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Analysis of Drift of Sea Ice and Icebergs in the Greenland Sea

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ABSTRACT
Nine Ice Tracking Drifters (ITDs) were deployed on several ice floes and icebergs in the Greenland Sea during a field campaign in September 2012. In this paper we perform analyses of the data retrieved from the drifters. This comprises drift trajectories, velocities, trajectory curvatures, angular velocities and causes of the drift. The role of semidiurnal tides is discussed for the drifting ice. The spectrum of the drift velocities is discussed.

1. INTRODUCTION
The last decade has seen an increasing public and commercial focus on the Arctic regions. Exploration and exploitation of the hydrocarbons in these waters pose significant challenges for industry, especially in the assessment and management of risks along the whole production chain, avoidance of disruptions arising from potentially manageable accidents, and the need to minimise costs arising from adverse environmental impacts. Presently the level of knowledge about physical Arctic environmental loads is insufficient to adequately address these challenges. The drift of sea ice and icebergs is a part of these challenges that impact marine operations and ice management.

The first efforts in studying the drift in sea ice were performed by Nansen in 1893—1896. His ship *Fram* was frozen into the pack ice close to the New Siberian Islands. He believed *Fram* could drift North due to the current set up by the discharge from the Northbound Russian rivers such as Lena River, and drift westward under the influence of Eastern currents (Wiki1, 2012). His idea was taken further by Soviet scientists and the world's first drift station "North Pole – 1" was opened in 1937 (Wiki2, 2012). It was followed by the International Geographical Year ice stations (IGY-A, IGY-B), Arctic Research Laboratory Ice Station (ARLIS), British Transarctic Expedition (BTAE). In modern time satellites enable GPS drift trackers to provide reliable and precise positioning of drifting ice and icebergs typically within 5 m in the horizontal plane. Drift patterns, drift speed variations and relative motion of ice and icebergs for a particular region can be extracted from the drift data.

A region that raises great industrial interest and challenges is Eastern Greenland which is rich with potentially recoverable carbon hydrates. At the same time it is an ice and iceberg rich area. A review on the metocean conditions in the KANUMAS region is given by Toudal et al. (2011).

The Norwegian University of Science and Technology (NTNU) and the Swedish Polar Research Secretariat (SPRS) established in 2012 collaboration in polar research under the umbrella of the memorandum of understanding "Nordic Cooperation in Polar Research" signed at January 29, 2010. A first step in the collaboration between NTNU and SPRS was to perform a research cruise with the Swedish icebreaker *Oden* in the autumn of 2012 to the waters Northeast of Greenland. This cruise called "Oden AT Research Cruise 2012" was supported by Statoil. During the cruise 9 ITDs (drift trackers) were deployed on several ice floes and icebergs in these waters. The goal of the present study is to analyze the drift of these trackers.

2. DEPLOYMENT OF TRACKERS

Five trackers were deployed on icebergs (in one case two trackers on one iceberg) while 4 trackers were deployed on sea ice (in one case two trackers on the same floe). Four of the trackers were deployed directly from *Oden* while 5 were deployed from the helicopter brought on board *Oden*. In the case of two trackers on one iceberg, an additional tracker was deployed on an ice floe close by to compare the drift of the iceberg and the sea ice (See Figure 1).

