Spatial and temporal variability of the fast ice in the Russian Arctic

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Abstract

Fast ice (sea ice, which is fastened to the coast or to the bottom) is a foremost element of the coastal system of both hemispheres. It forms an important interface between coast and pack ice/ocean where key high-latitude interactions between atmosphere and ocean occur. Remote sensing observations are extremely important in fast ice studies because of the difficulties to directly measure its extent in severe polar conditions. Processes driving the fast ice development are still not well understood. In this thesis the spatial and temporal variability of the landfast ice in the southeastern Laptev Sea was described. The fast ice information used in this study was derived manually from the active microwave satellite imagery covering a period of eight seasons (2003-2011). Furthermore, the possible linkages between the fast ice extent and the large-scale atmospheric circulation and the local wind pattern as well as the bathymetry of the study area were investigated. It was found that the bathymetry strongly affects the position of the fast ice edge and can therefore be assumed to be one of the key parameters controlling extent and shape of the fast ice. The impact of local winds on the fast ice development was considered for one season. Investigation reveals that offshore wind plays an important role during the fast ice formation in the beginning of winter. Small-scale variability in the fast ice extent during its fully developed stage might be also explained by winds. The large-scale atmospheric circulation exerts an influence on the fast ice extent as well.

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Contents

List of Figures

List of Tables

Glossary

ASAR	Advanced Synthtic Aperture Radar
ENVISAT	Environmental Satellite
IBCAO	International Bathymetric Chart
SAM	Southern hemisphere Annular Mode
SLIE	Seaward Landfast Ice Edge
SLP	Sea Level Pressure
SOI	Southern Oscillation Index
SSM/I	Special Sensor Microwave / Imager
NCEP	National Centers for Environmental Prediction

1 Introduction

1.1 Study area

The Laptev Sea is a marginal sea of the Arctic Ocean. It is situated between the Severnaya Zemlya islands, the Taimyr Peninsula, the Siberian mainland and the New Siberian Islands. The sea is located within the continental shelf and is therefore characterized by a generally low water depth (mostly less than 50 m). The southern part is extremely shallow with water depth between 20-50 m. A number of big rivers flow into the Laptev Sea. The biggest discharger among them is the Lena River. Together with Yana, Anabar, Olenek and Khatanga the total inflow of fresh water comprises approximately 750 km^3 per year [30]. This volume is equivalent to a 135 cm thick freshwater layer covering the entire Laptev Sea area. The enormous discharge has of course great impact on the strength of the stratification of the water layer. The climate of the Laptev Sea is one of the most severe in the Arctic. The mean January temperature is approximately 28°C. Between October (freeze-up) and June, the Laptev Sea is fully covered by sea ice [3], that can be divided into three features: pack ice, landfast ice and polynyas [11]. Pack ice is sea ice that is freely floating on top of the ocean, while landfast ice is ice that is attached to the coast and therefore not moving. Polynyas are areas of open water and young ice that form under the influence of strong persistence offshore winds, between the seaward landfast ice edge (SLIE) and drifting ice [1].

1.2 Landfast ice definition

A lot of definitions for landfast sea ice can be found in literature. They differ according to the particular interest of the study. However, two common features are present in all definitions, namely, 1) ice has to be contiguous with the land and 2) ice lacks of horizontal motion during a certain period of time, although this period is not specified in definitions. So in every special case one must determine a proper time interval for defining fast ice.

1.3 Landfast ice in the Arctic and in the Laptev Sea

Although in some parts of the Arctic multiyear fast ice was observed [29], the Arctic fast ice has mainly seasonal character. Normally it starts to form in October, reaches its usual winter areal extent at the beginning of January and decays by July. By the beginning of August, most of the shallow waters are free of fast ice [30]. The extent varies significantly across the Arctic. In the Alaskan Arctic fast ice extent is about 5 to 50 km from the coast [5], [31]. In the Siberian Arctic fasi ice is much more extensive, occupiying hundreds kilometers off the coast [33], [4]. In the shallow Laptev Sea, the fast ice can extend up to 500 km off the coast, covering as much as 50 % of the sea area [3]. Formation of the fast ice is possible in two ways: thermodynamically (usually limited to small bays and narrow straights) and dynamically (pack ice getting attached to coast/landfast ice by the influence of winds and ocean currents). The fast ice in the Laptev Sea can be divided into two regimes. These are nearshore bottomfast ice which usually extends out to water depth of approximately 2 m and floating fast ice covering much of the southern Laptev Sea with the seaward edge located usually around 20-25 m isobaths [3],[30]. For comparison, the Antarctic fast ice can be anchored to icebergs grounded in water depths of up to 400 m [26]. In the literature it was pointed out that in contrast to Alaska, where grounded ridges define the location of the seaward SLIE, in the Laptev Sea such processes are minor [24], [10], [11].

