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HIGH RESOLUTION ICE DYNAMICS DERIVED FROM ADCP AND ICEBOUND DRIFTER DATA IN THE GULF OF FINLAND, THE BALTIC SEA

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ABSTRACT
The aim of this study is to describe high resolution sea ice dynamics in relation to wind forcing using the bottom-track facility of the ADCP and icebound drifter buoys. The ADCP detects the presence and movement of the ice pack locally at the installation site while the drifters provide data on the spatial movements of ice packs. The instruments were deployed along a rough cross-section of the Gulf of Finland from Kunda to Kotka. ADCP measurements were performed in the most southern location (59.7 N, 26.4 E) from 12 January-27April 2010. With steps of about 15 nm to the north, two groups of three and two drifting buoys were released on 8 March. The relevant wind data were obtained from the meteorological station on Vaindloo island. In winter 2009-2010 the Gulf of Finland was covered with drift ice and ice-conditions were highly dynamic. Detection of ice cover and ice-free periods based on ADCP bottom-track error velocity values was successful. The rms of bottom-track error velocity for the ice cover periods were about five times smaller than those for the ice-free periods. Altogether five periods of ice cover presence with a duration from 6-12 days were determined at the measurement location. Ice-bound drifters revealed ice dynamics similar to those detected by the ADCP during the measurement period. The alternations of ice conditions, from both ADCP and drifter data, were in accordance with MODIS satellite images. For the ice cover period in March (sub-period C) the correlation coefficient between low-frequency wind and ice drift speeds was as high as 0.91. In accordance with other ice studies, the mean ice-to-wind speed ratio was 3.7% and the mean deviation of ice motion to the right from the direction of the wind vector was 26 degrees.

INTRODUCTION
One factor influencing navigation conditions on a relatively small timescale is ice dynamics, which causes rapid changes in compressive forces. These, in turn, act upon a ship's hull on a small scale. With this study we aim to describe the high resolution sea ice dynamics in relation to wind forcing by using the bottom-track facility of the ADCP (Acoustic Doppler Current Profiler) and icebound drifter buoys. The ADCP detects the presence and movement of the ice cover locally at the installation site with a high temporal resolution of 10 minutes. The drifters provide data on ice movement with a temporal resolution of 15 minutes and spatial resolution of less than 10 metres. Such measurements are very rare in the Baltic Sea as well as the Gulf of Finland, which is known as an area of intensive ship traffic. The gulf has an elongated form – 330 km long and 80-100 km wide – and the main shipways along the gulf are for tanker traffic and across it for passenger ship traffic. The presence of ice cover sets special requirements for navigation, both on the construction of the ships and their behaviour

in ice, as in many cases merchant ships need icebreaker assistance. Operations where several ships are involved and relevant navigation principles are very different from those in open waters also require detailed knowledge of ice conditions and their variability in the area surrounding ship operations. For these reasons, knowledge of local ice dynamics is essential. With this study we are focussing on experiments explaining local ice dynamics in the central part of the basin in a west-east direction, being sensitive to certain wind forcing patterns and directions rather than all wind directions. The EU project SAFEWIN, which deals with studies of ice compression and its forecasting, is the framework of our study.

Earlier investigations of ice dynamics and drift in the Baltic Sea have been based on surface drifters and SAR satellite data over relatively short periods (Leppäranta *et al.*, 1998), (Uotila, 2001). There are more recent ice drifter experiments lasting two months and more in the Gulf of Finland and the Gulf of Bothnia from 2010-2012 (SAFEWIN data reports), but these data are not well studied and at this stage describe only general patterns of ice drift in the gulfs. There are also recent observations from 2003-2005 and 2010-1011 using an airborne Electro-Magnetic (EM) sensor to measure ice thickness with high spatial resolution (EU projects IRIS, 2003 and SAFEWIN, 2010-2011). These data also provide a high-resolution overview of local ice properties, like the thickness of level ice, ridge height and ridge density, but unfortunately are fragmentary in time and expensive to carry out.

Bottom-mounted upward-looking Acoustic Doppler Current Profilers (ADCPs) have been successfully used for a couple of decades at different depths and in different parts of the world's oceans. The primary purpose of an ADCP is to measure the vertical profiles of currents, but there are also studies for the monitoring of ice cover (Belliveau *et al.*,1990; Visbeck & Fischer, 1995; Strass, 1998; Shcherbina *et al.*, 2005). This measurement technology has become more important as efforts to observe the remote polar seas have increased due to their critical role in the global climate system. In our case, with this instrument we were able to monitor the ice dynamic properties that are most critical for shipping, creating knowledge for analysis of compressive ice phenomena.