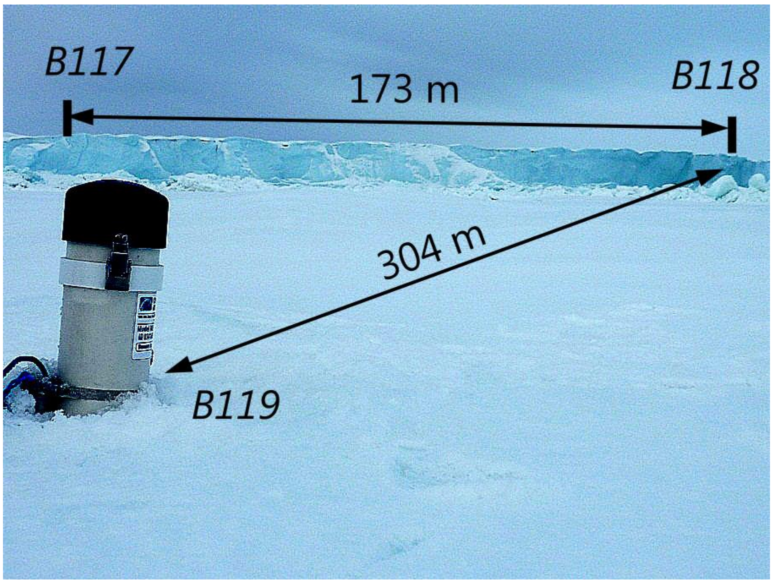

Figure 1. Deployment of trackers; two trackers (B117, B118) were deployed 173 m apart on Iceberg #12 (IB#12) and tracker B119 was deployed on an adjacent ice floe 304 m away from B118.

The deployment was done by means of the helicopter that landed on the iceberg and ice floe, respectively. The procedure was simply to drill a 300 mm deep hole (Ø150 mm) in the ice for fixation of the trackers. All the trackers were equipped with deadweight to secure sinking upon iceberg/ice floe deterioration so we could avoid reporting of drift of the trackers in water. Two different trackers were used: Ice Tracking Drifters produced by Oceanetic Measurement and Beacons produced by Canatec. The trackers of the first type recorded position every 10 minutes and transmitted a package of signals once per hour while the latter provided one measurement and transmission per hour. The Oceanetic trackers have a horizontal accuracy of less than 5 metres (50%), and less than 8 metres (90%). The battery capacity is enough to provide sampling during approximately one year, depending on ambient temperature conditions.

Ice conditions in the area during the deployment were represented by highly concentrated ice having thickness of approximately 1 m. All of the tracked icebergs were tabular having various size, the biggest tracked iceberg (IB#30) was grounded (Table 1).

Table 1. Tracked icebergs geometrical parameters and ice conditions.

ID	IB#4	IB#12	IB#13	IB#30
Estimated size (Length x Width)	100x40	260x120	200x100	300x150
Observed ice concentration	0.5	0.9	0.9	0.9
Additional info	Tabular	Tabular	Tabular	Tabular Grounded

3. MOMENTUM EQUATION AND CALCULATION PROCEDURES

In order to predict the drift of an iceberg the momentum equation is used (Broström et al., 2012). It usually includes terms related to water and air drag, and the Coriolis force in case of open water. Wave-induced forces, sea surface slope force, forces related to broken ice (in case it is present) may be added to the equation.

$$M\frac{d\vec{V}}{dt} = \vec{F}_a + \vec{F}_w + \vec{F}_c + \vec{F}_{si} + \vec{F}_{ss} + \vec{F}_{wave} \quad (1)$$

where M is the mass of iceberg (usually including 10 % added mass) and $\vec{V}$ is the velocity of the iceberg. An East-North coordinate system is used in the present iceberg drift prediction studies. The iceberg is assumed to be a point-mass but it has geometry as a property. The mass of an iceberg as well as the geometry cannot be measured both precisely and easily at the same time. Values based on statistical observations are commonly used.

The drag force depends on the density ρ and relative velocity $\vec{U}$ of the fluid. We assume an iceberg to be a layered structure with axial symmetry and cross-sectional areas A_i. The total drag force acting from a fluid is calculated in the following way:

$$\vec{F}_{drag} = \frac{1}{2} C\rho \sum_i A_i \left|\vec{V} - \vec{U}_i\right| (\vec{V} - \vec{U}_i) \quad (2)$$

The drag coefficient C is taken out from the summation sign because it's related to the whole body and not to a certain layer. The current velocity $\vec{U}$ can be either measured by an ADCP e.g. deployed as a mooring or calculated by one of the oceanographic models. Similar applies to the air drag.