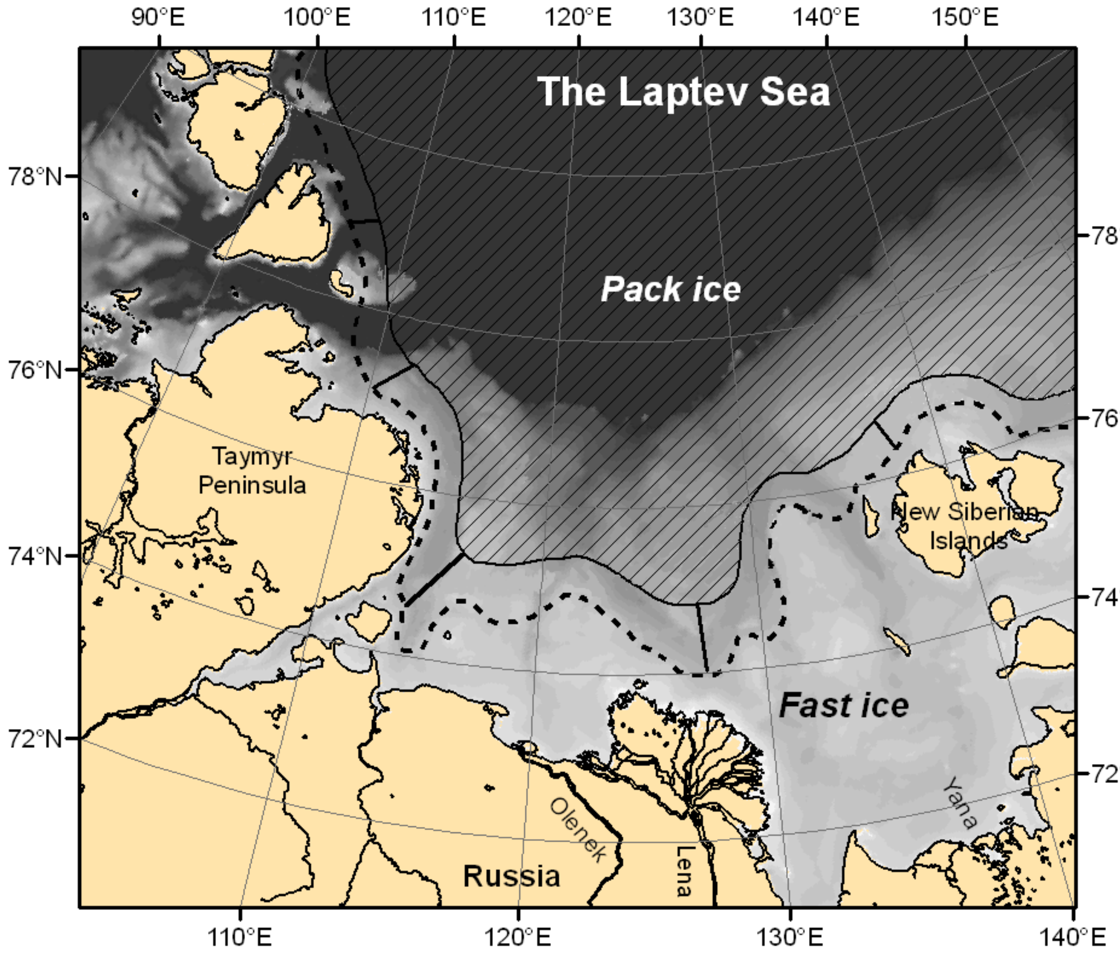


Figure 1: Map of the Laptev Sea. The solid red line shows the study area. The black dashed line represents mean extent of the fast ice at the end of winter. Northward from the black solid line the areas occupied by pack ice are situated. Between pack ice zone and fast ice edge, polynyas are formed.

1.4 Importance of landfast ice

Landfast sea ice is a key element of the coastal system in the Arctic. In the Laptev Sea fast ice further plays a key role in the fresh water cycle, since it stores discharged fresh water in winter and releases it in summer [3]. The position of the SLIE determines the location of polynyas. Extremely low air temperature leads to the formation of young ice in polynyas [21]. Then persistence offshore wind drives it to the pack ice fields and then it goes together with the pack ice to the Fram Strait. The Great Siberian Polynya (system of the Laptev Sea polynyas) is the key source area for sea ice transport by Transpolar Drift 20% of the ice area transported through the Fram Strait is produced there [3]. During generation of young ice in polynyas the intensive dense water formation occurs due to the strong brine rejection, thus the fast ice is connected to such a tremendous process as the global ocean circulation [2], [19]. Moreover, fast ice reduces wave-based coastal erosion by diminishing time of interaction between water and coast [20]. Bottomfast ice maintains submarine permafrost [28]. Fast ice has an important influence on the sediment transport; simply because fast ice occupies much of the potential sediment entrainment areas [12]. Also, it is a habitat for microorganisms and provides a hunting platform for large mammals and native communities [14], [18]. It plays significant role in marine navigation, nearshore oil and gas development.

1.5 Remote sensing of fast ice

Remote sensing observations are extremely important in fast ice studies because of the difficulties to directly measure its extent in severe Arctic conditions. Satellite imagery allows to detect fast ice using criteria of motionless and contiguity with the coast. The usual technique is the examination of correlation between two (or more) images covering the same area with pre-defined time lag between them. Methods in general include passive and active microwave based (independent on weather conditions such as clouds) and visible/thermal infrared based (strongly dependent on weather). However, passive microwave imagery has low spatial resolution and often can not detect small-scale ice motion which distinguishes pack and fast ice. Active microwave technique (based on Synthetic Aperture Radar (SAR) data processing) has a quite high spatial resolution, but it can mainly detect the roughness of a surface. Hence, SAR-based fast ice detection methods fail in stormy weather when the wind-roughened open water and newly formed ice can not be separated. Due to the fact that different methods have different advantages, it is often to use several methods together for supporting each other. Possibility of testing and calibration satellite imagery methods is important practical benefit of fast ice due to its motionless [15].

1.6 Overview and the aim of the work

A number of studies about Arctic and Antarctic landfast ice have been conducted in recent years. But processes driving the development of the fast ice are still not well understood. The current gaps in knowledge mainly steam from the lack of the fast ice data because the air and ship reconnaissance can not provide the sufficient coverage and methods for detecting of fast ice from satellite images are still far from being perfect Only the Alaskan fast ice has been investigated substantially. [23], [22], [25] investigated, based on SAR imagery, the extent and variability of fast ice as well as attachment and detachment events/mechanisms. Links between the extent and the coastal bathymetry and atmospheric forcing at a regional scale were studied by [24]. The authors examined key events (onset of freezing, development and break up) of fast ice during its annual cycle in conjunction with atmospheric parameters such as sea level pressure (SLP), freezing degree days and thawing degree days. Using bathymetry data they further investigated the linkage between the water depth and the SLIE.

Fast ice extent and variability have also been studied in the Kara Sea. [6], [7], [8] investigated temporal and spatial variation of the landfast ice from 1953 to 2001 using Arctic and Antarctic Research Institute (AARI) aircraft observations and Special Sensor Microwave/Imager (SSM/I) brightness temperature They found a bimodality in the spring fast ice area distribution. Analysis of surface wind data and SLP indicated that the wind during winter strongly influenced the fast ice development. Also they revealed an impact of cyclonic activity on the fast ice growth and break up.

In the southern hemisphere the influence of several large-scales modes of atmospheric variability phases on fast ice distribution and its variability was examined. Namely, the Antarctic Oscillation of Southern Hemisphere Annular Mode (SAM) and the Southern Oscillation Index (SOI) were assessed by [27] in relation to fast ice areal extent and nearest distance to open water. A strong correlation was observed between this parameters and the SAM index.

The aim of this study is to describe the spatial and temporal variability of the landfast ice in the Laptev Sea. Because information on fast ice extent is only available for the south-eastern part, this study exclusively focuses on the area north and north-east of the Lena Delta (See Figure 1). Note that the fast ice information used in this study was derived manually from active microwave satellite observations covering a period of 8 seasons (2003-2011). Furthermore, this study aims at investigating the possible linkages between the fast ice extent and the large-scale atmospheric circulation and the local wind pattern as well as the bathymetry of the study area.

2 Data and methods

2.1 Fast ice data

The location of the fast ice edge has been mapped manually by means of Environmental Satellite (ENVISAT) Advanced Synthetic Aperture Radar (SAR) images. In total, more than 1.500 ENVISAT SAR scenes, covering the pack ice and fast ice area of the south eastern Laptev Sea were acquired between 2003 and 2011. Note that data coverage is generally lower during first years of orbiting (2003-2006) and higher in the period from 2007 to 2011. The processed ENVISAT C-band wide swath data is VV-polarized and covers an area of approximately 400×800 km^2 with a spatial resolution of 150×150 m^2. Satellite data was processed in Geomatica, calibrated, georeferenced and stored in the polar stereographic projection as a GeoTiff file. Ice drift and new ice formation are easily identifiable on consecutive SAR images. Hence, the determination of fast ice edge and fast ice area is straight forward: Based on two consecutive SAR images, areas of freely floating pack ice, and ice that appears to be without any drifting were determined manually by toggling between image pairs. Areas fixed in space were then classified as fast ice. The clear boundary that exists between moving and stationary ice indicates the fast ice edge. The analysis was done in a Geographical Information System (GIS). The average time difference between image pairs is approximately seven days and shorter. For years with low data coverage, time lag can be larger than seven days but not exceeding two weeks. The fast ice area and edge location was stored in an ArcGIS shapefile. All in all 92 shapefiles were obtained. Table 1 shows the amount of data (shapefiles) available in each month of each year. x means data which can be used in the SLIE representation, but can not be used for analysis of area due to the large gap in the spatial coverage. (See also in Results)

Table 1: Data coverage

season/month	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
2003-2004	0	1	1	2	1	1	1	1
2004-2005	0	0	1	2	0	0	0	0
2005-2006	0	0	1	1	0	0	0	0
2006-2007	0	x	x	x	x	2	1	0
2007-2008	0	1	4	4	4	4	4	2
2008-2009	1	1	3	4	1	4	4	2
2009-2010	0	2+1x	4	4	4	2	0	0
2010-2011	0	0	3	3	5	3	0	0

For generalisation (due to the lack of the data spatial coverage in some years) all shapefiles were clipped using the common cliche which was created based on the data of 2003-2004 years when the coverage was minimal. Below, the linkage between fast ice extent and bathymetry and atmospheric forcing is investigated by means of fast ice area, rather than fast ice width information. Note that a method to derive fast ice width automatically by measuring width along transects which connect points on the coastline and on the SLIE was proposed by [24]. However, for this approach, the coastline investigated in this study is far too complex in shape (e.g. occurrence of deep embayments).

