

Chapter II. Investigation of ice drift patterns in the Kara Sea using remote sensing (A.Buzuev, Z.Gudkovich, S.Klyachkin, S.Kovachev, V.Loschilov, Yu.Scherbakov, V.Smirnov)

Abstract

The analysis results of historical data of constrained drift of ships in the Kara Sea are represented in this article. The statistic analysis of the parameters of ice drift for 10-day periods was performed by data from the Russian buoys. Ice drift was investigated by data from the “*Meteor-2*” Russian satellite obtained within summer months with the prevailing offshore ice drift in 1985 and with the prevailing coastward one in 1988.

1. Introduction

The main goal of the investigations of sea ice drift was to define the possibility and probability of transport of the contaminants by ice from the Kara Sea to the Barents one and to provide the actual data for model calculations to verify them.

Despite the intensive development of sailing and the research activities within last 50 years, there are no objective and regular data of sea ice drift in the Kara Sea. The ice drift in the Central Arctic currently was studied more significantly than that in the Kara Sea. The ice drift was investigated, at first, mostly, using the data of subjective analysis of composed ice charts, the accuracy and details of which significantly depended on year period, methods and means to perform the ice observations. All available objective data of ice drift in the Kara Sea were obtained within limited year periods for local regions and can not be used for solving the main tasks.

The data of ice drift obtained by the processing of images from the “*Meteor-2*” Russian satellite were used for the model verification. According to the request and the recommendations of the authors of the models the summer periods of 1985 and 1988 were selected for ice drift investigation. Therewith, 1985 was specified as the year with typical offshore drift, 1988 as the year with coastward one according to the data analysis of atmospheric pressure fields. Selecting these years it was accounted that within them the intensive oceanographic investigations in the Kara Sea were carried out, and the coastal meteorological stations were distributed more densely within the summer periods in order to provide the successful navigation. The results of oceanographic investigations and these of meteorological observations were used to emendate the initial data in the models and to increase the spatial resolution of calculation procedures.

Database of ice drift vectors in the eastern Kara Sea created by satellite data was used for the model verification and the analysis of summarized ice drift on polygon.

The unique historical drift data of icebound vessels were used to investigate the ice drift for long periods. The analysis results of long-term observation data drift of vessels proved the alternation of years with offshore and coastward ice drift in the Kara Sea. But it is true for past climatic age.

The statistical data of velocity and direction of the ice drift for 10-day periods were obtained by the qualified data from the Russian buoys (Drifting Automatic Radio Meteorological Stations – DARMS) used in 1953-1972.

2. Ice drift data from the ships

The most long-term observation data of the ice movement in the Kara Sea were obtained during the constrained drifts of the Austrian expedition aboard the “*Tegetthof*” (1872-1873), Danish expedition aboard “*Dimfna*” (1882-1883) and the Russian expedition aboard “*St. Anna*” (1912-1914). “*Tegetthof*” drifted somewhere along the boundary of the Barents and Kara seas (between Novaya Zemlya and Franz Josef Land), “*Dimfna*” drifted in the south-western sea area (Figure1). Only “*St. Anna*”, which drifted almost for 1.5 years and started near Yamal Peninsula, crossed the whole Kara Sea from south to the north. From December 1914 she drifted within the Arctic basin (to the north from Franz Josef Land). Brief information about these expeditions is presented in monograph of V.Yu. Vize (Vize, 1948).

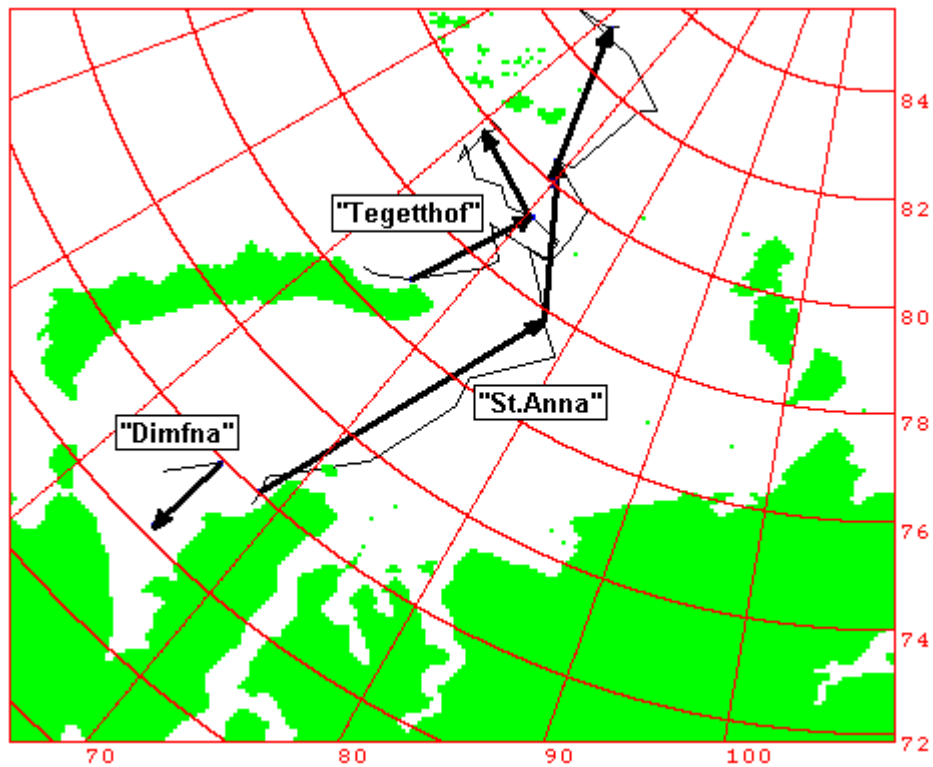


Figure 1. Chart of the long-term constrained drift of the vessels in the end of 19th and the beginning of the 20th centuries.

Table 1 presents the main characteristics of ice drift obtained by observation data of the expeditions mentioned above.

Table 1

Data of the resulting drift of vessels in the Kara Sea

Table 1 (a)

Vessel	Years	October-December		January-March		April-June		July-September	
		Direction (degree)	Distance (km)	Direction (degree)	Distance (km)	Direction (degree)	Distance (km)	Direction (degree)	Distance (km)
«Tegetthof»	1872-73	35	202	20	52	304	153	46	82
«Dimfna»*	1882-83	29	93	25	96	243	120	-	-
«St. Anna»	1912-13	47	441	25	258	349	123	343	208
	1913-14	14	272	303	64	-	-	-	-
Mean distance (km)		252		118		132		145	
Mean speed (cm/s)		3.5		1.5		1.7		1.8	

Table 1 (b)

Vessel/years	October-March		April-September		October-September	
	Direction (degree)	Distance (km)	Direction (degree)	Distance (km)	Direction (degree)	Distance (km)
«Tegetthof»/1872-73	32	252	335	159	10	364
«Dimfna»/1882-83	27	189	-	-	-	-
«St. Anna»/1912-13	39	687	345	330	22	921
«St. Anna»/1913-14	3	299	-	-	-	-
Mean distance (km)	357		245		643	
Mean speed (cm/s)	2.4		1.6		2.1	

Table 1 presents the data of the resulting ice displacement for 3 months (a), half of a year and one year (b) periods. The directions are given relative to 90°E. The significant interannual variability of ice drift velocity is shown up by these data. Despite the drift of expeditions aboard “Dimfna” and “St. Anna” started in similar region, the drift distance of “Dimfna” within winter period was less about by 3.5 times than that of “St. Anna”. The drift velocity within the winter periods (especially, within the first half of winter) is significantly higher than that within the spring-summer ones. In some years the most area of ice cover kept in the sea by the end of summer can be transported beyond within next winter due to interannual variability of ice drift velocity, whereas within the other years it remains within the Kara Sea.