Drag forces and the Coriolis force are the governing forces in most cases. The Coriolis force can be calculated as

$$\vec{F}_c = -f\vec{k} \times \vec{V} \tag{3}$$

where $f = 2\Omega \sin\varphi$, $\Omega = 7.2921 \times 10^{-5}\ \mathrm{rad/s}$ is the Coriolis parameter, φ is the latitude and $\vec{k}$ is a vector normal to the surface directed outwards. When moving deeper into the Arctic sea ice may be present and exert forcing on icebergs. To the best of our knowledge there is no physically-based model considering the effects of broken ice may have on iceberg drift forecasting. Thus measured data from field studies are valuable since they can be used to calibrate such prediction models.

4. ANALYSIS OF DRIFT DATA

Drift trajectories

Drift coordinates were originally provided in degrees. The procedure based on Snyder (1987) was used to transfer them to metres. As a result trajectories were projected in the UTM coordinate system for the zone 28N. In Figure 2, trajectories of icebergs and ice floes are coloured blue and red, respectively.

The drift path in a certain region depends strongly on the sea current which is partially determined by bathymetry. In the region studied of the Greenland Sea, the depth varied from 100 to 500 metres. It resulted in a relatively low drift velocity and the influence of tides was relatively weak. Therefore trajectories did not include many loops and the motion was mostly directed to the South. The initial part of the trajectories contained loops and it happened due to high ice concentration in the region.

It can be seen that during 41 days of observation objects drifting closer to the ice edge drifted up to 1000 km while the others drifted 5 times shorter. Drift speeds and the relative motions are discussed further.

In Figure 3 the trajectories are plotted on a Global Modis image that displays the ice edge. The Kanumas Blocks at NE Greenland are displayed as well. We observe that the easternmost ice floe (B5390) on average drifted parallel to the ice edge.

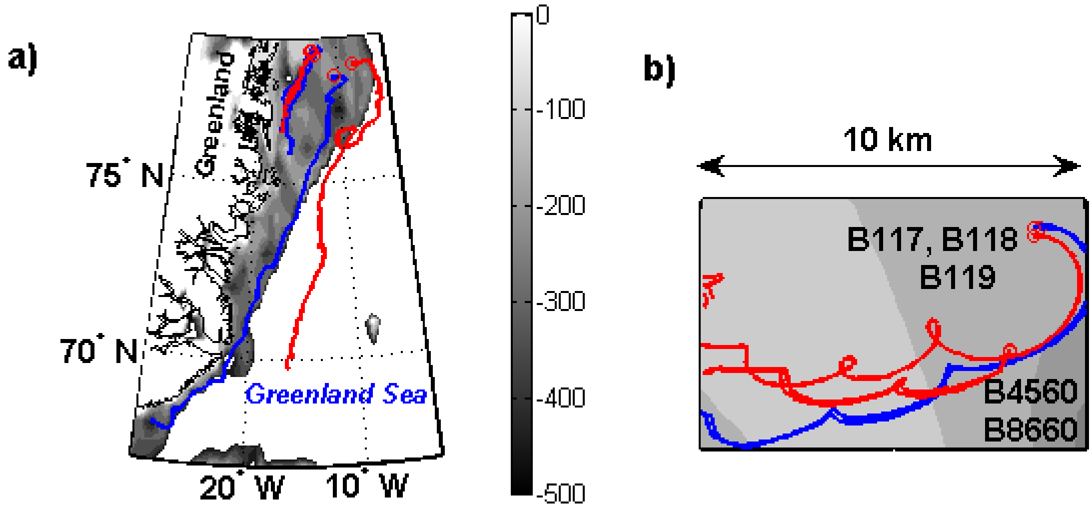

Figure 2. a) Drift trajectories of icebergs (blue) and ice floes (red) after approximately 40 days of observation; b) initially trajectories included loops; c) B117 and B118 were deployed on the same iceberg, B119 was deployed on the adjacent ice floe, B4560 and B8660 were deployed on the same ice floe.

