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Kinematic Characteristics of Sea Ice and Iceberg Drift in the Greenland Sea

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During the Oden Arctic Technology Research Cruise 2013 (OATRC'13) survey in the Greenland Sea, 14 drift trackers were deployed on sea ice and icebergs in order to study drift patterns and characteristics in the region. The trackers measured their own GPS position and sent this information by an Iridium modem. Three groups, comprising three trackers each, were deployed in a special way: One on each end of the longer horizontal axis of the iceberg, and one on an adjacent sea ice floe. The purpose was to track the rotation of the iceberg in the horizontal plane and to get an estimate of the relative motion of ice and icebergs. Drift speed, relative drift speed, and rotation speed were analyzed and compared with data collected in a similar field campaign to the same region in 2012. It was shown that, in general, ice drifts faster than icebergs, and relative velocity of close objects is low—just a few centimetres per second on average. Some of the icebergs rotate actively, with diurnal periodicity, making a full revolution in just a few hours.

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1. Introduction

In 2013, the government of Greenland granted exclusive exploration and exploitation licenses to three oil consortiums in four blocks in specific areas of the Greenland Sea. Oil exploration and production in the area is challenging due to the presence of multiyear ice and icebergs. In general, there is a lack of knowledge and experience regarding such operations in icy waters.

It is known that about 90% of sea ice in the Arctic Ocean is taken into the Atlantic Ocean by the Eastern Greenland Current (Bourke and Garrett, 1987). The current through the Fram Strait is directed southwards along the east coast of Greenland and carries cold waters from the Arctic, together with the sea ice. Low saline [31.0 to 34.8 parts per thousand (ppt)] and cold (-1.8 to -1.4 °C). Arctic water (Aagaard and Coachman, 1968) has velocities up to 80 centimetres per second (cm/s) at the surface, having an annual mean velocity at the surface of 24 cm/s (Woodgate, Fahrbach et al., 1999). Winds blowing along the coast are mostly directed southwards, accelerating ice drift.

Sea ice in the area is represented by a high amount of multiyear ice, which is, of course, highly concentrated in northern areas, reaching 90-100 % concentration. The mean ice thickness varied from 1.17 metres (m) in the southern Greenland Sea to 3.62 m in the Fram Strait (Wadhams, 1992). However, the amount of multiyear ice, in the last few years, has been decreasing. There is also a high concentration of ice ridges and icebergs. Drift patterns of sea ice and icebergs need to be studied to provide successful and low-risk operations in these waters.

Exploratory drilling, by means of dynamic positioning, remains challenging even with support from icebreakers. There is still no experience regarding the towing of icebergs in ice-infested waters. Drift patterns and different characteristics of drift were studied based on deployments made during the Oden Arctic Technology Research Cruise 2013 (OATRC'13) expedition carried out by the Norwegian University of Science and Technology (NTNU) in collaboration with the Swedish Polar Research Secretariat (SPRS) and Statoil.

Several Ice Tracking Drifters (ITDs) were deployed on icebergs and ice floes and tracked their positions. The trackers were installed in pairs on three icebergs to study rotation of the icebergs around a vertical axis. Some of the trackers were installed on an iceberg and adjacent ice or on two adjacent floes to estimate relative velocity of ice floes. This paper presents collected data, starting with the summer of 2013. Data is also compared to a similar study carried out in 2012 (Yulmetov et al., 2013).

2. Setup

In total, 14 trackers were deployed, consisting of three pairs on three icebergs, to study rotation, and eight more on ice floes. The trackers were transported to the deployment site by helicopter and installed in a 150 millimetre (mm) diameter predrilled hole in the ice. Deadweights were attached to the trackers, so that the trackers would sink after floe or iceberg destruction. The trackers consisted of a GPS module, battery, and Iridium modem that sent collected GPS coordinates with a 10 minute frequency. The pairs with identifications (IDs) (127, 129), (128, 130), and (131, 132) were deployed on icebergs (IB1, IB2, IB3). The rest of the trackers were deployed on second-year ice floes.

Drift trajectories are shown in **Figure 1**. The red lines correspond to the ice floes and blue lines correspond to iceberg trajectories. Disappearance sites are marked with "+". It is possible to see that IB1 and IB2 are grounded or captured by coastal ice; velocity analysis supports that observation.