3. Statistical characteristics of ice drift in the Kara Sea

Much data of ice drift in the Arctic seas was obtained in 1953-72 by the buoys (DARMS) developed at AARI. The coordinates of these buoys were defined by medium-frequency (MF) direction-finders located on the coast and islands of the

Arctic seas. Unfortunately, the mean coordinate error was equal to 10-15 km and more in dependence on the distance to direction-finders and the angle between the bearings. So, the error of ice drift and ice drift velocity is commensurable with mean values of these characteristics for short time periods (some days).

Drift data from DARMS and buoys were used to study the ice movement in the Arctic seas (Gudkovich & Nikolaeva, 1961; Gorbunov & Moroz, 1972). But, in the Kara Sea such investigations were not performed because of the observation data insufficiency. Nevertheless, it is considerable to make a prompt to obtain the statistical characteristics of ice drift using the proportions between the distribution of two-dimensional random variable (Kuznetsov, 1935) and the summations of the vectors obtained by DARMS. Such method, which was used in climatology of wind earlier and for study of ice drift later (Gudkovich, 1974), allowed to reach the high accuracy having the insufficient observation data.

The resulting vectors for 10-day periods, which were obtained by buoys in the water area of the Kara Sea limited by 74-78°N and 70-90°E lines were taken from the AARI database to perform the analysis. It was accepted that the spatial changes of ice drift within the specified zone are significantly less than ice drift changes in time. Two data sets, the first of which includes the data for spring period (March-May), the second includes these for summer period (June-August), were formed to account the seasonal features. There are no data, practically, for the other months.

The analysis results of the ice drift data for the Arctic basin (Gudkovich, 1974) showed up that velocity vectors of ice drift in most cases subject to the law of standard elliptic distribution. The most elementary numerical characteristics of this distribution are the following parameters (Marchenko, 1964):

W_x, W_y - components of mean resulting vector;

σ_x, σ_y - standard deviations of random vector components;

W_s - mean value of random vector module;

σ_s - scalar standard deviation of random vector;

r - coefficient of correlation between the random vector components.

The following parameters are the derivatives of these characteristics:

W_r - module of mean resulting vector;

θ_r - its direction

σ - vector standard deviation of random vector;

l - degree of dispersion ellipticity of drift vector;

β - direction of long axis of dispersion ellipse;

q, λ - parameters of climatic constancy of ice drift.

The named parameters are calculated by the following ratios:

$$W_r = \sqrt{\overline{W_x^2} + \overline{W_y^2}} \quad \text{tg} \theta_r = \frac{\overline{W_y}}{\overline{W_x}} \quad \sigma = \sqrt{\sigma_x^2 + \sigma_y^2} \quad l = \sqrt{1 - L^2}$$

$$\text{where } L = \frac{2\sigma_x\sigma_y\sqrt{1-r^2}}{\sigma_x^2 + \sigma_y^2}$$

$$\operatorname{tg} 2\beta = \frac{2\sigma_x \sigma_y r}{\sigma_y^2 - \sigma_x^2} \quad q = \frac{W_r}{W_s} \quad \lambda = \frac{W_r}{\sigma}$$

The main standard deviations, i.e. these in coordinate system, which is defined by the main axes of dispersion ellipse (long (ξ) and short (η)), are the important characteristics of standard elliptical distribution. These values are defined by the following expressions:

$$\sigma_\xi^2 = \sigma_x^2 \sin^2 \beta + r\sigma_x \sigma_y \sin 2\beta + \sigma_y^2 \cos^2 \beta$$

$$\sigma_\eta^2 = \sigma_x^2 \cos^2 \beta - r\sigma_x \sigma_y \sin 2\beta + \sigma_y^2 \sin^2 \beta$$

Theoretically, the probability of getting of the vector endpoint into the dispersion ellipse with σ_ξ and σ_η main semiaxes is equal to about 40 %, in the case of threefold semiaxes it is equal to 99 %. Table 2 presents the calculation results of statistic characteristics of vectors of ice drift velocity for 10-day periods for two seasons. Figure 2 demonstrates the corresponding dispersion ellipses.

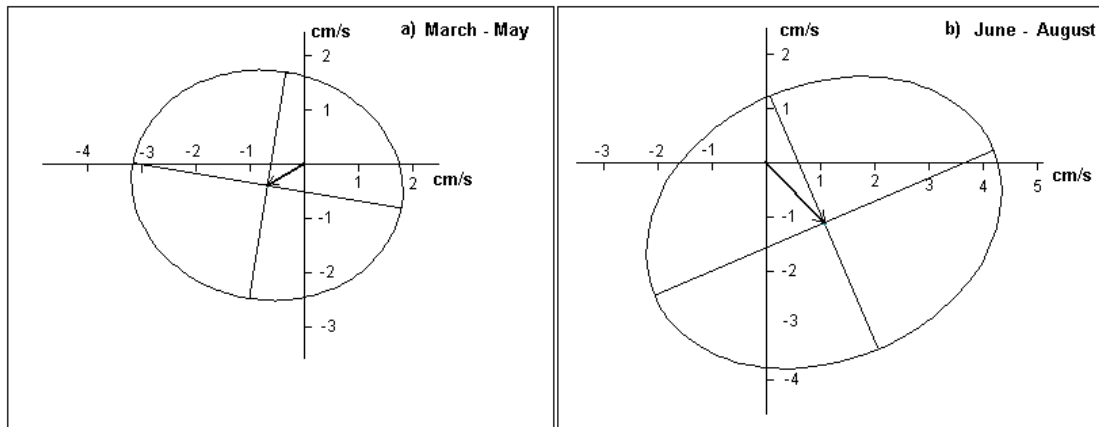


Figure 2. Dispersion ellipse of DARMS drift for 10-day periods

Table 2

Statistical characteristics of DARMS drift for 10-day periods

	March-May	June-August
N (amount of vectors)	25	42
W_x	-0.007	0.011
W_y	-0.004	-0.011
W_s	0.043	0.055
σ_x	0.032	0.041
σ_y	0.037	0.050
σ_s	0.022	0.035
R	-0.051	0.213
W_r	0.008	0.016
θ_r	212.832	-45.845

σ	0.048	0.064
L	0.157	0.288
β	-9.412	23.220
Q	0.181	0.283
λ	0.162	0.245
σ_{ξ}	0.037	0.051
σ_{η}	0.031	0.038

Vectors of the resulting ice drift speed (Fig. 2), which link up the origin of coordinates and the center of ellipses, characterize the most probable drift. Drift velocity is low (0.8-1.6 cm/s), contraclockwise changing of the direction from spring to summer corresponds to the regime of prevailing winds due to monsoon processes. Mean scalar velocity (4.3-5.5 cm/s) well agree with data obtained for the Arctic basin (Gudkovich, 1974) from more representative data sets (about 1700 cases). According to these data, the mean velocity of ice drift decreases when temporal scale increases by power law from 7.5 cm/s (day) to 4.9 cm/s (10-day period), 3.5 cm/s (month), 2.8 cm/s (season), 2.5 cm/s (half a year), 2.2 cm/s (year). Mean values of scalar and vector standard deviations, which are equal to 2.9 cm/s and 5.1 cm/s accordingly for 10-day periods, presented in Table 1 well agree with data for the Arctic basin. So, the statistic characteristics of ice drift velocity obtained for the north-eastern Kara Sea are the reliable ones.