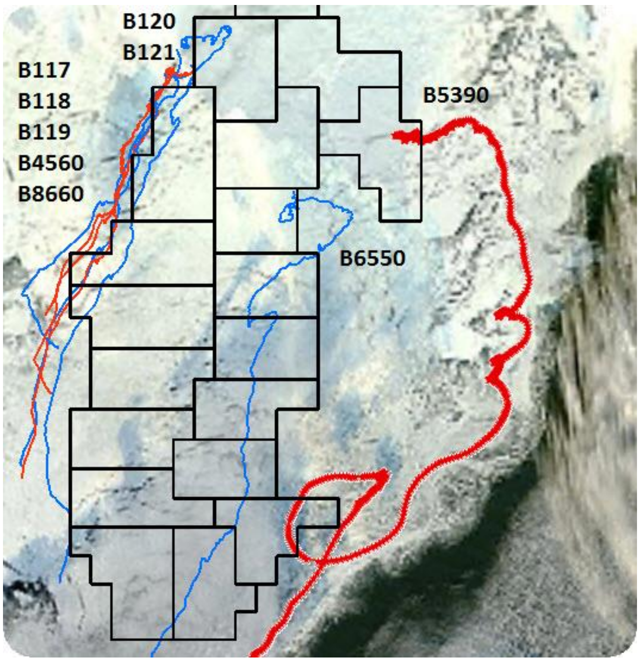

Figure 3. The trajectories through the Kanumas Blocks at NE Greenland. The MODIS image is from mid October 2012 with a spatial resolution of 1 km.

Drift velocities and curvature

Coordinates were differentiated with respect to time in order to provide drift velocities. Since measurements were provided once per 10 or 60 minutes, the trackers travelled a long enough distance to minimize errors from the GPS. For instance, if we assume that the error in coordinate estimation is 5 m, the error in velocity estimation is less than 1 cm/s for 10 minutes measurements and 0.14 cm/s for hourly measurements.

The velocities varied in time and had periodical oscillations (see Figure 4). Mean values and standard deviations for all the trackers are shown in Table 2. This information proves the fact that ice floes and icebergs that are closer to the ice edge drift several times faster. Firstly it might happen because the sea current has higher vorticity closer to the shore and the flow direction is not constant. Secondly, immobile and concentrated ice slows down iceberg motion while less concentrated ice provides mobility to an iceberg.

In general the mean drift speed is slow in comparison to e.g. Storfjordbanken in the Barents Sea. A plausible reason is that the water depth is much bigger in the Greenland Sea compared to Storfjordbanken (60-100 m) (Broström et al., 2012). For deep water the tidal motion is not so strong too.

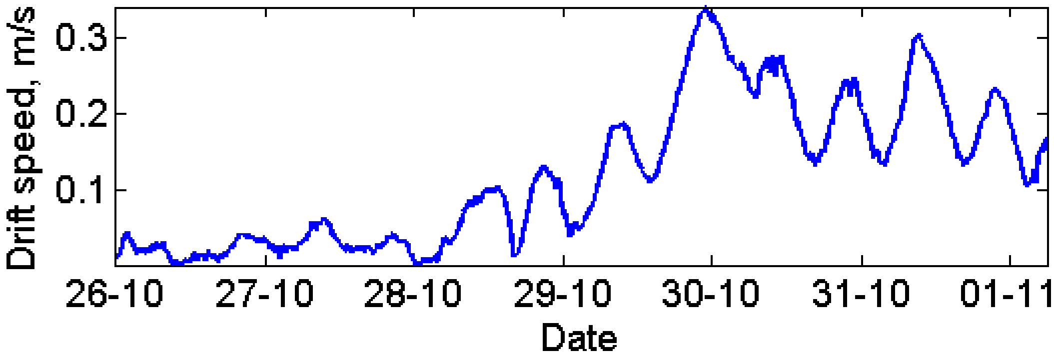

Figure 4. Velocity oscillations for IB#12.

Table 2. Statistics on the trackers. All dates refer to 2012 and UTC. $\langle V \rangle$ - mean drift speed, σ_V - standard deviation, $\max(V)$ - maximum velocity. *)B4560 and B8660 were deployed on the same ice floe.