Local ice dynamics form a basis for the development of ice compression and wind is the main forcing parameter in this highly variable process. The Gulf of Finland is tailored to the development of ice compression with its elongated shape: the wind blowing along the gulf produces much more intensive compressive situations than the wind blowing across it. The sea area off Kunda, in the middle of the Gulf of Finland, is known for severe ice conditions. The dominating ice type is drift ice, which heavily ridges around small islands and the shallow sea in the area. Westerly and easterly winds create ice compression here which acts on ships; icebreaker assistance is therefore needed more or less permanently during the ice season. Based on these circumstances, this area was selected as the location for ADCP measurements of local high resolution ice dynamics. The Gulf of Finland freezes to a greater or lesser extent every winter, starting from the shallower and fresher eastern part. Mean ice thickness varies depending on the severity of the winter and is typically 30-80 cm in the case of level ice (Leppäranta & Omstedt, 1990). The main ice type in the gulf is drift ice; fast ice only forms in limited areas along the coast landward from the 10 m isobath (Granskog *et al.*, 2006). The shape of the gulf has a remarkable influence on the ice regime – it is large enough for the wind forcing to overcome the ice strength, so ice ridges during strong wind events and compressive ridges are formed (Uotila, 2001; Leppäranta, 1981). Ridges are typically 5-15 m to a maximum of about 30 m (Leppäranta & Hakala, 1992). The wind pattern is not uniform across the basin because of its elongated shape and creates a kind of 'wind tunnel' along the gulf (Soomere, 2003). The size of the gulf is relatively small compared to the typical scale of atmospheric low-pressure systems. Hence, pressure and compressive ridges are primarily formed on the windward side of the basin and leads are formed on the upwind side.

The outline of this paper is as follows: in Chapter II an overview is provided of the data, measurements and data processing methods; Chapter III presents results and discussion; and Chapter IV sets out the main conclusions and outcomes of the work.

MATERIAL AND METHODS

Ice drift and deformation parameters can be monitored using drifter buoys which are frozen into the ice and follow its movements. Buoys periodically record their position and transmit data to the shore. There are several constructions for such buoys, from large ones installed using a helicopter to smaller ones that can be installed manually. In our case we used compact drifters developed by a local engineering company. The buoys are around 1 m long, with a diameter of 11 cm and weighing around 10 kg. They transmit data at intervals of 15 minutes to two hours, which can be set remotely during field experiments. Data are transmitted in real time via GSM networks, using a GPRS protocol, if a cellular service is available. If a GSM service is not available the positions of the buoys are still recorded on a memory card and transmitted once the buoy returns to area with GSM service. So even if a drifter is lost, data can be retrieved. Altogether five drifter buoys were installed during the R/V ARANDA cruise in the Gulf of Finland in 2010. The main study area selected was between Kotka and Kunda. The period of the experiment was 66 days (8 March-14 May). The buoys were launched in two groups – buoys 3, 5 and 6 in the middle of the gulf around 15 nautical miles north of the ADCP station, with a maximum distance between buoys of around 2 nautical miles.

Table 1. Summary of drifter experiment in Gulf of Finland

Buoy no.	Date & Time (UTC) start/end	Lat (N)	Lon (E)	Distance from launching point (km)	Drift (km)	Drifting Speed (average, m/s)	Drifting period (days)
3	08/03/2010 13:30 22/03/2010 19:39	59°56.46´ 59°42.43´	26°4.66´ 26°44.25´	44.9	223.2	0.09	14.26
5	08/03/2010 16:46 15/03/2010 20:00	59°56.92´ 59°52.20´	26°9.14´ 26°58.77´	46.8	79.6	0.09	7.13
6	08/03/2010 17:30 14/05/2010 07:18	59°58.75´ 60°23.22´	26°1.32´ 26°56.38´	68.2	559.7	0.11	66.57
8	08/03/2010 17:30 14/05/2010 07:18	60°14.76´ 60°30.81´	26°38.29´ 28°7.54´	87.8	447.9	0.08	60.56
10	08/03/2010 17:30 14/05/2010 07:18	60°14.75´ 60°16.87´	26°38.28´ 27°49.59´	66.1	233.6	0.08	43.24

Buoys 8 and 10 were launched even further to the north, around 32 nautical miles from the ADCP station. In order to use the information recorded by the drifters (ice drift properties) a web-based user interface (http://on-line.msi.ttu.ee/gmap/) was built where the positions of the buoys and their movements were visible in real time. A summary of the drifter experiment is given in Table 1.