2.2 Bathymetry data

The linkage between ocean depth and fast ice edge location is examined via sea floor depth information taken from the International Bathymetric Chart of the Arctic Ocean (IBCAO), Version 2.2 (1 minute resolution) [16]. The water depth under the SLIE was obtained as follows. For each point on the SLIE (all in all approximately 100-150 points on each SLIE) the nearest point from the bathymetry grid was found. And the value of grid point was assigned to the SLIE point.

2.3 Vorticity index

The vorticity index was used in this study to investigate the linkage between atmospheric circulation and fast ice extent. It was first introduced by [32]. The vorticity index characterizes the direction and intensity of the atmospheric circulation over the central Arctic. When the vorticity index is positive, the Siberian High (high SLP center) in the western Arctic is weaker while the Islandic Low (low SLP center) is stronger. That means the circulation tends to be cyclonic. Conversely, if the index is negative, the Siberian High is strong while the Islandic Low is suppressed and circulation is anticyclonic (See Figure 2)

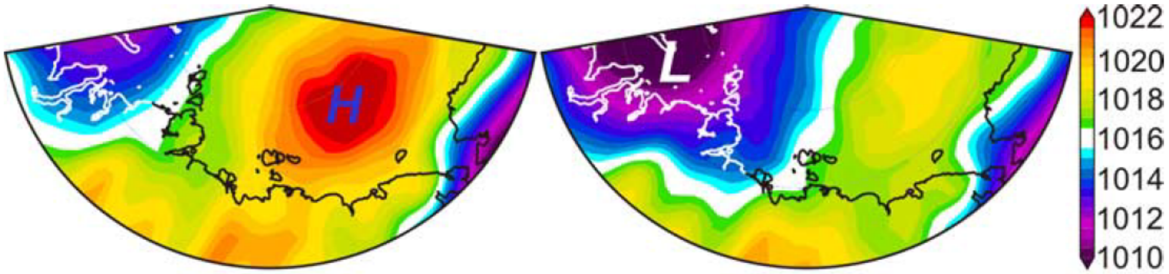


Figure 2: Winter (November-May) long-term mean SLP (mb) for negative (left) and positive (right) vorticity years. Figure is taken from [9]

The vorticity indexes of each month for the period of interest were obtained by calculating the finite-difference numerator of the Laplacian of SLP values for the area between 125°E - 150°E and 77.5°N - 82.5°N. (See Figure 3).The monthly SLP data were taken from the National Centers for Environmental Prediction (NCEP). [17]

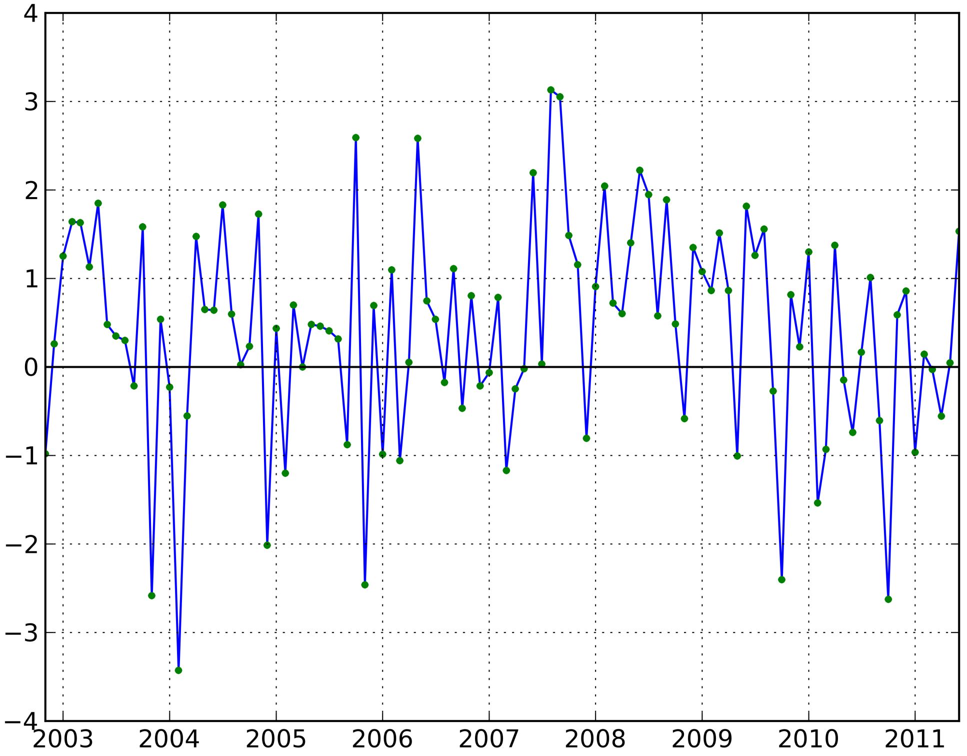


Figure 3: Winter index, computed from monthly mean SLP for the period from 2003 to 2011

2.4 Daily zonal and meridional winds

Beside the impact of large scale atmospheric circulation, this study further examines the role of local winds on the fast ice development. However, due to temporal restrictions of this thesis, the investigation is limited to a single year only (2007-2008). For 2007-2008, information about surface zonal and meridional winds were taken from NCEP([17]) for point situated at 132.5°E, 75°N. Figure 4 shows the wind direction and strength from December 2007 to July 2008.

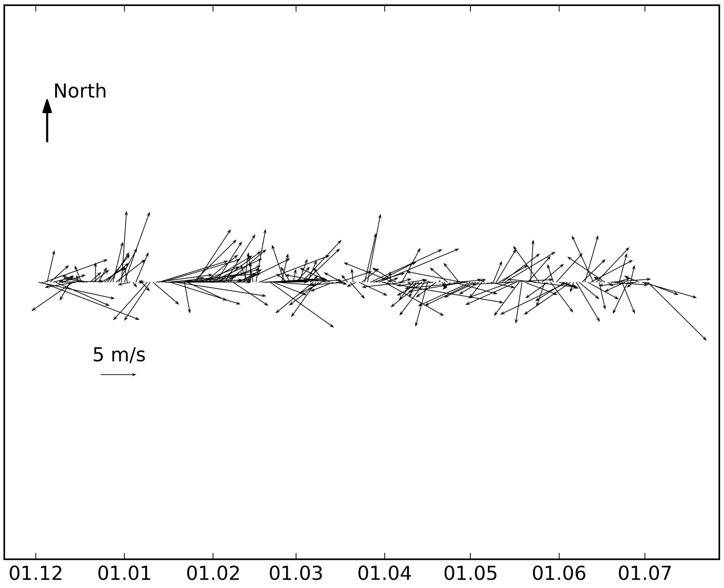


Figure 4: Wind speed and direction between December 2007 and July 2008 at 132.5°E, 75°N. The arrows point towards the direction of flow, with their length representing the strength

3 Results

3.1 Variability of fast ice

Below, the spatial and temporal variability of the fast ice within the study area from 2003 to 2011 are investigated. Figure 5 shows the development of fast ice mainly from December to May. Because the temporal resolution of the fast ice data is not very consistent (see Table 1) and the coastline is complicated, a monthly mean extent cannot be calculated easily. Instead, for months with high temporal data coverage, the most representative fast ice extent was used.