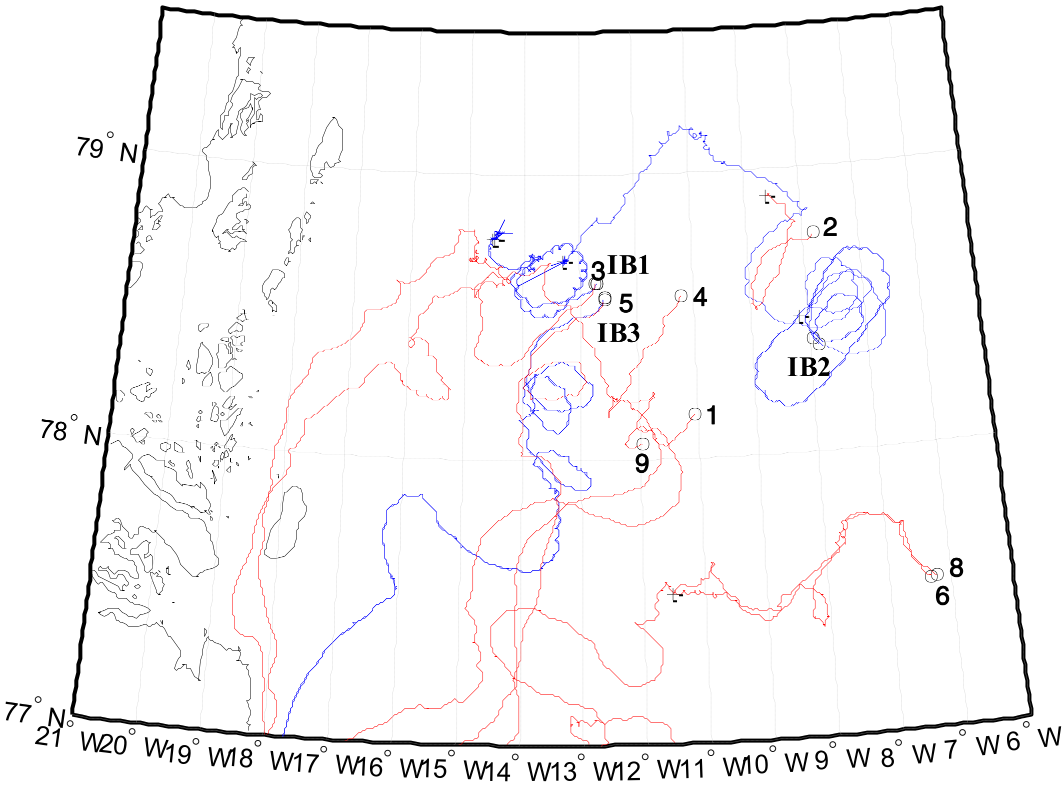

Figure 1. Drift trajectories of ice trackers (blue = icebergs; red = ice floes).

Later in the season, when the icebergs stopped moving, the concentration was much higher (**Figure 2**). Therefore, it may be concluded that icebergs are trapped where there is a high concentration of coastal ice. However, one cannot exclude grounding because bathymetry maps show shallow waters of less than 100 m in depth.

Ice conditions during deployment were variable. Concentration varied from very low up to 90% concentrated broken ice (**Figure 2**). Most of the trackers were deployed on sea ice in the transition between first-year and second-year ice.

After nine months of drift, five out of six trackers deployed on the icebergs are still working. Only one tracker stopped transmitting, in less than a month, due to the disintegration of IB2. Data showed the presence of water inside this tracker and a change of inclination in one of the last data packages. The trackers deployed on the ice floes stopped transmitting due to floes' destruction, three months after deployment.