The ADCP was deployed in the central part of the Gulf of Finland from 12 January-27 April 2010. The observation site (59°42.09 N, 26°24.23 E; depth 63 m) was located in the deep basin extending south-easterly towards Kunda Bay, around 15 km from the coast (Figure 1). We used a 307.2 kHz broad-band ADCP (Workhorse Sentinel, RD Instruments) deployed on the bottom with a trawl-resistant Barnacle 60P platform. The ADCP was configured to measure bottom-track (BT) velocities with a sampling interval of 10 minutes (an average of five high-frequency pings).

Relevant data on wind, which is the main force in ice drift, were obtained from the meteorological station on Vaindloo island (59°49.66 N 26°21.60 E) around 7 nautical miles north of the location of the ADCP. Wind is measured at a height of 32 m and wind parameters as 5-minute averages and maximums, where the registration interval is also 5 minutes.

In order to measure the properties of the local ice dynamics the bottom-track (BT) option of the ADCP was utilised. In this case, the ice cover is tracked from below with an upward-looking ADCP mounted on the sea bed. Bottom-tracking in this mode enables the surface of the sea to be monitored i.e. the reflected signal from the underside of the ice can be used to determine the ice velocity. BT output includes velocity components, error velocity and depth (the distance from the instrument's head to the surface). The BT velocities have a single-ping accuracy of a few mm/s; the depth resolution is approximately 0.1 m. The four-beam geometry of an ADCP allows two independent vertical velocities to be computed. The difference between these two vertical velocities determines the error velocity. If the flow field is homogeneous, the difference will average out to zero. To place the error velocity on a more intuitive footing, it is scaled so as to be comparable to the variance in the horizontal velocity. In other words, the error velocity can be treated as an indication of the standard deviation of the horizontal velocity measurements. BT error velocity (characterising instrument performance and data quality) is the main parameter describing the presence of ice cover, as in this case the error velocity reduces significantly.

Generally obtained data were continuous, but specific short periods of missing BT velocity data were detected, during both the ice formation phase (around one week in January) and the ice break-up stage (nearly three weeks in March). While the data quality of the rest of the measurement series was good, we attribute the missing data to distorted backscattering of acoustic signals from unstable new ice formations – like frazil, brash ice and slush – while the ice is forming. During break-up, the rising air temperature and even more sunlight cause the ice to fill with more and more of the surrounding seawater. Thus, the density of the ice becomes very close to seawater, which probably also causes distorted backscattering of the acoustic signal.

BT velocity time-series for each ice cover period were first filtered with a 1-hour moving average filter and then decimated to obtain hourly values for further analysis. The same procedure was applied to the time-series for wind. For low-frequency analysis all data series were filtered with a 36-hour moving average filter. Such a low-pass filter window was chosen to remove inertial oscillations (period: 13.9 hours) and seiche-driven oscillations with typical periods in the Gulf of Finland of around 26 hours (Alenius *et al.*, 1998) as well as other variability components higher than the seiche frequency.

Obtained from the ADCP data, the time-series of BT error velocity for the ice periods in March are given in Figure 2 and serve as a basis for further analysis and discussion. As we focus on ice cover periods which have parallel data from both types of measurements in this paper, we do not discuss ice cover periods A and B from January and February.