First Signal (mm-dd HH:MM)	ID	Deployment position	$\langle V \rangle$, m/s	σ_V, m/s	$\max(V)$, m/s
09-18 16:20	B6550 (IB#4)	77.98ºN,-10.59ºE	0.17	0.15	0.8
09-21 16:00	B117 (IB#12)	78.60ºN,-13.06ºE	0.07	0.08	0.43
09-21 16:00	B118 (IB#12)	78.60ºN,-13.07ºE	0.07	0.09	0.43
09-21 16:00	B119 (Floe)	78.60ºN,-13.07ºE	0.07	0.09	0.43
09-21 18:00	B120 (IB#13)	78.70ºN,-13.15ºE	0.10	0.09	0.43
09-21 19:00	B121 (IB#30)	78.67ºN,-13.41ºE	0.05	0.09	0.50
09-22 07:05	B4560 (Floe*)	78.57ºN,-13.10ºE	0.06	0.08	0.49
09-22 07:05	B8660 (Floe*)	78.57ºN,-13.10ºE	0.05	0.07	0.43
09-23 14:40	B5390 (Floe)	78.26ºN,-08.13ºE	0.33	0.21	1.13

Ice management operations do also need information about sudden changes of drift directions. Thus we have performed analyses of the curvature of the trackers. Assume that we have a curve in a Cartesian coordinate system; then the curvature radius R can be calculated in the following way:

$$\frac{1}{R} = \frac{\left|\vec{V} \times \vec{a}\right|}{\left|\vec{V}\right|^3} \quad (4)$$

where V_x, V_y are the velocity projections, a_x, a_y are acceleration projections and $|V|$ is absolute value of the drift velocity.

Acceleration is the second derivative of the coordinate so it is problematic to derive it from the measurements (the error value grows after every numerical differentiation). The data were cut into equal sized blocks (75 points) and for every block the velocity was fitted by an 8-term Fourier series. A MATLAB fitting algorithm with '*fourier8*' fitting type was implemented. The number of points in each block was determined by the velocity oscillations (semidiurnal as described further) so that measurements fitted into the semidiurnal time interval. The resulted fit function was analytical and possible to differentiate so accelerations were calculated more "clean".

The calculated curvatures of the trajectories are shown in Figure 5 as a function of a drift speed for icebergs (blue) and ice floes (red). It can be seen that ice floes had higher maximum drift speed than icebergs. In order to make better comparison we divided all the points into groups having velocities in the same 5 cm/s wide intervals. Then we calculated mean curvature radius within the interval. In Figure 5 the solid black line corresponds to icebergs and the dashed line corresponds to ice floes. There is no sufficient difference between icebergs and ice floes with respect to drift curvatures.