Actual ice drift velocities can significantly differ from the mean ones. According to the observation data of the expedition aboard the icebreaker “Otto Schmidt” in November 1979 to the east from Zhelaniya Cape, the resulting ice drift velocity for 8 days was equal to 21 cm/s, in some days it exceeded 60 cm/s (Abramov & Gudkovich, 1985). A method for calculation of maximum ice drift velocity with given probability is presented in publication of Gudkovich et. al. (1989).

4. Ice drift data obtained by satellite

4.1. Initial data and the processing method

The images of visual range (0.5 - 0.8 μm) of scanning radiometer *MP-900* from the “*Meteor-2*” Russian satellite, which were transmitted in the APT regime (scanning bandwidth is equal to 2100 km, resolution 3.2 x 1,6 km), were used as the initial data.

Satellite images at AARI communication receiver in these years were fixed by photographic camera. That is why, the images processing became more complicated.

The half-tone photo images were scanned with 300 x 300 resolution of the elements in one inch in order to perform geolocation and define the ice drift vectors. After such conversion the last version of the updated geolocation software, which provides the transformation of the images into the files of standard squares in integrated composite photomap of polar stereographic projection, can not be used. So, the geolocation was performed using the VIDEOBOX software, which was developed within these years.

In this software each orbital data image was approximately transformed into the especial photomap of stereographic projection with axial meridian, which is parallel with the track of subsatellite pixels.

The image was displayed, and the coastline image developed by the estimated coordinates of image corners was superimposed on it. Then, the differences of the coordinates of the identical image pixels and the coastline map were measured. The coefficients of the correction equations were defined in order to pass to the coordinates of especial photomap from the coordinates of approximately transformed image.

These rectangular coordinates, which are individual for each image, were recalculated by the software into the geographic ones (degrees and minutes of latitude and longitude). The geolocation accuracy of residual differences of image coordinates and the map lies in the range of 1-3 resolution elements and can be accepted to be equal to 2-5 km (depending on the supporting by control points).

Ice drift was defined, as it was pointed out, in June, July and August. The prompts to define the vectors automatically were not successful due to the intensive ice redistribution and its breaking within the summer period, the distortion of tones and contrasts during the developing of images, low resolution of them and additional image distortions during scanning. That is why, the ice drift vectors were defined only by interactive method by the recognition of the same ice floes on the continuous images in the cloud-free regions. There were 5 continuous observation periods (the total duration period was 806 hours) in 1985 with 4 breaks between the observations. The duration of breaks was from 2 to 16 days (the total duration period was 685 hours), when it was impossible to carry out the satellite ice observations of the visual range due to unfavourable meteorological conditions.

In 1988 the observation conditions were more favourable. There were 3 breaks in observations with duration period of 7, 12 and 5 days. The total duration of observation periods was equal to 1488 hours. The total duration of breaks between the observations was equal to 574 hours.

It is necessary to point out, that each vector field covers not the whole polygon, but only its part free of clouds.

The created database of ice drift vectors for the north-eastern Kara Sea includes 14 ice drift fields in 1985 and the 27 ones in 1988 obtained with the interval from 1 to 5 days. This database was used directly to verify the developed models.

To perform the further analysis and statistic processing of drift data, the geographic coordinates of vectors were recalculated into the rectangular ones of the polar stereographic projection map of 1:1 000000 main scale, i.e. 1 resolution element corresponded to 1 km on locality in the point of tangency. The origin of coordinates was in the pole point. The x-coordinate is directed from pole to equator along the 110 ° E, y-coordinate – along the 200°E. The constant equal to 500 is added to x and y coordinates for all points in order to exclude the negative values in the further calculations. So, the pole coordinates are $X_p = 5000$ and $Y_p = 5000$.

The investigations were performed on polygon in the eastern Kara Sea limited by the coordinate lines of 5800 and 6400 along the x-coordinate and 4000 and 4600 along the y-coordinate. Geographic coordinates of the polygon corners are: 78°52'N, 58°66'E; 81°97'N 83°44'E; 76°96'N, 94°05'E; 74°62'N, 74°46'E. The polygon was divided into grid of squares limited by coordinate lines multiply of 100 resolution elements (100 km). The number of square is accepted to be the number of the shortest coordinate line, which limits it, in the several hundred resolution elements.

Assuming that the fields of ice drift vectors somehow characterize the ice transport for the whole polygon, the mean components of dX, dY vectors were calculated by x- and y-coordinates for each drift field. Then these mean components were summarized by months and for the total summer period.

But little vectors were defined in all drift fields both in 1985 and 1988 also, in the northern square sets, the numbers of which were defined by 58 and 59 x coordinate, because of clouds. In these sets (12 squares) of 14 drift fields in 1985 in 4 squares non of the vectors was defined, in 2 squares one vector accordingly was defined, and only in 1 square 4 vectors were defined. That is why, these square sets were excluded from the further analysis, the polygon was limited by X = 6000 line from the north. Accordingly, the mean vector projections of the measurement range presented in Tables 3, 5 and on Fgs. 3, 5 are related to 6243 point.

The data of ice drift vectors in specified squares (2 for each drift field) excluding the mean vectors in the fields are presented there to investigate the spatial drift variability. The squares were selected accounting the highest possible frequency of observations and the spatial farness of squares from each other. If the selected square did not is related to any field, it was interchanged by the neighbor one.

In connection with the low quality of the initial data and the methods to define the ice drift vectors for summer period, the maximum amount of vectors in each selected square did not exceed 5, and in most cases, was equal to 1-2. That is why, the ice drift vectors were not interpolated into to the grid points and were averaged and related not to the grid points but to the centers of the squares as well as the data for the fields.

Beside the reasons, which caused the ice drift (wind field, surface currents), the velocity and direction of drift of the concrete ice floe depend on the ice distribution and ice characteristics in the zone (concentration, structures), location relative to coastline, islands, stamukhas and morphometric characteristics of proper ice floe (its size, roughness of the above and below surfaces). So, the data set of ice drift is one of the data sets of alphanumeric format for the coding of ice charts developed at AARI. It allows to account all named factors.

4.2. Ice drift in summer 1985

Table 3 presents the mean values of the drift vector projections (components) on the axis of rectangular coordinate system for June, July and August, 1985. Tables 3 and 4 present the charts of ice conditions for the end and the beginning of the observation periods in 1985 with marked summarized vectors of drift fields in total and for the concrete squares.

Mean projections (components) of drift vectors on the axis of rectangular coordinate system for June, July and August, 1985