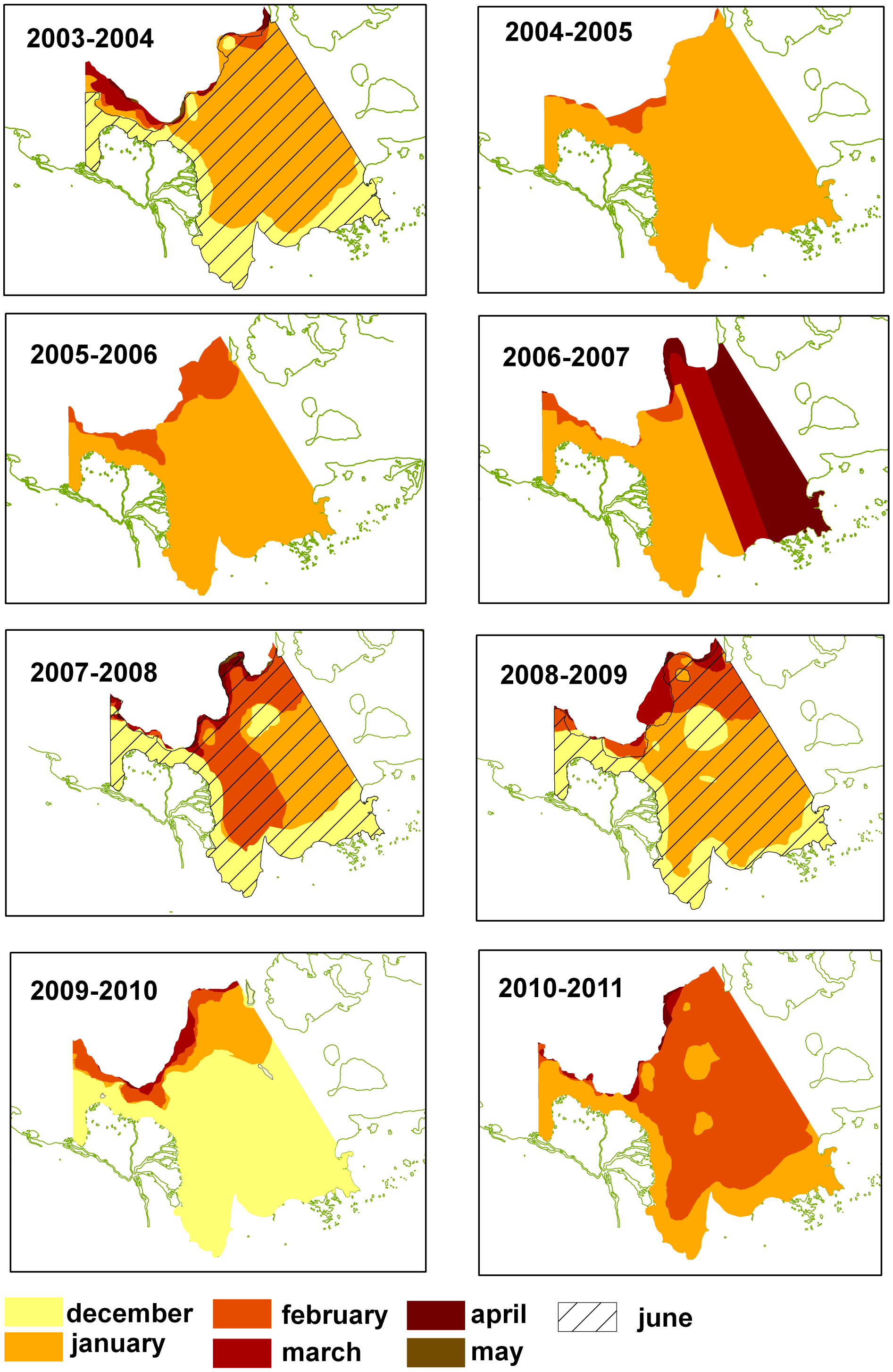


Figure 5: Spatial and temporal variability of fast ice extent from December to June between 2003 and 2011

Intraannual variability is mainly characterized by quite rapid growth of the fast ice from comparatively narrow near-shore band to a fully developed stage. On average, this process takes one month, sometimes even less.. The band has a minimal width in the north and northeast of the Lena Delta (20-30 km) .The width is maximal in the Bour-Khaya Gulf and in the southeastern part of the Yana Bay (100-130 km). The rapid growth was observed usually between the end of December and the end of January. But in single seasons rapid growth occurred in November-December and January-February. After the fast ice has reached its fully-developed stage, changes in extent are only minor, until the summer decay. However, summer is not covered by the satellite data. In addition to the nearshore landfast ice bands that develop usually in early December one can observe the presence of partially grounded ice further offshore. Possible mechanisms of the fast ice development at this stage will be discussed later in this thesis.

Summary of each season:

2003-2004:

Date of the first observation: December 7

Date of the last observation: June 18

Maximal area in April 15

2004-2005:

Date of the first observation: January 1

Date of the last observation: February 5

2005-2006:

Date of the first observation: January 1

Date of the last observation: February 1

2006-2007: significant gap in the data spatial coverage. Only April 21 and May 10 data were taken for area analysis. In Figure 5 all data are shown for observation of ice edge at least on the limited area.

2007-2008:

Date of the first observation: December 28

Date of the last observation: June 21

Maximal area in May 6.

The feature of this season is nonuniform growth in January. From January 7 till January 19 the fast ice advanced only in the eastern part of the sea, leaving the huge region in the western part free of fast ice. This season will be considered further as an example for investigating local wind impact on the fast ice extent.

2008-2009:

Date of the first observation: November 14

Date of the last observation: June 28

Maximal area in March 4.

2009-2010:

Date of the first observation: December 7 (gap in the coverage)

Date of the last observation: April 10

Maximal area in March 18.

This season was notable for the enormous early advance from the nearshore band in December 7 to the vast extent in December 16. By this date fast ice occupied 80 % from the maximal area in this season.

2010-2011:

Date of the first observation: January 2

Date of the last observation: April,19

Maximal area in April 6.

In this season quite late advance was observed. By January 25 fast ice occupied only 40% from the maximal area. Then by February 7 a big advance (97 % from the maximal area) took place.

Time series of fast ice area for each season are given in Figure 6. The x-axis represents the day of the year, with 0 corresponding to January 1. The y-axis corresponds to the fast ice area given in km^2, $\times 10^3$. 2008-2009 and 2009-2010 seasons show highest overall fast ice extent in winter. The most extensive area of 155 000 km^2 was observed in March 18, 2010. Rough estimation of a fast ice width at the same time gives about 550 km off the coast in the broadest part. The minimal area in the fully developed fast ice stage was observed in 2006-2007 season, although only two data for this season are presented. In 2009-2010 a significant loss of area was observed. In 10 days fast ice lost 25% of area and then, after two weeks, recovered in size again. Figure 7 shows this event in more detail.