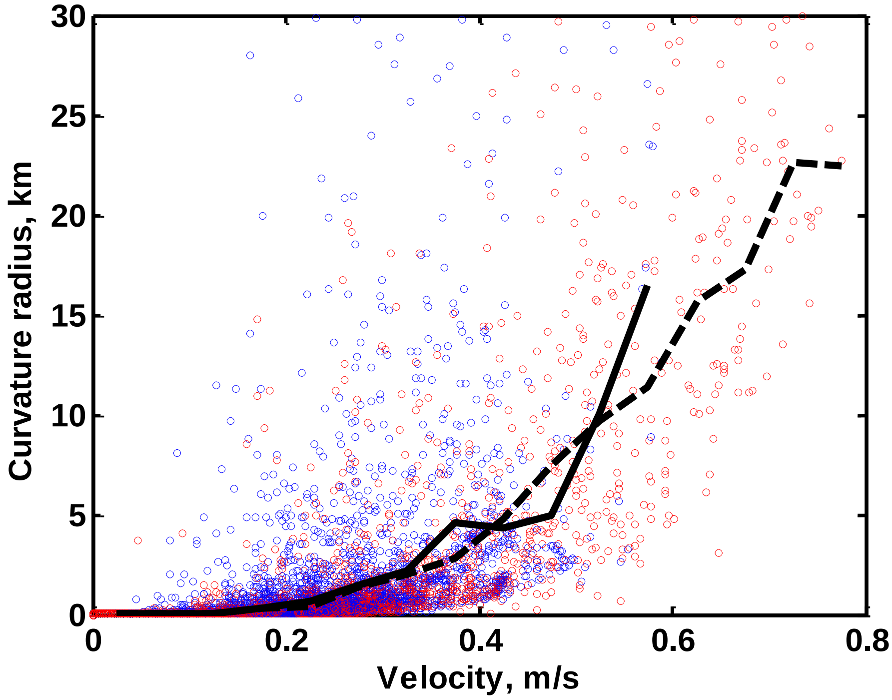

Figure 5. Curvature radius vs. drift speed of icebergs (blue circles) and ice floes (red circles). Averaged data for icebergs (solid black line) and ice floes (dashed black line).

Drift spectrum

Since velocities projections are oscillating, discrete Fourier transform was performed to detect tidal motions. Assume that we have measured the discrete signal x_n, then

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i2\pi \frac{k}{N} n} \quad (5)$$

where N is the number of measurements, X_k are the complex numbers that reflect amplitude and phase of a certain harmonic component in a signal. The Fast Fourier Transform (FFT) algorithm was used in MATLAB for the calculation of harmonic components. The amplitude-frequency spectrum is shown in Figure 6.

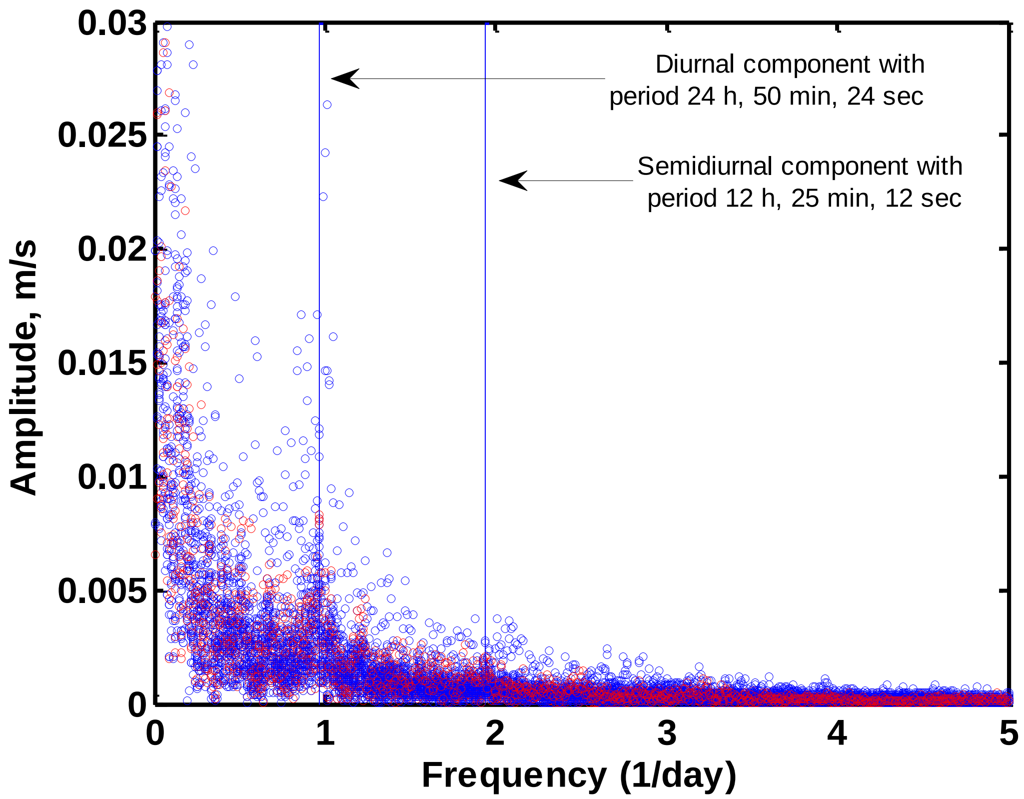

Figure 6. Drift velocity spectrum (icebergs (blue), and ice floes (red).