№ vector field	Beginning	End	Period Hours	Amount of vectors	Mean for field		Mean for the concrete squares 100 x 100 km					
	Day; Hour,	Day; Hour,			dX, km	dY, km	№ Square	dX km	DY km	№ Square	DX Km	dY km
	June											
1	06; 5,8	14; 4,8	95,0	29	- 2,03	6,97	6143	- 12	30	6340	8	- 20
2	14; 4,8	18; 12,6	103,8	25	- 2,08	10,12	6243	- 1	-18	6340	-48	0
Break	18; 12,6	19; 7,0	18,4									
3	19; 7,0	21; 7,6	48,6	35	4,91	-12,46	6143	10	- 4	6340	6	- 6
Разрыв	21; 7,6	01.07; 4,9	237,3									
Total	June		227,4	89	0,80	4,63		- 3	8		-34	- 26
	July											
4	01; 4,9	03; 8,4	51,5	16	15,88	5,69	6043	17	2	6341	18	9
5	03; 8,4	04; 4,1	19,7	29	3,48	- 1,14	6043	8	- 8	6341	6	- 3
6	04; 4,1	08; 8,2	100,1	31	13,87	-17,13	6043	23	-34	6341	28	-28
Break	08; 8,2	24; 6,5	382,3									
7	24; 6,5	25; 8,5	26,0	22	- 9,00	- 8,82	6143	- 11	- 7	6241	-12	- 8
8	25; 8,5	26; 8,8	24,3	35	- 0,54	- 9,71	6143	15	-32	6241	- 4	-10
9	26; 8,8	29; 8,0	71,2	17	- 4,82	- 1,18	6141	0	- 2	6241	- 10	-17
10	29; 8,0	30; 8,2	24,2	47	- 0,34	- 2,83	6043	4	3	6341	- 7	7
11	30; 8,2	31; 8,6	24,4	47	- 0,60	0,28	6043	8	- 1	6341	- 25	7
Total	July		341,4	244	17,93	-34,84		64	-78		- 6	-43
Break	31; 8,6	02.08; 7,4	46,8									
	August											
12	02; 7,4	07; 7,5	120,1	7	- 62,71	- 0,57	6143	- 65	11	6343	- 51	2
13	07; 7,5	09; 6,3	46,8	10	- 13,10	- 3,20	6143	- 14	- 2	6243	- 12	1
14	09; 6,3	12; 5,0	70,7	12	- 4,82	- 1,18	6143	- 26	11	6344	- 37	3
Total	August		237,6	29	- 80,63	- 4,95		-105	20		-100	6
	Sum											
Sum	Total		806,4	362	-61,90	-35,16		- 44	-50		-140	- 63

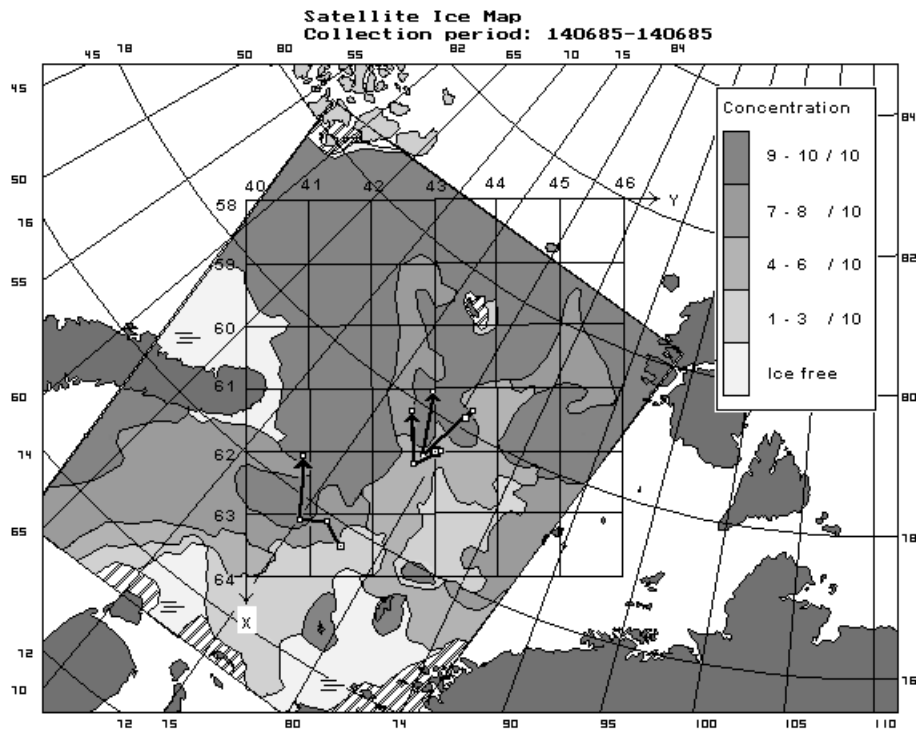


Figure 3. Ice distribution on the polygon in the Kara Sea on June 14, 1985, the resulting vectors (map scale) for observation periods in June-August for the whole polygon (6243 point) and for the concrete squares (6341, 6143).

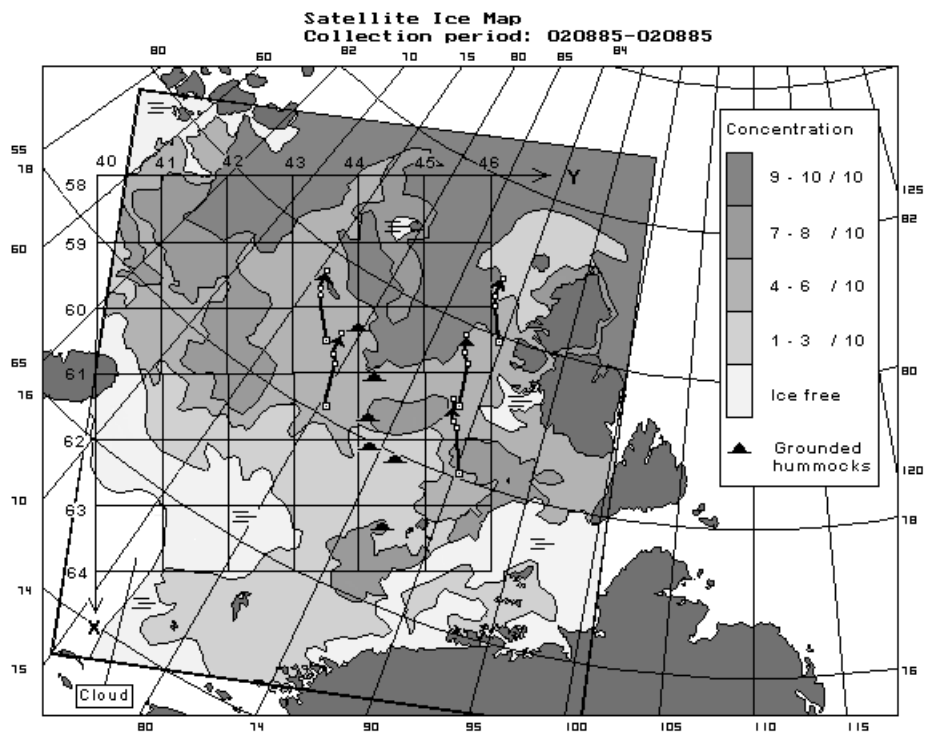


Figure 4. Ice distribution on the polygon in the Kara Sea on August 2, 1985, the drift vectors (map scale) for 3 periods of continuous observations from August 2 through August 12 in concrete squares (6043, 6143, 6145, 6245, 6046).

Analyzing the data of the Table 3 the ice drift for the summer period, 1985 can be divided into the following periods:

- June 6-18: Ice drift was of East direction with small north component, drift velocity is equal to 1.7-2.5 km/day;
- June 19-21 and July 1-8: Ice drift was of SW direction (on July 1-3 – SE direction), drift velocity was equal to 5-7 km/day;
- July 24 -August 12: Ice drift was of NW direction, drift velocity was equal to 1-12 km/day.

The northward outflow ice drift was observed within the period August 2-12. Vector projections on x-coordinate for this period are equal to -80.6 km, these on y-coordinate -5 km. The summarized projections of mean field vectors for the whole summer period are equal to -62 km (x-coordinate) and -35 km (y-coordinate) (Table 3). We name these projections as the summarized projections, but not the resulting ones, because there were the breaks up to 16 days between the observations. Such significant breaks between the observations do not allow to define directly the resulting ice drift vectors for the total summer period. Obviously, it can be done performing the calculations by the models after their correction. But the values of outflow ice drift can be estimated indirectly considering the ice distribution changes within the summer period (Figs. 3, 4).

