3-sumC2) ./ (sumC1+sumC4));
c1 = cos(theta).*sumC1;
c2 = sin(theta).*sumC2;
c3 = sin(theta).*sumC3;
c4 = cos(theta).*sumC4;
F  = (c1+c2+c3+c4) ./ (sumu2+sumv2);
r  = (c1+c2+c3+c4) ./ (sqrt(sumu2+sumv2).*sqrt(sumU2+sumV2));
r2 = r.^2;
cu = UMean - F .* (uMean.*cos(theta) - vMean.*sin(theta));
cv = VMean - F .* (uMean.*sin(theta) + vMean.*cos(theta));

%% Save
save(strcat('1month10gridVariables',num2str(year),'-
',num2str(month),'New'),'c1','c2','c3','c4','cu','cv','F','iceBox','nDataPoin
ts','r','r2','sumC1','sumC2','sumC3','sumC4','sumu2','sumU2','sumv2','sumV2',
'theta','U','uMean','UMean','V','vMean','VMean','X','Y','xMin','yMin','xN','y
N');

    end
end
%% write out time:
toc
```

Appendix E: PlotMap.m

```
%{

This program plots the speed reduction factor, the squared correlation
coefficient, the number of data points, turning angle, wind speed, ice
speed and calculated ocean current, and saves the figures.

%}

% Load the data to plot, and tell what quarter that is plotted
% load 3months10gridVariablesQ3New
load 3months10gridVariablesQ1New
load 3months10gridSpeedQ1
Title = 'Quarter 1';
quarter = 'Q1';

% calculate current speed
 cAbs = sqrt(cu.^2 + cv.^2).*100;

% remove content of grid boxes with too few data points
limit = 10;
for i=1:length(X)
    for j=1:length(Y)
        if nDataPoints(i,j)<limit
            F(i,j) = NaN;
            r2(i,j) = NaN;
            UVAbs(i,j) = NaN;
            uvAbs(i,j) = NaN;
            cAbs(i,j) = NaN;
            theta(i,j) = NaN;
            speedWindMean(i,j) = NaN;
            speedIceMean(i,j) = NaN;
            UMean(i,j) = NaN;
            VMean(i,j) = NaN;
            uMean(i,j) = NaN;
            vMean(i,j) = NaN;
            cu(i,j) = NaN;
            cv(i,j) = NaN;
        end
    end
end
%% First I have to create the lat and long reference matrices by taking
the inverse of the polar stereographic equations
% input: x, y, lambda0, k0, R
% output: lat, long

lambda0 = 0; %central meridian, longitude
k0 = 1; % scale factor
R = 6371.0; % km
phi1 = pi/2; %central latitude
```

```
latRef = zeros(length(X),length(Y));
longRef= zeros(length(X),length(Y));

for i=1:length(X)
    for j=1:length(Y)
        % Start with calculating the longitude
        rho = (X(i)^2 + Y(j)^2) ^ (1/2);
        c   = 2*atan(rho/(2*R*k0)); %output in radians
        if Y(j)<0
            longRef(i,j) = lambda0 + atan(X(i)/(-Y(j)));
        else
            longRef(i,j) = lambda0 + atan(X(i)/(-Y(j))) + pi; % output in
radians!
        end
        % Next: latitude
        latRef(i,j)  = asin(cos(c)*sin(phi1) +
Y(j)*sin(c)*cos(phi1)/rho);
    end
end

% from radians to degrees
latRef = rad2deg(latRef);
longRef= rad2deg(longRef);

%% Remove values from those boxes outside the frame and inside the shadow
at the North pole

for i=1:length(X)
    for j=1:length(Y)
        if latRef(i,j)<65
            F(i,j) = NaN;
            r2(i,j) = NaN;
            UVAbs(i,j) = NaN;
            uvAbs(i,j) = NaN;
            cAbs(i,j) = NaN;
            theta(i,j) = NaN;
            speedWindMean(i,j) = NaN;
            speedIceMean(i,j) = NaN;
            UMean(i,j) = NaN;
            VMean(i,j) = NaN;
            uMean(i,j) = NaN;
            vMean(i,j) = NaN;
            cu(i,j) = NaN;
            cv(i,j) = NaN;
        end
        if latRef(i,j)>87.5
            F(i,j) = NaN;
            r2(i,j) = NaN;
            UVAbs(i,j) = NaN;
            uvAbs(i,j) = NaN;
            cAbs(i,j) = NaN;
            theta(i,j) = NaN;
            speedWindMean(i,j) = NaN;
            speedIceMean(i,j) = NaN;
```

```
            UMean(i,j) = NaN;
            VMean(i,j) = NaN;
            uMean(i,j) = NaN;
            vMean(i,j) = NaN;
            cu(i,j) = NaN;
            cv(i,j) = NaN;
        end
    end
end

%% Next step: draw the maps
% Input: latRef, longRef, what to plot
close all

%F: in percent
figure
title(strcat(Title,', F'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = F*100;
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
load coast
plotm(lat,long,'k')
caxis([0 2.5]) %sets the scale of the colorbar
savefig(strcat('3m',quarter,'F'))

% r2:
figure
title(strcat(Title,', r2'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = r2;
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
plotm(lat,long,'k')
caxis([0 1]) %sets the scale of the colorbar
savefig(strcat('3m',quarter,'r2'))

% number of data points
figure
title(strcat(Title,', number of data points'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = nDataPoints;
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
plotm(lat,long,'k')
caxis([0 500]) %sets the scale of the colorbar
savefig(strcat('3m',quarter,'nDP'))
```

```
% theta
figure
title(strcat(Title,', theta'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = rad2deg(theta);
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
plotm(lat,long,'k')
caxis([-35 35]) %sets the scale of the colorbar
savefig(strcat('3m',quarter,'theta'))

% ice velocity: (cm/s)
figure
title(strcat(Title,', real ice speed, cm/s'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = speedIceMean.*100;
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
load coast
plotm(lat,long,'k')
caxis([0 20]) %sets the scale of the colorbar
% arrows:
quivermc(latRef,longRef,UMean,VMean,'reference',0.1)
savefig(strcat('3m',quarter,'ice speedArrows'))

% wind velocity: (m/s)
figure
title(strcat(Title,', real wind speed, m/s'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = speedWindMean;
surfm(latRef,longRef,plotVar);
colorbar('southOutside')
load coast
plotm(lat,long,'k')
caxis([0 10]) %sets the scale of the colorbar
% arrows:
quivermc(latRef,longRef,uMean,vMean,'reference','median')
savefig(strcat('3m',quarter,'wind speedArrows'))

% Current velocity: (cm/s)
figure
title(strcat(Title,', ocean current'))
axesm('MapProjection','ups','fLatLimit',[25 -Inf]) %ups means universal
polar stereographic, 30 is the lat-radius of the map and -Inf just has to
be there
plotVar = cAbs;
surfm(latRef,longRef,plotVar);
```

```
colorbar('southOutside')
load coast
plotm(lat,long,'k')
caxis([0 20]) %sets the scale of the colorbar
% arrows:
quivermc(latRef,longRef,cu,cv,'reference',0.075)
savefig(strcat('3m',quarter,'currentArrows'))
```