It is clearly seen that the drift spectrum has maxima on frequencies equal to the semidiurnal and diurnal frequencies (blue lines). Blue circles correspond to the icebergs and red ones to the ice floes. It seems to be no difference in between them.

Relative motion and rotation

As it was said above two trackers were deployed on the same iceberg (IB#12) and one of the trackers was deployed on an adjacent ice floe (see Figure 1c). It is possible to calculate relative distance and heading of an iceberg using the measured coordinates.

The ice trackers were deployed on the opposite ends of the iceberg so we could assume that the center of the iceberg was approximately in the middle between the two trackers (B117, B118). The distance between the ice floe and the defined center of the iceberg was calculated for every time step. The trackers deployed on the same iceberg were always at the same distance. The mean distance derived from oscillating GPS signals is ~172.8 m. The standard deviation of the calculated distance gives an absolute value of error in relative distance measurements which is ~3.17 m. This results in a maximum error in the relative velocity measurements of about ~1 cm/s.

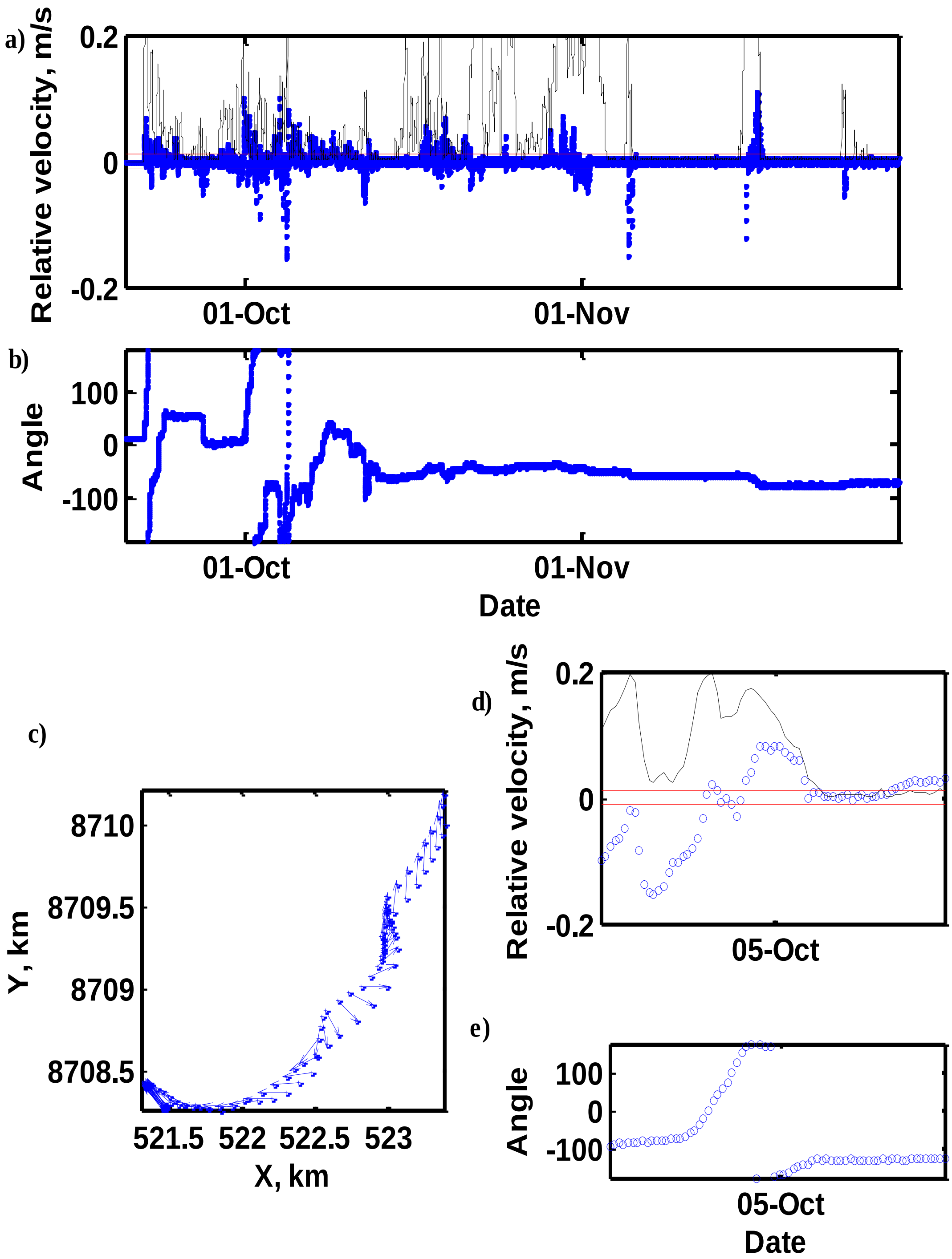

Figure 7. a,d) Velocity of the ice floe relatively the iceberg (blue), error level in relative velocity (red) and the iceberg drift speed (black); b,e) heading angle of the iceberg (blue); c) positions of B118 and B117 trackers and their relative vectors (blue arrows).

The derived relative velocity and heading angle are shown in Figure 7 where the heading angle is measured clockwise from the Eastern direction. The red lines are maximum error level. We can conclude that the relative velocity rarely exceeds 10 cm/s.

Taking into account the error level we may conclude that relative motions happen in a repulsive manner, what means there are short intervals of acceleration and braking. And almost every relative motion is accompanied by a change in the iceberg heading. Most probably it has happened due to changes in wind speed and direction or unbalanced moment from some ice floes. But it could also happen because the iceberg has touched the ground and rotated due to the current or wind or ice forces.