The southern concentration boundary between 70°E and 90°E in the beginning of observation period (June 14, 1985) extended approximately along 75°N, westerly from 70° N it lowered southward. Along the eastern coast of Novaya Zemlya island the ice massif of 9-10 /10 concentration was observed.

The concentration boundary between 70°E and 80°E displaced northward approximately by 200 km by the beginning of August due to drift and melting of ice; the ice in the south-western sea area melted; ice of 1-3/10 concentration with separate ice patches of 7-8/10 concentration were located easterly from 80°E almost up to the coast.

It can be pointed out that the zones of general configuration with 9-10/10 concentration are kept, and their area is somewhat decreased, the concentration is decreased also up to 7-8/10 and 4-6/10.

The spatial ice drift variability is shown up by the data of mean vector projections located in especial squares. Accounting that the period of the main outflow ice drift within the period August 2-12 is of the great interest for model verification and investigation of spatial drift variability, Table 4 and Fig. 3 present the ice drift data for this period in 5 squares. All vectors both in especial ice drift fields and the summarized ones (in this case they are the resulting ones) are rather close between each other. So, a conclusion can be made that the spatial interpolation can be possible on a radius of 100-200 km when the air transfer is persistent.

Table 4

Mean projections (components) of ice drift vectors on axis of rectangular coordinate system for 3 periods of continuous observations by 5 separate squares in August 1985

№ fields of vectors	Beginning	End	Number of squares and projections of averaged vectors									
			6043		6046		6143		6145		6245	
	Day; Hour,	Day; Hour,	dX km	dY km	DX Km	dY km	dX, km	dY km	dX km	dY km	DX Km	dY km
	August											
12	02; 7,4	07; 7,5	- 73	- 7	- 53	- 5	- 65	11	- 66	13	- 69	- 3
13	07; 7,5	09; 6,3	- 11	3	- 13	- 1	- 14	- 2	- 12	- 3	- 7	- 4
14	09; 6,3	12; 5,0	- 20	10	- 27	11	- 26	- 11	22	3	- 35	2
Total	August		-104	6	- 93	5	-105	20	-100	13	-111	- 5

Table 3 presents the ice drift data in squares more distant from each other. In most cases they are close between each other and differ a little from the mean ones within the whole field. However, in some cases, ice drift in the squares distant from each other approximately by 300 km significantly differs and sometimes occurs in opposite directions. Therewith, these differences (even when they are insignificant for each drift field) are increased. As a result, the summarized vector projections of some squares for months and these for total summer period differ significantly both between each other and from the summarized mean vectors for fields.

4.3. Ice drift in summer 1988

Table 5 presents the ice drift data in 1988. Figs. 4, 5 demonstrate the ice distribution in the beginning and end of summer period.

Ice drift of, mostly, West direction was observed in June 1988. The ice drift with North components was observed within the period June 2-16. Then it had the South components and rather high velocity (3-17 km/day).

In July and August the ice drift of East direction with North and South components prevailed. As a result, the summarized vector was close to zero for the total summer period ($dX = 2.39$ km, $dY = - 4.66$ km).

Ice distribution in June 1988, generally, was analogous to that in 1985. By the end of August the ice in the south-western sea area (westerly from $80^{\circ}E$) melted completely up to $77^{\circ}N$. Northward (up to $80^{\circ}N$) ice concentration became to be equal to 1-3/10 with some ice patches of 4-6/10 and 7-8/10 concentration.

The ice areas of 9-10/10 concentration formed by fast ice breaking-up and ice inflow from the north were located easterly from $80^{\circ}E$.

Some preliminary conclusions about the spatial variability of ice drift made according to the data of 1985 were proved completely by data for 1988. Therewith, it is necessary to point out that within the summer periods of these years all summarized monthly vectors had significant North component in square 6341 in 1985 and 6342 in 1988. This squares were located to the south-west from the balanced midpoint of observation fields.

Table 5

Mean projections (components) of ice drift vectors on axis of rectangular coordinate system in June, July and August, 1988

№ field of vectors	Beginning	End	Period Hours	Amount of vectors	Mean in field		Mean in especial squares 100 x 100 km.					
	Day; Hour,	Day; Hour,			dX, km	dY, km	№ square	dX km	dY km	№ square	dX km	dY km
	June											
1	02; 10,5	03; 23,1	36,6	10	- 9,50	11,10	6143	- 5	11	6342	- 16	17
2	03; 23,1	06; 22,2	71,1	21	4,62	- 7,33	6143	16	- 1	6342	2	- 9
3	06; 22,2	09; 23,1	72,9	26	7,19	3,77	6143	14	26	6342	6	14
4	09; 23,1	11; 22,0	46,9	21	-11,52	3,19	6143	- 2	10	6342	- 20	- 6
5	11; 22,0	12; 22,2	48,2	35	- 5,74	5,83	6143	0	12	6342	- 8	1
6	12; 22,2	13; 12,4	14,2	35	- 6,83	- 0,74	6143	- 6	6	6342	- 10	- 1
7	13; 12,4	16; 23,4	83,0	22	-31,86	-11,77	6143	- 52	- 14	6342	- 22	- 25
8	16; 23,4	17; 22,0	22,6	41	8,49	-10,73	6143	7	- 7	6342	12	- 14
9	17; 22,0	18; 20,5	22,5	28	10,68	- 4,79	6143	9	0	6342	8	- 5
10	18; 20,5	20; 17,7	45,2	20	14,25	- 7,60	6143	11	8	6443	17	- 3
11	20; 17,7	21; 21,4	28,0	24	10,75	-16,71	6144	3	- 19	6443	14	- 30
12	21; 21,4	22; 21,6	24,2	30	4,27	-13,43	6143	- 5	- 15	6342	- 2	- 12
13	22; 21,6	23; 20,2	22,6	40	4,90	- 9,68	6143	7	6	6342	- 5	- 9
14	23; 20,2	24; 20,5	24,3	62	- 1,32	- 0,68	6143	- 7	0	6342	- 8	- 11
Break	24; 20,5	01.07; 12,2	159,7									
Total	June		562,3	415	- 1,62	-83,33	6143	- 10	23		- 32	- 93
	July											
15	01; 12,2	06; 11,5	119,3	14	-10,29	20,79	6244	17	25	6342	- 29	11
16	06; 11,5	07; 10,0	22,5	30	3,40	- 5,37	6244	13	- 3	6342	- 1	- 7
17	07; 10,0	14; 13,9	171,9	18	8,17	3,22	6244	-	-	6342	18	12
18	14; 13,9	20; 05,9	135,9	11	-13,91	25,55	6244	- 49	34	6342	- 21	0
Break	20; 05,9	01.08; 09,3	291,5									
Total	July		449,6	73	-12,63	44,19	6244	- 19	56	6342	- 33	16
	August											
19	01; 09,3	02; 04,4	19,1	81	2,91	2,23	6043	- 9	3	6343	7	4
20	02; 04,4	03; 13,0	32,6	51	0,44	5,31	6042	- 9	3	6343	1	4
21	03; 13,0	04; 11,6	22,6	36	6,39	1,81	6042	1	7	6343	17	- 2
22	04; 11,6	05; 10,1	22,5	62	2,82	2,68	6042	- 2	0	6343	7	- 1
23	05; 10,1	16; 10,2	264,0	23	- 3,48	25,17	6042	42	- 21	6343	- 25	82
24	16; 10,1	17; 06,7	20,6	79	1,10	- 2,18	6143	7	1	6343	7	- 9
25	17; 06,7	19; 07,4	48,7	6	17,00	6,50	6045	26	7	6245	10	5
Break	19; 07,4	24; 10,6	123,2									
26	24; 10,6	25; 05,8	19,2	65	- 3,71	- 4,60	6042	5	- 3	6343	- 7	- 10
27	25; 05,8	26; 08,8	27,0	88	- 6,80	- 2,44	6042	- 8	2	6343	- 16	- 5
Total	August		476,3	491	16,64	34,48		53	0		0	68
Total	sum		1488,2	979	2,39	- 4,66		24	79		- 65	- 9