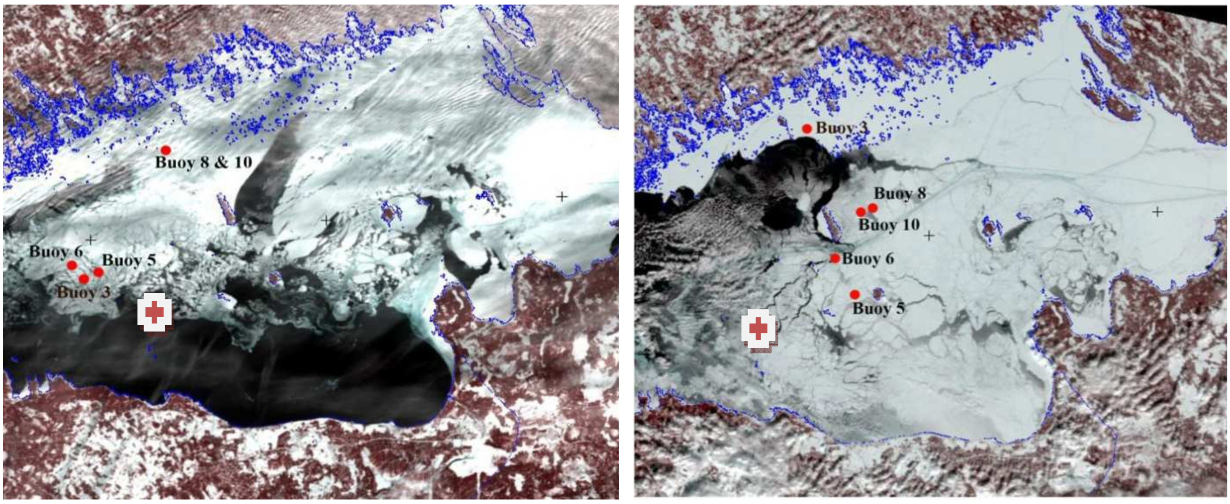
RESULTS AND DISCUSSION

General characteristics of ice dynamics derived from icebound drifter data

Characteristic to this particular ice season in this area was a mean drift speed of around 0.1 m/s as well as a long distance of drift by the ice during the ice season (up to 560 km, see Table 1). The latter clearly indicates that drift ice was the dominant ice type in this case. The most prominent movement of the ice according to the drifters occurred between 10 and 13 March, when strong NW winds pushed most of the ice mass from the northern coast of the Gulf of Finland to the south-east, towards Suursaar (Gogland) and Narva Bay. This massive ice drift is shown in Figures 1a) and b); these also mark the initial positions of the buoys and their sites after the strong winds died down. The drifters registered the highest drift speeds for the entire measurement period during this event – up to 0.7 m/s. After this event the drifter speeds rarely reached 0.3 m/s, posting an average of around 0.1 m/s.

Ice cover periods derived from ADCP and MODIS data

In the following, the time-series of BT velocity and BT error velocity are analysed to distinguish periods of ice cover and open water during the measurement period. The primary feature to be determined in the measured data series are periods with ice and no ice on the surface of the sea and periods with higher and lower variability of BT error velocity. Longer and more stable ice periods throughout the ADCP measurement time-series are marked with the letters A, B, C, D and E. Coinciding with buoy measurements are ice cover periods C, D and E. BT error velocity is known to be a good tool in differentiating between ice and open water above the instrument (Belliveau *et al.*, 1990; Björk *et al.*, 2008). Further interpretation explains that lower variability periods mean the presence of ice cover on the sea. Ice and non-ice periods were validated using MODIS (a MODerate Imaging Spectrometer, NASA) satellite imagery – in Figure 2 the red dots mark the dates when ice was observed in the area and the blue dots when ice was not observed. Different ice situations according to the MODIS imagery are presented in Figure 4 for ice cover periods C, D and E, which show how dynamic the ice conditions were in the Gulf of Finland during the period of our study.



a) 25 February 2010 b) 16 March 2010

Figure 1 a) MODIS satellite image of the eastern part of the Gulf of Finland from 25 February 2010 showing ice conditions immediately prior to installation of the drifter buoys. The initial positions of the drifters are marked with red dots. The location of the ADCP is marked with a red cross.
b) MODIS satellite image from 16 March 2010 showing ice conditions after a strong NW wind event, when the ice drifted massively to the SW, taking the drifter buoys with it.

Thus, a total of five periods with ice cover were detected during the observation period using the method described above. The standard deviations of BT error velocity within the ice cover periods were 3-5 times smaller than in open water conditions.