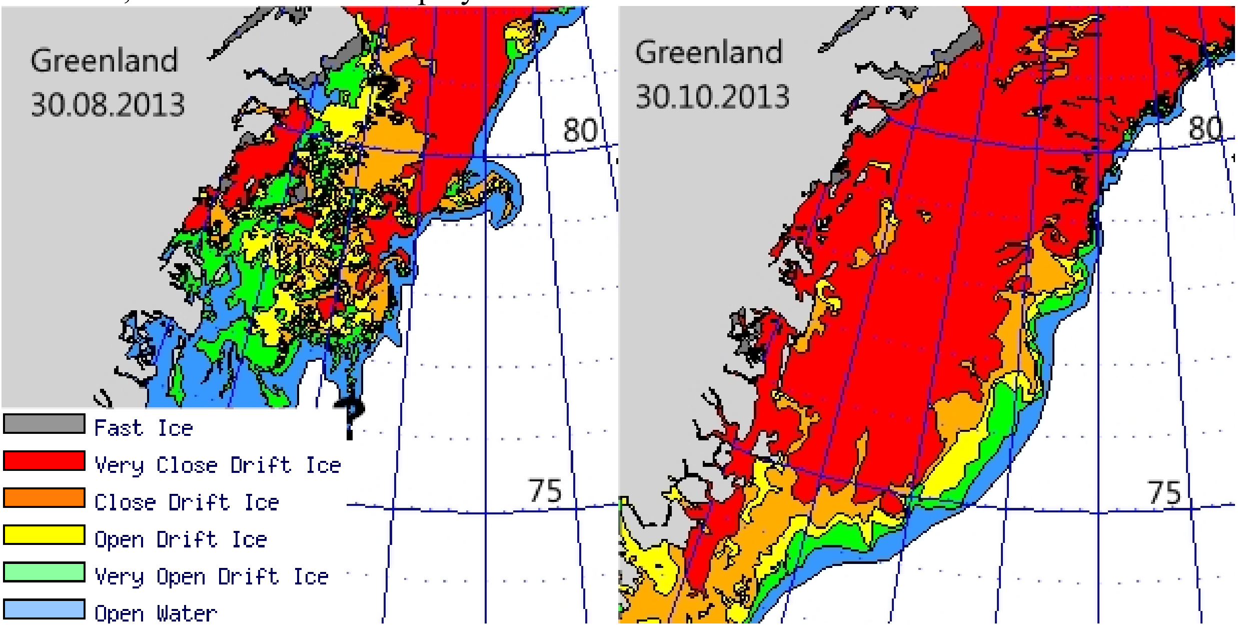

Figure 2. Ice maps at deployment time, and after icebergs were stuck in costal ice.

3. Velocity analysis

Drift velocities were analyzed to find the variations in velocity and to discover differences between iceberg and ice floe drift. First, in order to calculate velocity, we differentiated coordinates with respect to time. Due to large GPS errors, velocity history was smoothed using standard MATLAB smoothing [for details, see Yulmetov et al. (2013)]. Secondly, for icebergs that were grounded, part of the time, we excluded from consideration any data corresponding to the grounded state of the iceberg by using a threshold value for a velocity of 0.05 m/s. It was found that the maximum drift speed of ice floes is, in general, higher than the drift speed of icebergs (**Table 1)**. The variance (Std) of the drift speed was less for icebergs than for sea ice; that is logical, due to the larger mass of icebergs and, thus, a greater effect from inertia. However, no correlation between the distance from the coast of Greenland or on latitude of the drift was found. However, there was less grounding time (time when icebergs were trapped) by high concentrated ice for the icebergs that drifted in a marginal ice zone.

Velocity history reflected a periodical process that can be represented as a sum of sine functions. Fourier analysis showed a clear spectral maximum corresponding to the semidiurnal or Coriolis component. Coriolis frequency can be expressed as

$$T_C = \frac{\pi}{\Omega \sin\phi} = \frac{1[day]}{2\sin\phi} \qquad \textbf{[1]}$$

where Ω is the angular velocity of Earth and ϕ is latitude. For objects drifting at, for instance, 78°N, the Coriolis period is approximately 12 hours and 19 minutes, according to **[1]**. This value is very close to the semidiurnal tides period of 12 hours and 25 minutes. As for the previous year's data, it is hard to distinguish between those two components.

Table 1. ITD's statistics on velocity.

ID	Mean velocity, m/s	Std, m/s	Max velocity, m/s
127	0.19	0.08	0.43
128	0.16	0.08	0.54
129	0.20	0.09	0.50
130	0.16	0.08	0.48
131	0.20	0.14	0.89
132	0.20	0.14	1.05
1	0.15	0.18	1.03
2	0.19	0.09	0.38
3	0.27	0.23	1.14
4	0.31	0.22	1.10
5	0.08	0.18	1.06
6	0.21	0.14	0.99
8	0.15	0.08	0.41
9	0.32	0.21	0.99

4. Relative motion

Following experience from previous years (Yulmetov et al., 2013), we deployed buoys on separate objects at a close distance to capture the relative motion of ice. It was found that similar objects continued drifting in a close vicinity to each other. However, the analysis of OATRC'13 deployments showed very high divergence for one of the icebergs.