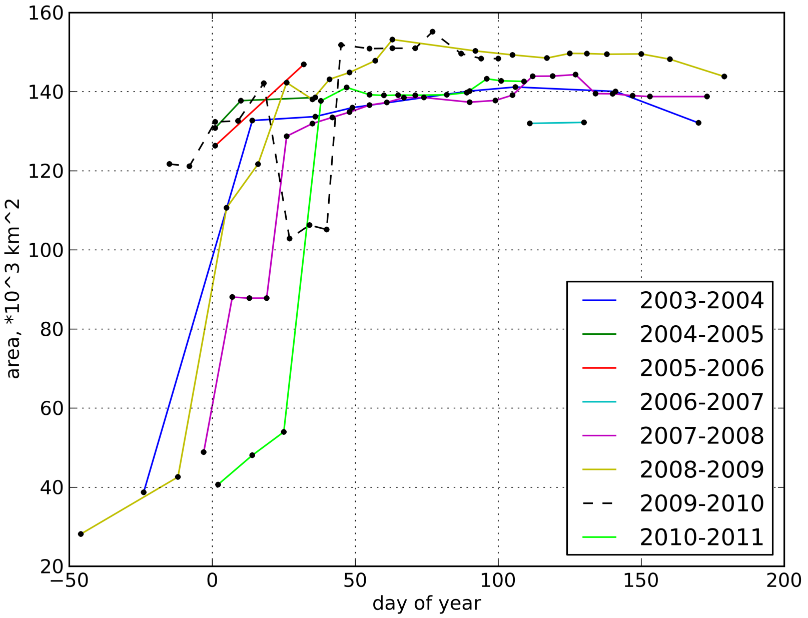


Figure 6: Fast ice area development (dashed and solid lines) in the south-eastern Laptev sea. The dots refer to the date of observation. The color coding of the line represents the year of observation.

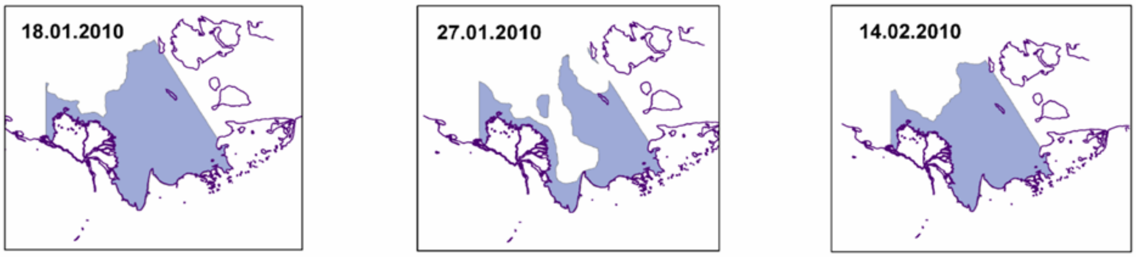


Figure 7: Break up event

Figure 8 shows the position of the SLIE in January, February, March and April between 2003 and 2011. January is the month with the highest variability in the position of the SLIEs. Other months show much less variability. On average it amounts to 60 km, with less variability to the north of the Lena Delta (40 km), and higher variability (80 km) in the northeastern part of the study area. February, March and April do not show clear the most southward and northward SLIE; it varies within the study area (except perhaps, April, when 2007 year shows the obvious most southward extent).

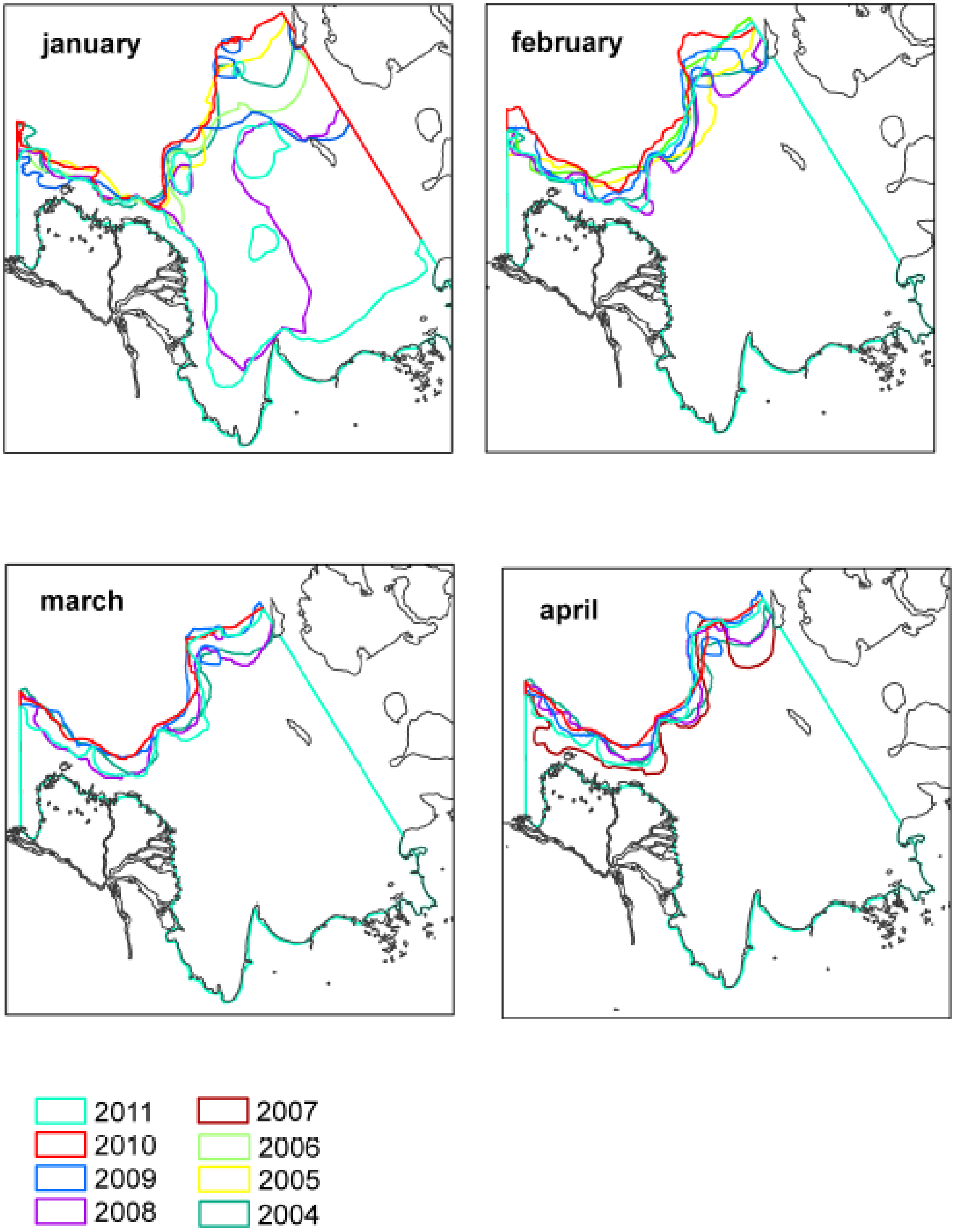


Figure 8: Position of the SLIE in January, February, March and April for different years. Colors represent years of observation.