Analyzing angle values (Figure 7e) we detected an iceberg's 360º twist around the vertical axis. To exclude grounding scenario we also analyzed iceberg velocity (black line in Figure 7a,d). The iceberg velocity is big enough to prove that it was not grounded or plowed the seabed. Moreover the value of the relative velocity is equal to the iceberg drift speed and mostly corresponds to the changes in heading. It means that drag forces play an important role for an iceberg but they are less sufficient for the ice floes. The drag coefficient is lower for ice floes therefore ice reacts slower on wind and current changes. We also studied the motion of the iceberg which proved the rotation (Figure 7c).

The calculated mean value for the drift speed of the ice floe with B119 relatively to IB#12 is $\langle V_{rel} \rangle = 0.21 \mathrm{cm/s}$. The standard deviation is $\sigma_{V_{rel}} = 1.61 \mathrm{cm/s}$. From here we may conclude that the interaction rate during collisions is really low and ice failure is a rare scenario. Most probably there will be no ridging or rafting.

5. CONCLUSIONS

Nine trackers were deployed in the Greenland Sea on 3 ice floes (two trackers on one floe) and 4 icebergs (two trackers on iceberg IB#12). Tracker B119 was deployed on an ice floe adjacent to IB#12. A complex analysis of the data provided by trackers was carried out. The major findings are as follows:

- Drift trajectories are parallel to the Greenland shoreline and drift is directed to the Southwest. In a high ice-concentration area drift velocities were lower than in the marginal ice zone. Drift patterns contained loops in the beginning. One of the icebergs was grounded and started to move two weeks after the tracker deployment day.
- Drift velocities were in general low; the mean drift speeds of the objects in the concentrated ice were less than 0.1 m/s. A maximum drift speed of 1.13 m/s was reached by the most Eastern ice floe. Periodical oscillations of the drift speed were due to tidal motion. The influence of semidiurnal and diurnal tides was identified by means of Fourier analysis.
- Trajectory curvatures were calculated for the different drift speeds in order to know if the drift direction had sudden changes. It was shown that ice floes drift equally to icebergs.

- The motion of sea ice relatively an iceberg was proven to be very slow, having relative drift speed $V_{rel} = 0.21 \pm 1.61 \text{cm/s}$. The relative motion happens repulsively, during changes in the drag force direction or collisions. The iceberg 360º turn around the vertical axis was detected directly from the coordinate measurements.

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