Three sets of trackers were deployed on icebergs and adjacent sea ice, namely, a pair of trackers on IB1 and a tracker on Floe #3; one more pair on IB3; and one on Floe #5; and, finally, two trackers on Floes #6 and #8. Since there were two trackers set at a certain distance on each of the icebergs, we assume that the centers of the icebergs were in the middle between the trackers. Thus, the distances measured between the initially adjacent floes and the icebergs were measured from the icebergs' centers.

The relative distance evolution with time is shown in **Figure 3**. For the IB1 and Floe #3, the relative velocity is very high and reaches 10 kilometres (km) in less than one day. That corresponds to approximately 0.25 m/s relative velocity. The value is higher than the mean drift speed of icebergs, and the iceberg and the floe are drifting almost in opposite directions. We believe that this happens due to a higher Coriolis term for iceberg, in relation to the drag forces, and due to differences in surface currents and deep water currents.

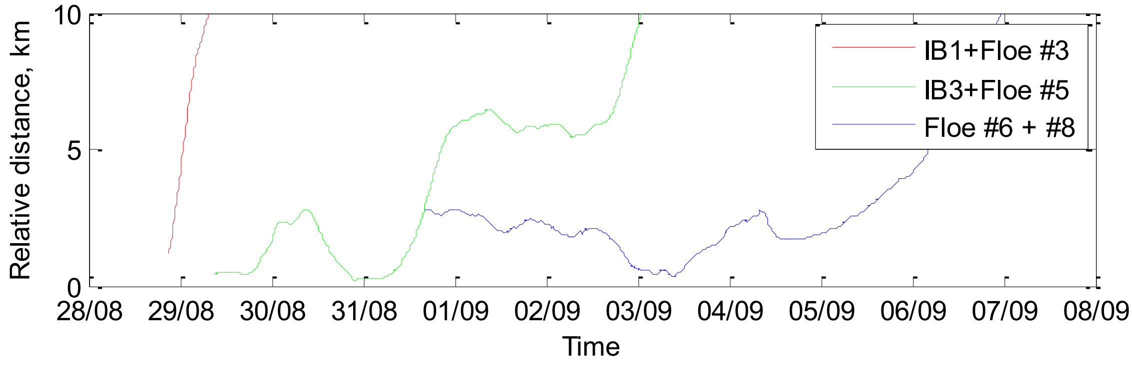

Figure 3. Relative distance between different trackers deployed on icebergs (IB1 and IB3) and adjacent ice floes (Floes #3 and #5 respectively) or on two adjacent floes (Floe #6 and Floe #8).

For another pair, the relative velocity is moderate, and, while objects are drifting close to each other, it is on average 0.026 m/s for IB3 and Floe #5 and 0.018 m/s for Floes #6 and #8. In 2012, similar measurements demonstrated 0.0021 m/s—a much lower value than in 2013. From this range of velocities, we can conclude that no large deformations and failure processes in the ice cover occurs for the iceberg and the adjacent ice floes.

5. Rotation analysis

Iceberg stability is an important issue related to physical ice management operations. When the probability of iceberg collision with an offshore structure is high, it is possible to deflect the iceberg. Towing is performed by one or several thug vessels that pull an iceberg using a towing rope or net. During these operations, rotation of an iceberg may occur that produces high angular momentum and may lead to mission failure.

The three icebergs we studied, with a pair of trackers deployed on each of them, demonstrated more rotation than in 2012. In 2012, for a two-month-long period, only one of the icebergs made a full revolution. In 2013, by contrast, the icebergs were rotationally instable. In **Figure 4,** the rotation angle and rotational velocity are shown for a certain period of drift. The angle is measured in degrees from the direction to the north. Rotational velocity is calculated as the derivative of angle measurements, smoothed using MATLAB built-in function. For some icebergs, angular velocity reaches values of 0.02 degrees per second. This is a high value considering an iceberg's size and mass.

It can clearly be seen that IB1 rotates, and the rotation is periodical. It was also observed that the rotation period is close to 24 hours. Additionally, Fourier analysis showed a maximum on the rotational velocity spectrum, corresponding to a diurnal period or perhaps double the Coriolis period. As stated previously, it is hard to distinguish between those two periods in latitudes close to 77°N because the Coriolis period is very close to semidiurnal, that is, 12 hours 19 minutes and 12 hours 25 minutes, respectively.