3.2 Linkage with bathymetry

Figure 9 shows the IBCAO dataset with the SLIEs for single months plotted on top (all in all 37 SLIEs). Land areas are shown in dark red, while points, deeper than 50 m are shown in deep blue. The position and shape of 20-25 m isobaths coincides with many of the SLIEs shown in Figure 9. Note that the variability of SLIE locations in shallow areas (3-10 m), where potential grounding takes place, is generally much lower than over deeper areas (¿ 10 m). This suggests that at least in the shallow areas of the south-eastern Laptev Sea, the fast ice extent seemed to be strongly linked with the bathymetry. The pink line in the figure represents the position of fast ice edge in February, 9, 2010, when the break up, described in a section 3.1, took place. As easy to see, fast ice is still present on the most prominent zones of bottom topography.

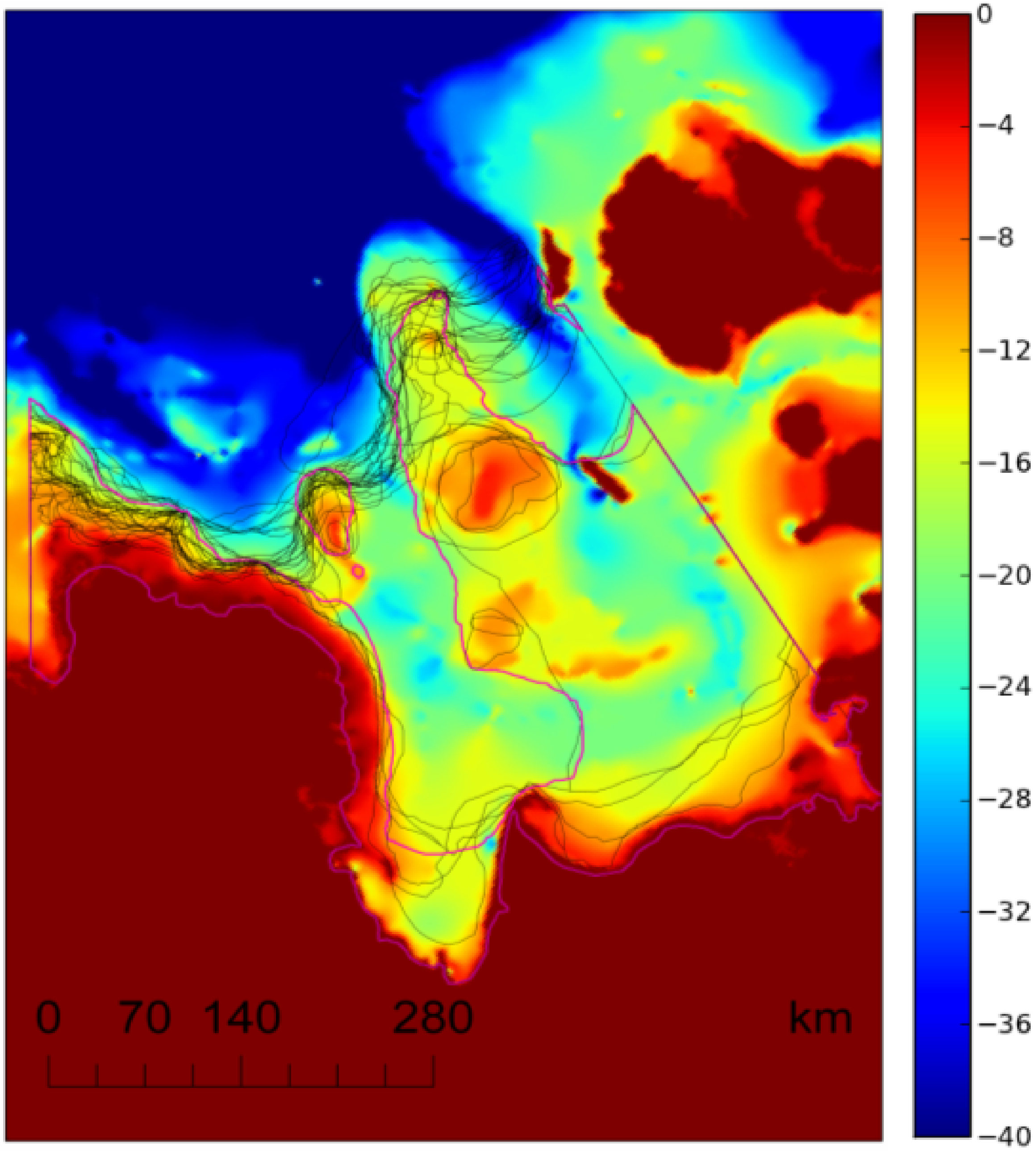


Figure 9: Bathymetry map of the study area. Black solid lines represent a position of the SLIE for single months of each year from 2003 to 2011. The pink line shows the position of fast ice in February, 9, 2010 (during the break up event).

Further evidence of an existing linkage between the fast ice edge location and the bathymetry underneath is given by Figure 10. The figure shows the distribution of water depths occupied by the SLIE in December, January, February, March and April for all years. One can easily see that towards late winter, the position of the SLIE advances into deeper water. In December three modes with 4-5 m, 10 m, 14-15 m water depths are observed. In January these modes are shifted to 10 m, 15 m and 19 m respectively. By March the histogram reaches unimodal distribution with the modal value equals to 19 m. In April this mode is not so pronounced, but 19 m water depth is still the most frequent.

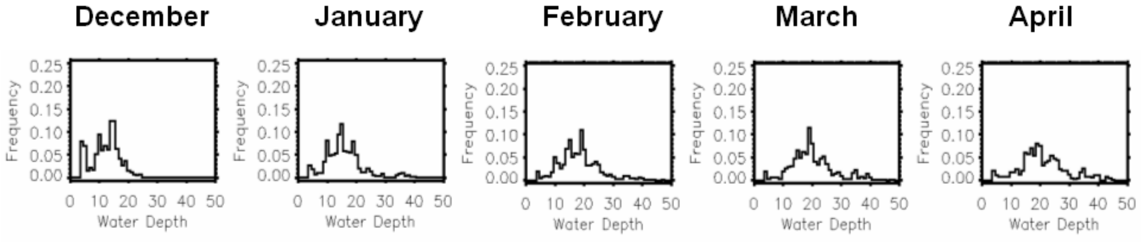


Figure 10: Monthly histograms of water depth at the SLIE.