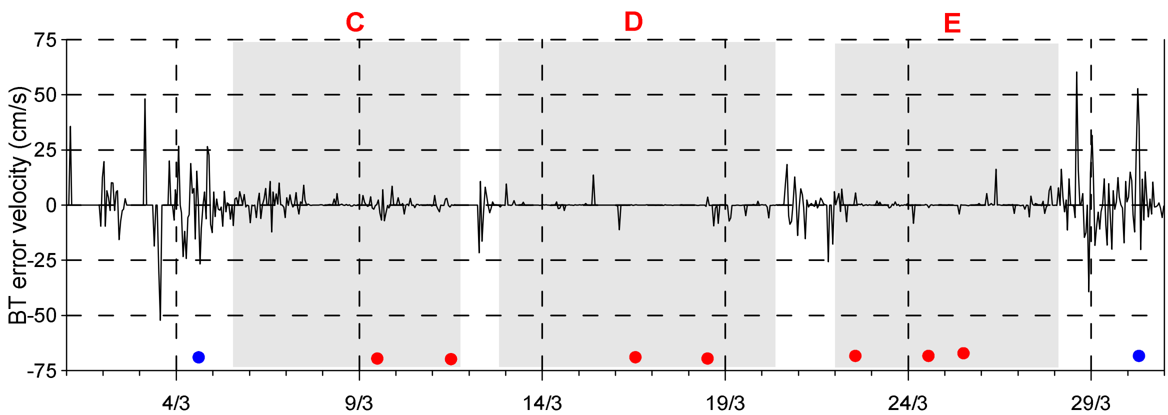
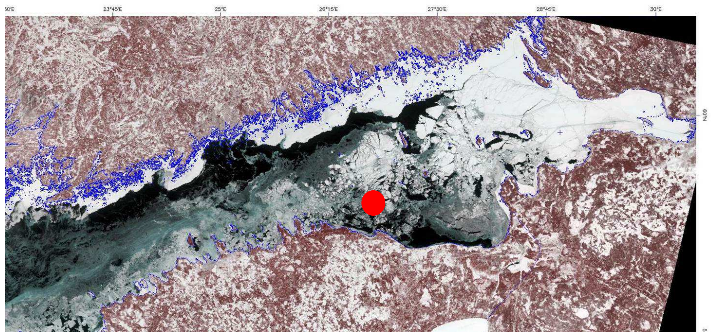


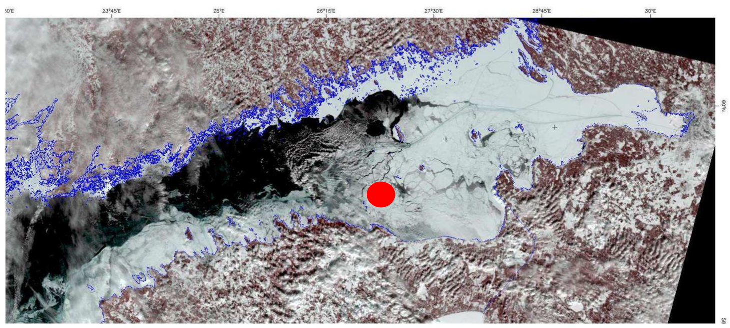
Figure 2. Bottom-track error velocity during the March period. Shaded areas with labels C, D and E show the periods where ice was detected above the ADCP. The timing of available cloud-free MODIS images confirming the ice (red dots) and open water (blue dots) at the measurement site is shown above the x-axis.

Ice conditions in the Gulf of Finland are very dynamic. Unmovable fast ice forms only in the coastal zone; offshore drift ice is the dominant ice type. Ice conditions in the gulf as a whole are highly dependent on the wind regime. If westerly winds dominate, the ice is pushed further and further to the east, which creates relatively stable ice cover consisting of compact and very compact drift ice, and also layer and ridge ice, which can almost be as stable as the fast ice in the coastal zone. There can also be local sites of ice compacting – one such sea area being the area where our ADCP measurements were made, off Kunda, near the Uhtju islands.