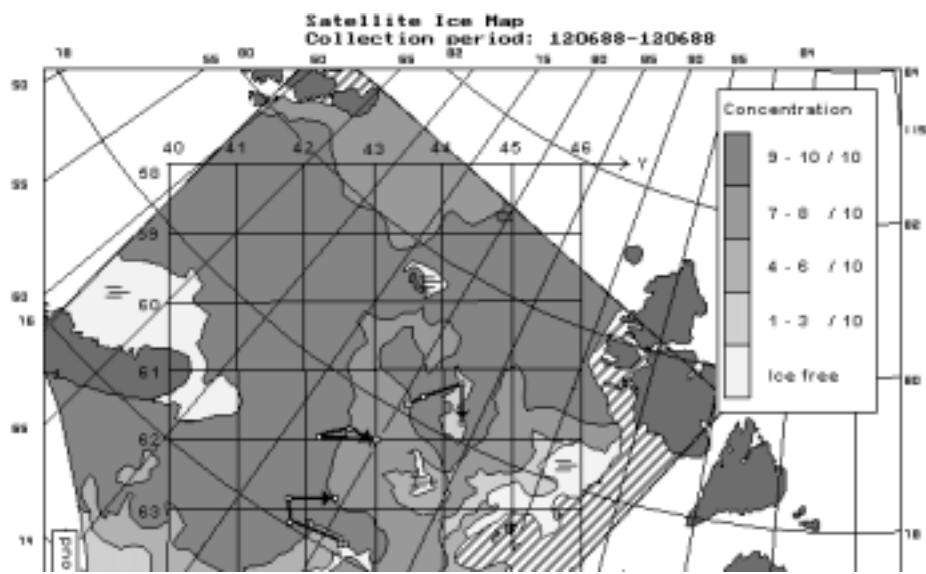
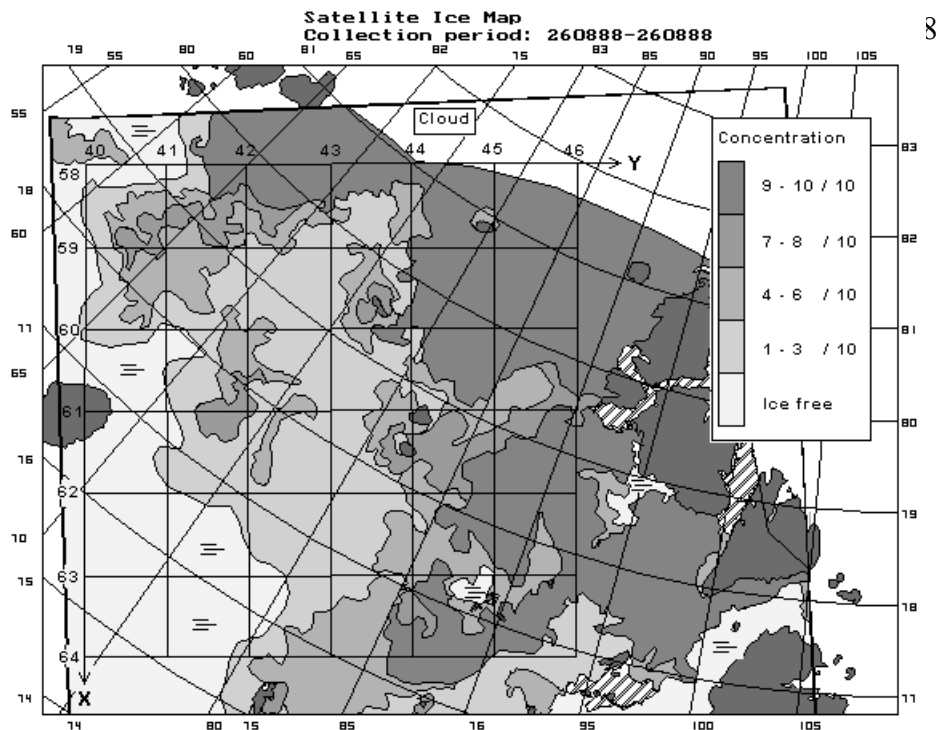


Figure 5. Ice distribution on polygon in the Kara Sea on June 12, 1988, resulting factors (map scale) for the observation periods in June, July and August within the polygon (6243 point) and in especial squares (6342 and 6143).



4.4. Some regional and local features of ice drift

Conclusions about the comparatively little spatial variability of ice drift made on the base of the analysis results of ice drift on polygon concern to the central sea area. Obviously, near the coasts and in the straits the ice drift will be significantly distorted, and these regional and local features have to be accounted in the models.

The islands located approximately along 80°E on, so called, Central Kara plateau make the most significant influence on ice drift. There are many local basins (banks) of 1-8 m depth, on which the stamukhas are formed. Some stamukhas are kept almost without distortion within the whole summer. For example, in 1985 and 1988 they are kept up to late August (Fig.4). Stamukhas are the accretion of ice hummocks on the banks and significantly deformed small ice floes, which are the combined into uniform structure. Mean diameter of stamukhas amounts to 12-14 miles. That is why, they impede the ice drift like the small islands do. In some cases, the influence of stamukhas can bring to the errors of the model calculation results of ice drift. So, this information about the geographic location of stamukhas, their sizes and the period of their life is of great interest and has to be accounted in the models. However, the obtaining of information about stamukhas and their influence on ice drift in the Kara Sea is a subject of special investigations.

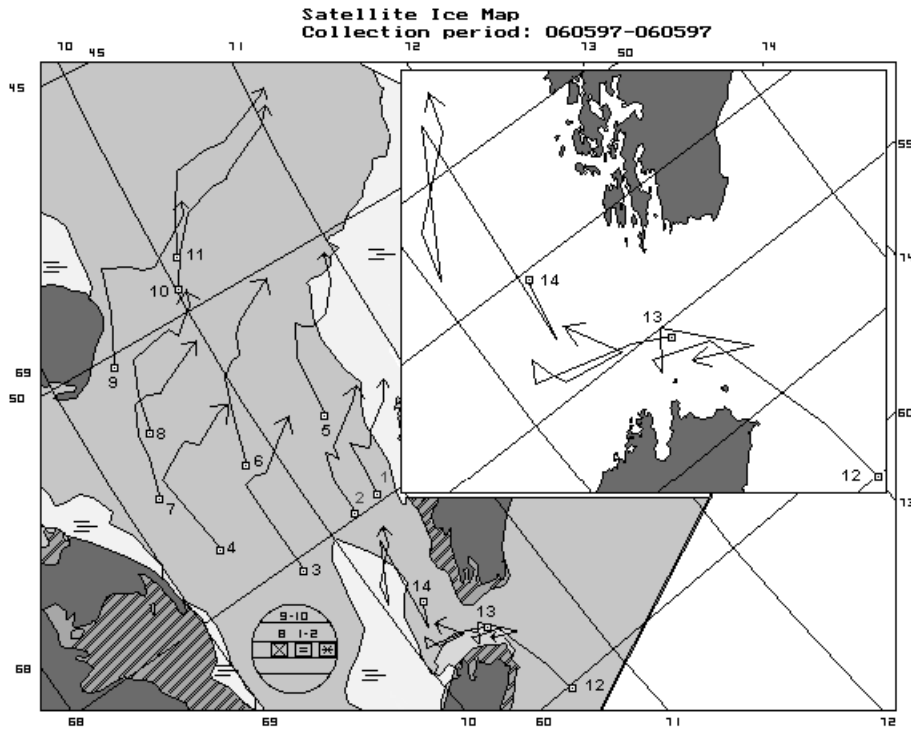
It is necessary to point out that, during the definition of ice drift vectors by satellite images the small-scale eddy ice movement was shown up. For example, ice drift vectors in some cases had the opposite directions on periphery of compacted ice patches, the size of which did not exceed 100 km. Most often, such phenomena were observed in zones of open floating ice or near the ice edge. The especial cases of local features of ice drift in the Kara Sea are presented below.