3.3 Linkage with large-scale atmospheric circulation

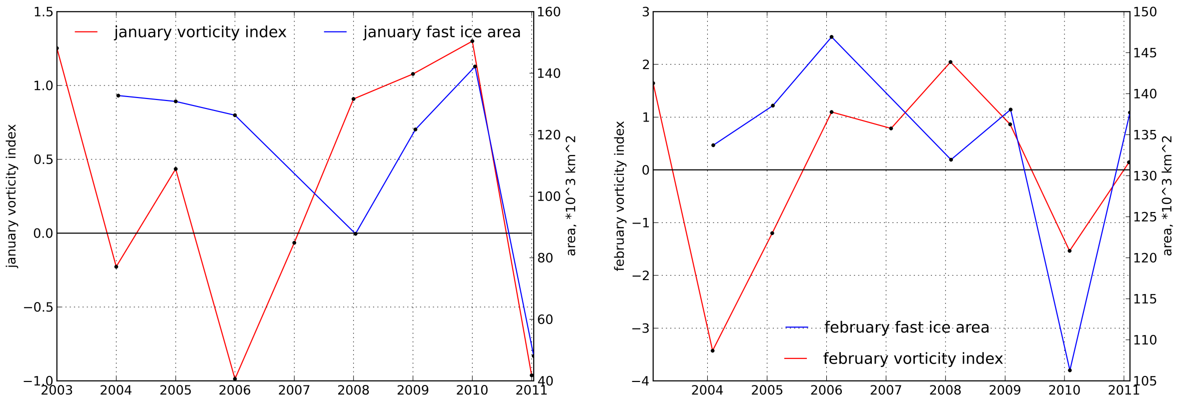
A correlation analysis was performed to investigate possible links between fast ice extent and vorticity index. Correlation between monthly fast ice area for the whole period from 2003 to 2011 and vorticity index (taken for corresponding months) displays low correlation coefficient (R=0.16). However, more detailed analysis including separate correlation assessments for different years shows higher coefficients for three out of five years. Results are shown in the Table 2. Years from 2005 to 2007 were excluded from analysis due to the lack of the data,

Table 2: Correlation coefficients (fast ice area and vorticity index)

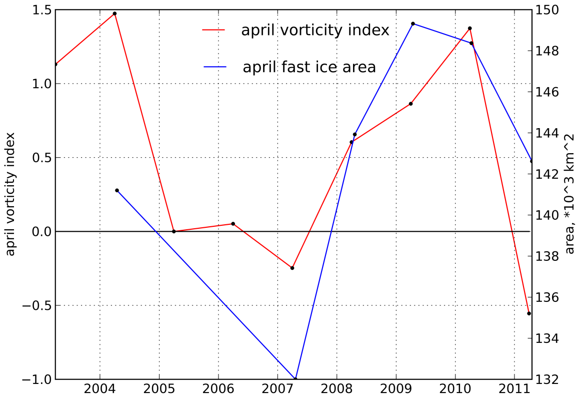
season	coefficient
2003-2004	R= - 0.16
2007-2008	R= 0.75
2008-2009	R= 0.23
2009-2010	R= 0.48
2010-2011	R= 0.8

Seasons 2007-2008, 2009-2010 2010-2011 demonstrate high correlation coefficients. It suggests that increasing (decreasing) of fast ice area might be connected with cyclonic (anticyclonic) activity.

Correlation between January, February and April fast ice area and corresponding vorticity indexes was also investigated. It gave quite high coefficients: R=0.55 for January, R=0.35 for February (including break up event), R=0.48 for April. Time series of fast ice area and vorticity index are shown in Figure 11 a),b),c):



a) b)



c)

Figure 11: Time series of fast ice area (2004-2011) and vorticity index (2003-2011): a) January, b) February, c) April

Correlation analysis of January fast ice area and vorticity index averaged through November, December and January gave a coefficient R= -0.15. However, April fast ice area correlated with averaged through November to April vorticity index with the value R=0.47.

3.4 Linkage with the local wind pattern

Examination of the influence of the large-scale atmospheric circulation on the fast ice variability probably does not give the full understanding of observing processes. Thats why we should consider the impact of wind strength and direction on the fast ice extent in more regional scale. Unfortunately, the lack of time did not allow investigating the whole time period from 2003 to 2011. Only one season 2007-2008 was considered. Following mechanism for fast ice growing and breaking up is suggested. On the early stages of formation offshore wind can lead to the anchoring of newly formed drifting ice to existing spots of grounded ice which was described in sections 3.1 and 3.2 and, therefore, to increasing fast ice extent. In a fully-developed stage, conversely, offshore wind can break up big floes from fast ice and onshore wind can push together drifting pack ice and fast ice. In Figure 12 the development of the fast ice area for 2007-2008 is shown (upper panel) as well as the North (South), North-East (South-West) and South-East (North-West) wind components (down panels, gray lines). The running average over seven days was calculated and shown in red. The window size corresponds to the temporal resolution of the fast ice data. As easy to see, the biggest amplitude has the North-East (South-West) component, whereas the South-East (North-West) component is weak. Quite strong North component at the end of December-beginning of January and strong North-East component from the middle till the end of January support the idea, described at the beginning of this section. Indeed, the period of the area growth coincides with the period of strong offshore winds.

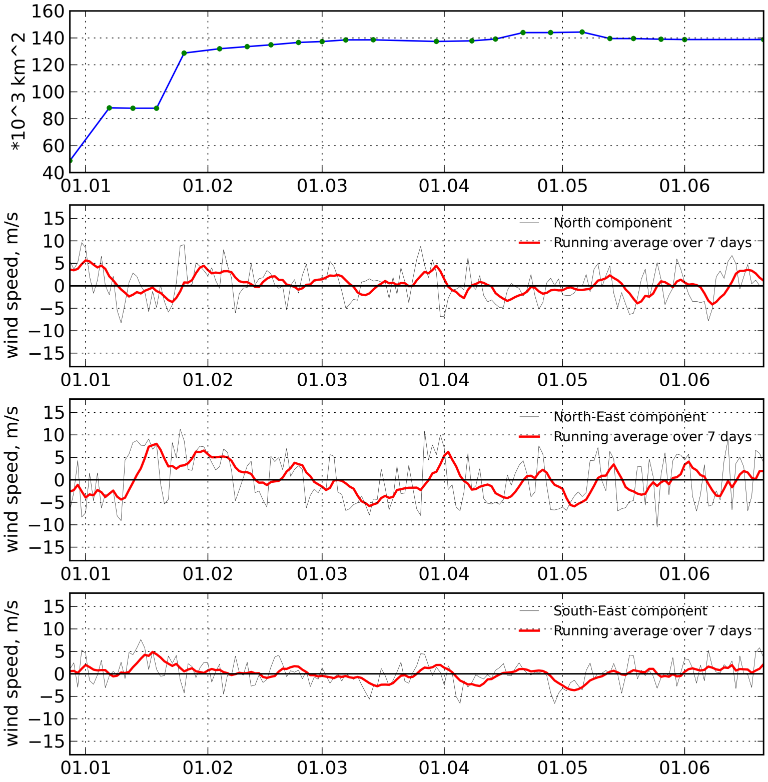


Figure 12: Time series: upper panel: fast ice area development from December 2007 to July 2008; lower panels: different wind components. Red line shows running average over 7 days interval.

In Figure 13 fast ice area and wind components are shown again, but the early stage of formation was left out to enlarge the scale of fully-developed stage of the fast ice formation. This was made for the investigation of possible wind impacts on the fast ice changing at this stage. Slight decrease of area in the end of March was conducted by strong North and North-East wind components. However, comparatively rapid increase of area from the middle of April to the beginning of May hardly ever can be explained by onshore winds the South and South-West components were not strong and persistence. However, offshore winds in this period were absent as well so, fast ice could develop thermodynamically in this relatively calm time interval.