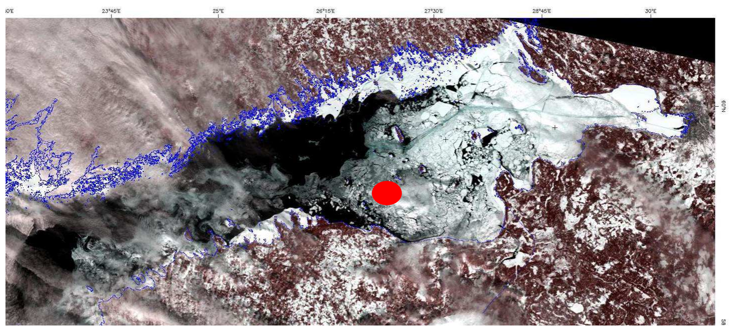
These small islands restrict the eastward-moving ice mass and heavy ridges form, which then freeze together and form a stable ice cover. A NW wind is the most favourable in pushing ice formed on the Finnish coast towards Kunda. As the surface roughness of ridged ice is much higher than that of level ice, stronger southern sector winds can still break such ice cover and transport the ice mass northward again to the Finnish coast. This is comparably easy, as frequently there is open water or young ice on the Finnish side. These effects of wind forcing caused an interchange of ice periods and open water in our study area (Figure 3). The leads seen in Figure 3 on the north and south coasts of the Gulf of Finland made the fast alternation of ice regimes at our ADCP mooring site possible. The characteristics of leads and their importance to ship traffic are thoroughly discussed for the region in Pärn and Haapala (2009).



9 March 2010 Sub-period C



16 March 2010 Sub-period D



25 March 2010 Sub-period E

Figure 3. Three cases of the ice situation in the Gulf of Finland corresponding to the ice-covered sub-periods C, D and E. The ADCP measurement site is marked with a red dot (origin of images NOAA, processed by Dr. Liis Sipelgas).

Ice dynamics on a smaller time scale

BT velocity was used to determine the hourly averaged velocity of ice drift from time-series of bottom-mounted upward-looking ADCP. These data were converted to eastward and northward distances and compared with the simultaneous trajectories of the buoys (Figure 4). The drift ice period C revealed that in both locations (that of the ADCP and buoys 5 and 6) the ice drifted quasi-coherently. However, closer to the south coast (the ADCP location) the ice drift speed was higher than in the middle of the gulf. Characteristic of ice cover period D is that at all three measurement sites across the gulf the ice was drifting differently. Namely, in the middle of the gulf the ice was barely moving (or was doing so in a circular motion) and relative to that location in the northward and southward locations the ice drift had similar velocities but in different directions. During ice cover period E in the most southerly location the ice drift was completely different from that in the middle and northernmost location. The latter two cases reveal similarities in drift trajectories. The observed patterns of hourly averaged ice drift are probably the result of the low compactness of drifting ice (the presence of leads either close to the southern or northern coast of the gulf); the latter makes ice drift highly mobile in a changing wind field. The drift velocities of sub-period C for both instruments show similar direction frequency and speed distribution (Figure 5), but the ADCP data show slightly higher velocities.

Ice drift velocity in relation to wind speed

The scatter plots of ice drift versus wind speeds (Figure 6) and vector correlation coefficient introduced to physical oceanography by Kundu (Kundu, 1976) were used to elucidate the response of the ice drift to the wind forcing during ice cover period C. The magnitude of the coefficient measures the overall correlation of ice drift and wind vector series and the phase angle between these two vectors displays the average phase angle between the ice drift vector and the wind speed vector. The scatter plot revealed a good relationship between ice drift speed and wind speed values during ice sub-period C, but the character of the relationships still varied within the sub-period. Namely, two linear fits display two different ice speed *vs.* wind behaviours during sub-period C: the thin line probably represents a situation where ice drift was already well developed; the bold line the developing face of the ice drift. Another explanation is that at the beginning (the thin line) of the ice period the drift ice arriving in the measurement site was more dynamic because its concentration was low. If wind forcing continues and the ice concentration grows, less mobile ice cover is observed. Ice period A revealed that, similar to the early part of the ice period, at the end of the period the ice drift speed also increased (not shown).

The averaged ratio of the ice drift speed to the wind speed was 0.037, which is about two times greater than the normally estimated ratio of current speed to wind speed. These ratios are in accordance with earlier estimates. Typically, the ratio can vary between 0.02 and 0.035 depending on the roughness of the ice: the low value represents a smooth ice surface and the higher value deformed ice cover (Leppäranta, 2005). For comparison, an ice/wind speed ratio of 0.03 was estimated in the northern part of the Bothnian Bay (Björk *et al.*, 2008). The correlation between the wind and ice drift vectors was very high: 0.91. The heading of the ice drift vector to the right of the wind speed vector was, on average, 26º. Typically, the angle value is 30º in the case of free ice drift (Thorndike & Colony, 1982). As the dimensions of the Gulf of Finland – especially its width – are not large, free drift could be very short-term, and most of the time the morphometry of the coast plays a major role in the local ice dynamics, as it did at our measurement site. Similar measurements made in the Bothnian Bay produced a turning angle of ice drift compared to wind direction of around 10º (Björk *et al.*, 2008).