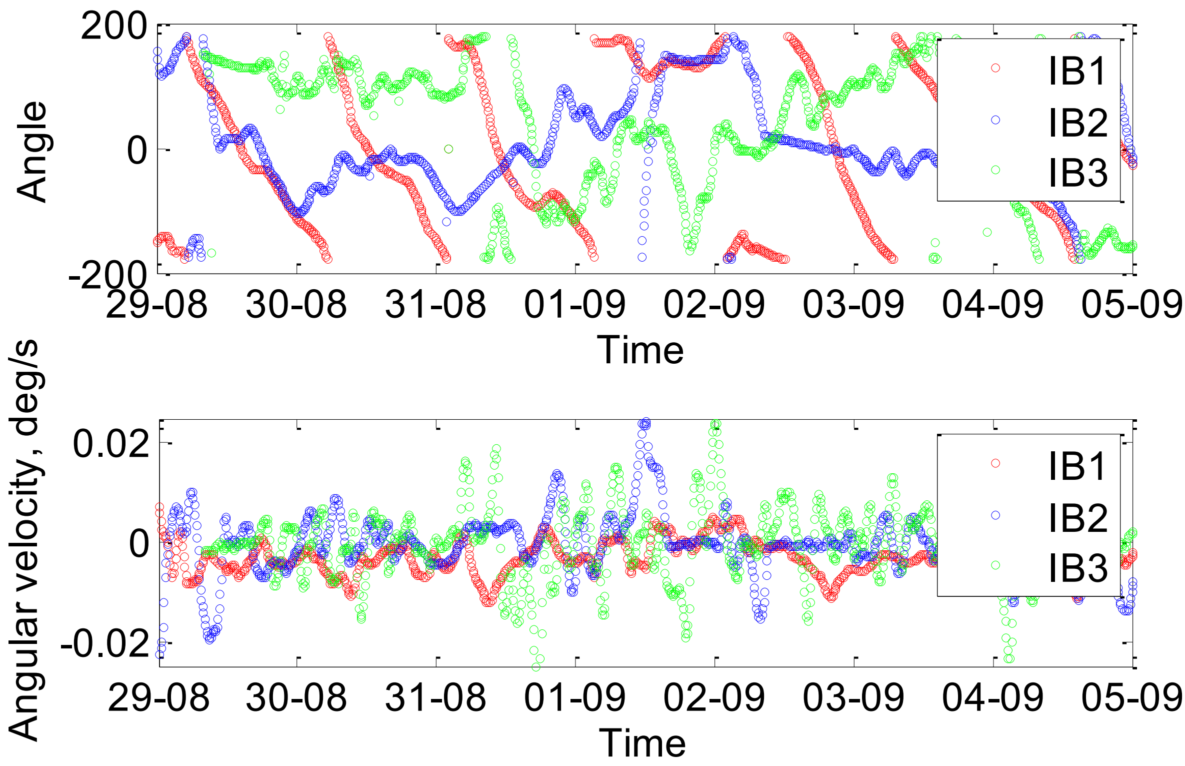

Figure 4. Rotation angle and angular velocity history for the icebergs provide insight into the rotational stability of the drift.

6. Conclusions

A set of 14 ice trackers was deployed on sea ice and icebergs in the Greenland Sea, in order to study kinematic drift characteristics of the sea ice and icebergs. Three pairs of trackers were deployed on icebergs to obtain rotation data. The rest were deployed on second-year ice. Some of the trackers were deployed at a close distance to each other to estimate how fast different floes move relative to each other and in relation to the icebergs.

The following results were obtained:

- In the Greenland Sea, icebergs can be captured by highly concentrated ice, close to the coast, or they can be grounded.
- The mean drift speed of icebergs and sea ice is approximately 0.2 m/s. The maximum speeds and variance of the velocity are higher for ice floes. This happens due to the lower inertia for ice floes. Measurements showed maximum drift speeds of ice floes and icebergs of 1.15 m/s and approximately 1.0 m/s, respectively.
- Drift velocity oscillates with a period close to semidiurnal tide, that is, 12 hours, 25 minutes.
- Icebergs and ice can drift in almost opposite directions, possibly due to different surface and deep-water currents.
- We found the values of relative ice and iceberg drift velocity as 0.25 m/s and 0.026 m/s, respectively, which is 100 and 10 times higher than that observed in the 2012 campaign. The trackers deployed on two close ice floes had relative velocity of 0.018 m/s.

- Icebergs rotate considerably during drifting. In these measurements, the angular velocity reached 0.025 degrees per second, which is high for a large iceberg. Rotation is periodical, and that period is close to diurnal.

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