Kara Strait

The observation results of ice drift in Kara Strait and adjacent water area of the Barents Sea are presented as an example. The parameters of ice drift of the same ice floes were measured by AVHRR data from NOAA satellite within the period from May 6 through May 16, 1997 with 1-2 day intervals of vector measurements.

Figure 7 presents the chart of drift trajectories of ice floe selected in 14 different points of compacted ice massif of 90-110 cm thickness. The trajectories of three ice floes firstly located eastward in the center and westerly from Kara Strait are presented on sub-map in larger scale.

Figure 7. Ice conditions on May 6 and ice drift trajectories (map scale) of 14 ice floes in Kara Strait and in adjacent areas of the Barents and Kara seas for the period May 6-16, 1997 (the square symbols mark the initial location of ice floes)



Trajectories of ice floes with numbers 1-11 (Fig. 7) significantly differ from these with numbers 12-14, which were located directly in the Strait or near it. That is why, the especial analysis of ice drift velocities for the periods between the measurements of the ice floe coordinates is of great interest. Figure 8 demonstrates the diagrams of ice drift velocities in the adjacent area of the Barents Sea. Figure 9 demonstrates it for the strait.

The analysis of the diagram (Figs. 8, 9) showed up, that the ice drift velocities in the central area of the strait (ice floe 13) did not exceed 20 cm/s. At that time, they exceeded 50 cm/s eastward and westward from the strait. Trajectories of ice floes have the general unregulated character and change the direction within some periods to the contrary. But, the resulting displacement within the total measuring period was directed from the Kara Sea to the Barents Sea. It can be assumed that such character of ice drift across the strait is connected with periodical tidal currents.

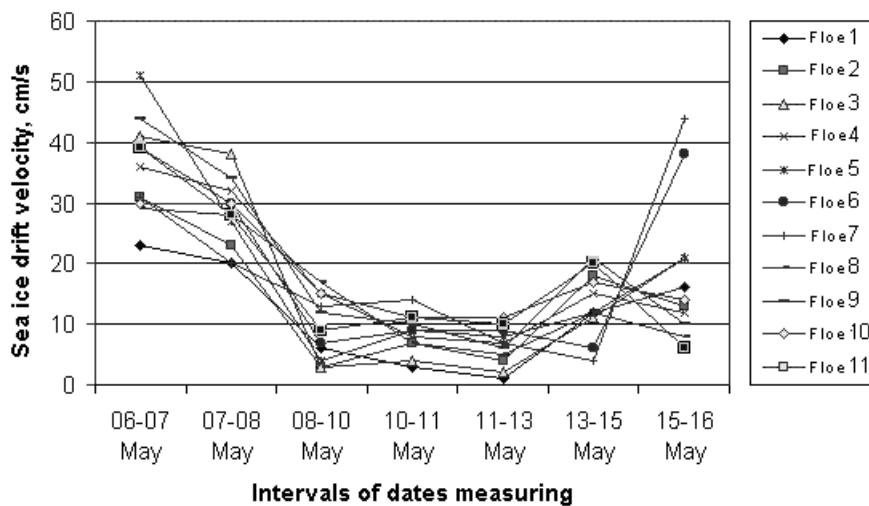


Figure 8. Diagram of the velocities of movement of 11 ice floes in the adjacent area of the Barents Sea to the strait for the consequent time intervals between the measurements of their coordinates for the period May 6-16, 1997.

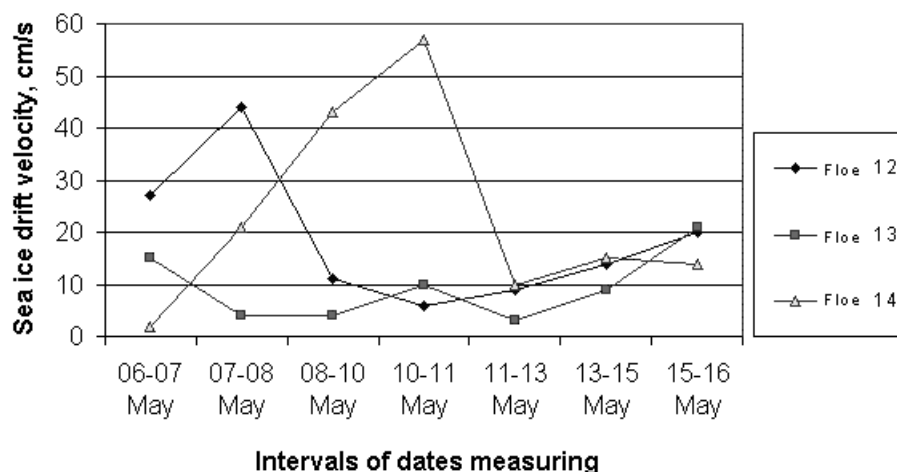


Figure 9. Diagram of the velocities of movement of 3 ice floes in Kara Strait for the consequent time intervals between the measurements of their coordinates for the period May 6-16, 1997

Ice drift in the adjacent area of the Barents Sea has the character of general flow with concurrent increase or decrease of velocity in different its parts (Figs. 6, 7). Ice drift velocities in the beginning of the measuring period were extreme highest (from 20 cm/s to 50 cm/s) and in the middle of it did not exceed 10 cm/s.

The results described above, of course, do not explain all features and consequences of ice drift in this strait. Moreover, the analysis of meteorological conditions, phases of tidal currents within the period of ice drift changes or the model calculation results are not presented there. However, the used method of ice drift investigation allows to find the unobvious ice drift features in the local sea regions.

Vilkitskiy Strait

The ice drift vectors and information about the degree of concurrent compacting and strain of young ice with concretion of residual first-year ice in the strait for the period October 20-23, 1997 were defined by data obtained from ERS-2 satellite. Compact first-year ice and the gray-white one, which covered the strait eastward from 101°E, was forced together to the northern coast (Fig. 10).