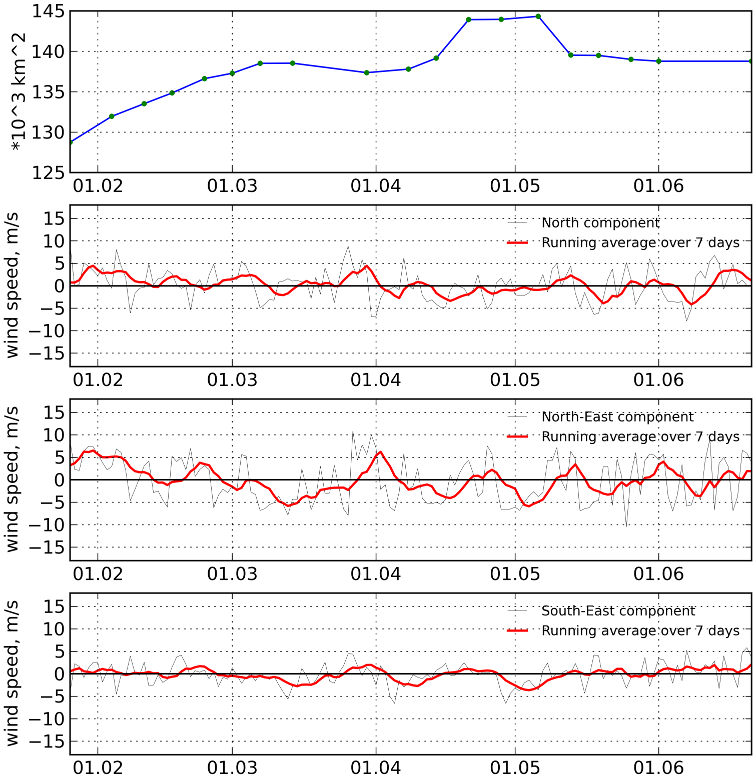


Figure 13: Time series: upper panel: fast ice area development from February to July 2008; lower panels: different wind components. Red line shows running average over 7 days interval.

4 Discussion

Although a number of studies in recent years considered the fast ice, it is still not presented in global climate circulation models or coupled ice-ocean-atmosphere models. That's why the investigation of possible links between fast ice variability and different envi-ronmental factors is of importance. From the analysis of ASAR imagery spatial and temporal variability of fast ice in the south-eastern Laptev Sea was investigated. Variability was linked to the coastal bathymetry, the large-scale atmospheric circulation and regional-scale forcing. It was found that the bathymetry strongly affects the position of the fast ice edge and can therefore be assumed to be one of the key parameters controlling extent and shape of the fast ice. In particular, shallow banks situated in the center of the south-eastern Laptev Sea, with a minimum water depth of 3-4 m play a key role in the formation of the fast ice on its early stage. The ice, grounded on these banks, acts as a bottle neck. This significantly reduces pack ice movement in the center of the south-eastern Laptev Sea, leading to the rapid formation of extensive fast ice areas. A similar study was made by [24] in the Alaskan Arctic. They revealed that the position of the SLIE stabilizes at approximately 20 m isobath. They also noticed that the Alaskan fast ice, in distinction from the Arctic fast ice, is more narrowly confined by the coastal bathymetry and less sensible to atmospheric forcing. In particular, grounded ridges in Alaskan regions play a key role in fast ice stabilization. However, heavily ridged ice that may lead to grounding has not been observed in the Laptev Sea by now. It stands to mention that the bathymetry data has an inaccuracy which steams from sev-eral ways. The IBCAO was created basically on ship measurements which may have some inaccuracy. Measurements were proceeded not uniformly and the interpolation also contributed to inaccuracy. In the coastal regions of the Laptev Sea the rate of sedimenta-tion is rather high due to the river discharge and the coastal erosion. It changes bathym-etry significantly. Local offshore wind was identified in a present work as an influence factor for the early fast ice development. It drives newly formed ice towards grounded ice where it then gets stuck. Once the fast ice is fully developed, the wind may further influence the observed small-scale variability at the fast ice edge. The mechanism is following. Drifting pack ice can be attached to the main fast ice extent by onshore wind. And big floes can be breaking away from the main extent by offshore wind. Some authors investigated the local wind impact on the fast ice as well. [6] revealed that in the north-eastern Kara Sea west-erly wind tends to impede fast ice development, whereas easterlies lead to the expansion of the fast ice. [13] examined several discrete case studies in Antarctic (such as anomalous extents and break ups of fast ice) during 8-years period in relation to wind strength and direction. For two of four considered sub-regions wind was identified as a strong influence on fast ice extent. NCEP wind reanalysis data, used in a present work, has a quite large discrepancy with real observations. In Figure 14 zonal and meridional reanalysis wind components for the period from January to May 2008 are shown in red. Real 3-hours data from Tiksi Observatory and their 1-day running average are shown in gray and black correspondingly. Figure was taken just for general illustration of discrepancy. Point (75°N, 127.5°E) differs from the point, taken for representation of wind data in a present work. However, it gives an understanding that true and reanalysis data often are not coincided.

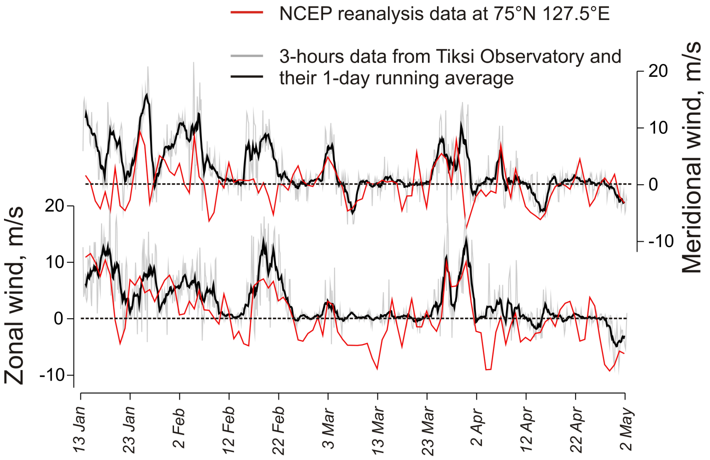


Figure 14: Comparison of real observations and NCEP reanalysis data.

5 Conclusion

The spatial and temporal variability of Laptev Sea fast ice was investigated for the period from 2003 to 2011. Results show that after freeze up fast ice starts to develop near shore and on the shoals, remote from the coast. Usually from the end of December to the mid (end) of January fast ice then undergoes a dramatic increase in extent. The mechanisms that is responsible for the observed rapid growth is as follows. Offshore wind drives newly formed ice towards ice, grounded on shallow banks, where it then gets stuck. The beginning of 2008 year showed that even a few days of strong offshore wind were enough to cause the rapid growth in fast ice extent. By the end of January usually the extent is fully developed and only small-scale changes (except of early breakups) can be observed till the summer decaying. These changes might be explained by local wind as well. Strong offshore winds can breakaway parts of fast ice, whereas onshore wind can drive and then merge pack ice with the basic fast ice extent. However, time limits of this work did not al-low the investigation of the whole fast ice dataset in relation to the wind impact. Only one season was considered. Linkage with bathymetry revealed a coincidence between shape and position of 20 (25) m isobath and those of many seaward fast ice edges on the stage of full development. Histograms of water depth under the fast ice edge distribution showed an advance of fast ice edge towards deeper water. By March distribution reaches unimodality. Depth of this mode is 19 m. Linkage of fast ice area with large-scale atmospheric circulation was investigated as well. Interannual correlation analysis revealed a connection between January, February, April fast ice area and cyclonic (anticyclonic) activity in these months. Intraannual links between atmospheric vorticity and fast ice area displayed high correlation coefficients for single years.

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