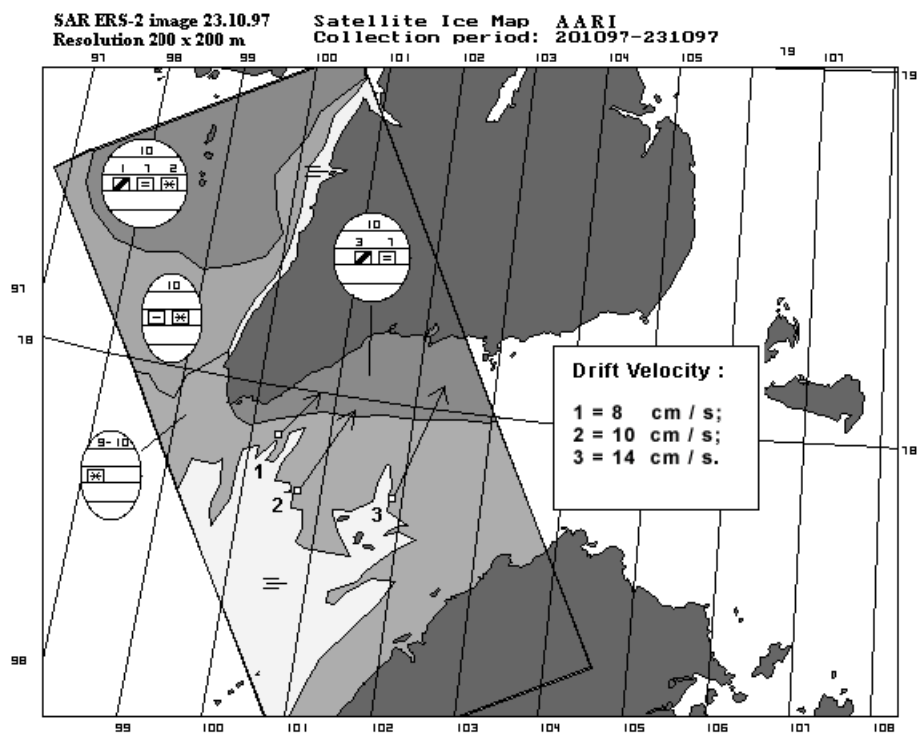


Figure 10. Ice map of the western area of Vilkitskiy Strait on October 23, 1997 and ice drift vectors (map scale) for the period October 20-23 obtained by the data from ERS-2 satellite (the resulting velocities of ice drift are demonstrated on sub-map)

The drift velocity of ice floe (1) near the northern coast is equal to 8 cm/s and almost less by 2 times than that of ice floe (3) in the center of the strait (look the sub-map on Fig. 9), when the directions of three vectors are the same. It can be explained by that the distance from the initial position of ice floe (1) in direction of movement to the barrier is significantly less than that of ice floe (3). So, the ice drift velocity in the direction of the barrier directly depends on the distance up to this barrier and, obviously, on the angle. The same effect of the decrease of wind ice drift velocity can be observed near islands and stamukhas in the ice free sea.

The presented example is a particular case of ice drift in the Vilkitskiy Strait. In August and September the maximum ice drift velocity in the strait sometimes amounts to 115 cm/s (Borodachev, 1998)

The influence of islands

Some islands and the groups of islands significantly impede the wind drift of sea ice. As it was pointed out above, from the windward side the ice drift velocity lowers and ice gradually floats around the barrier forming the polynyas and zones of open floating ice leeward. Ice drift velocity in the direction to the barrier of the compacted ice in winter and the open floating ice in summer depends on the distance up to the barrier. The influence of the barrier on the cruising velocity of ice is observed at the distance more than 500 km (Bushuev & Loschilov et. al., 1998). The sea ice drift in such flow gradually lowers approaching to the barrier. Obviously, the contrary effect of velocity change can be expected in the case when ice drift occurs in the direction of ice free water area. But it is not proved yet.

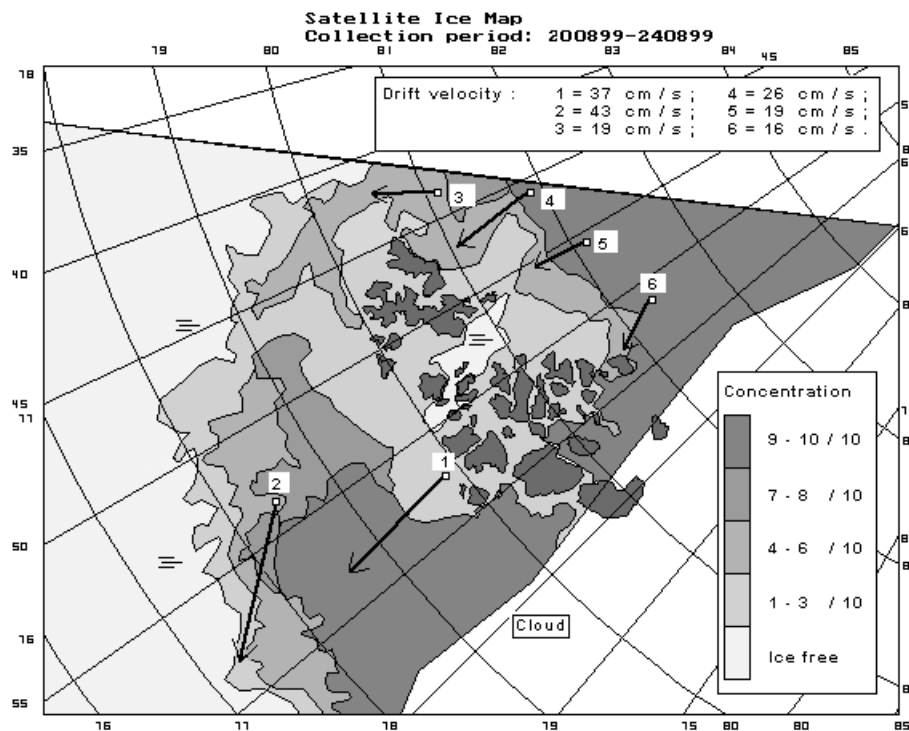


Figure 11. Ice map of the region of Franz Josef Land archipelago on August 24, 1999 according to the data from AVHRR NOAA-14 and the vectors (map scale) of ice floe drift for succeeding 3 days (in the frame of sub-map the velocities of ice floe drift are presented).

Figure 11 presents the map of ice conditions around the Franz Josef Land archipelago developed using the AVHRR NOAA data on August 24, 1999 and the vectors of the resulting ice drift for the previous three days (98.1 hours) northerly and southerly from the archipelago. All vectors are directed approximately southward, the ice drift

velocity southerly from the archipelago amounts to 37-43 cm/s (floes 1, 2, Fig. 11). The ice drift velocity is equal to 16-26 cm/s to the north from the archipelago, i.e. the velocity of coastward drift in the direction to the archipelago is almost less by 2 times than that to the south from it.

The presented above examples of the local ice drift show up that in the process of the regular interaction between atmosphere and ocean the short-periodic and small-scale ice drift changes are formed, which significantly specify the regional ice conditions in each concrete time moment. The mounting of many buoys for this purpose on drifting ice floes is not actual from the view of economics and does not allow to meet the requirements for information necessary to solve the practical and scientific tasks. So, the satellite images of sea ice, which are regularly obtained, are only one really possible source of obtaining the data of detailed ice drift in the open sea.

Conclusion

The performed investigation is the first prompt of the regular monitoring ice drift within summer period. The obtained results allow to make some conclusions and to define the methods for further investigations and improving the drift monitoring technology.

The regularity, details and accuracy of cartography of the ice drift fields are estimated by the quality of the initial satellite images and the possibility of obtaining the information independently on meteorological conditions (cloudiness).

When the data of satellite images of optical range are used as the initial ones, the long breaks between the observations are certain, after which the recognition, even the interactive one, of the same ice floes is impossible. So, performing such investigations later on the principally radar satellite images RADARSAT, "Ocean" with survey range of 400-500 km have to be used. It does not exclude the using images of optical range (visible and IR) with resolution not less than 1 km and enough width of survey range as the additional initial data. It is true, for example, when the ice maps are developed using these images, one of the data arrays is ice drift.

It is necessary to improve the technology for definition of the elementary vector field including the particular automation of interactive method, which have to be used within the summer period.

Elementary accidentally located ice drift vectors have to be interpolated into regular grid points for further calculations and forecasts. It is necessary to perform special investigations to select the optimal algorithm of such conversion.

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