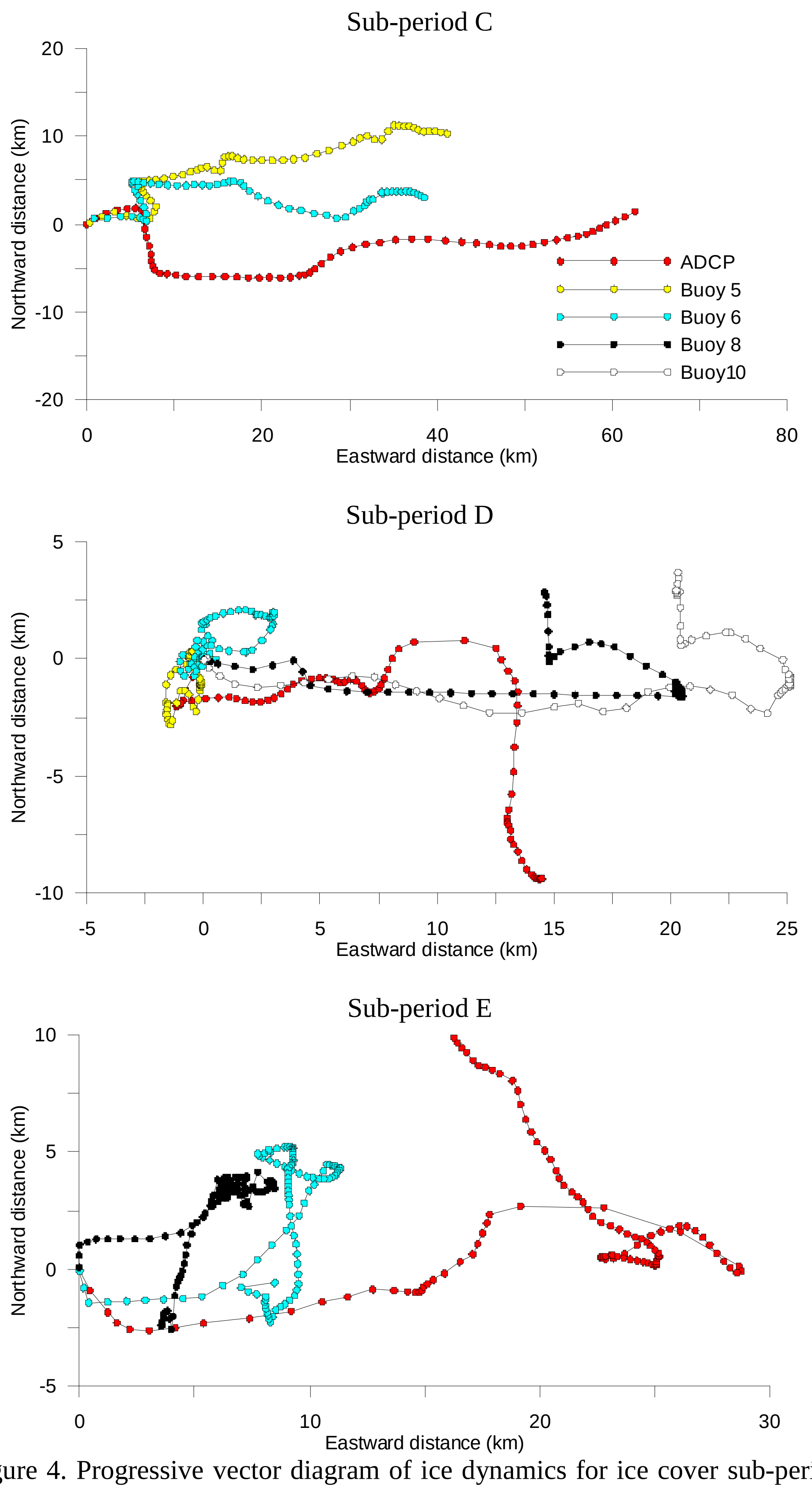


Figure 4. Progressive vector diagram of ice dynamics for ice cover sub-periods C, D and E. The starting point of the buoys and the ADCP current vectors are shifted together. The buoys' trajectories with gaps in data coverage are not displayed.

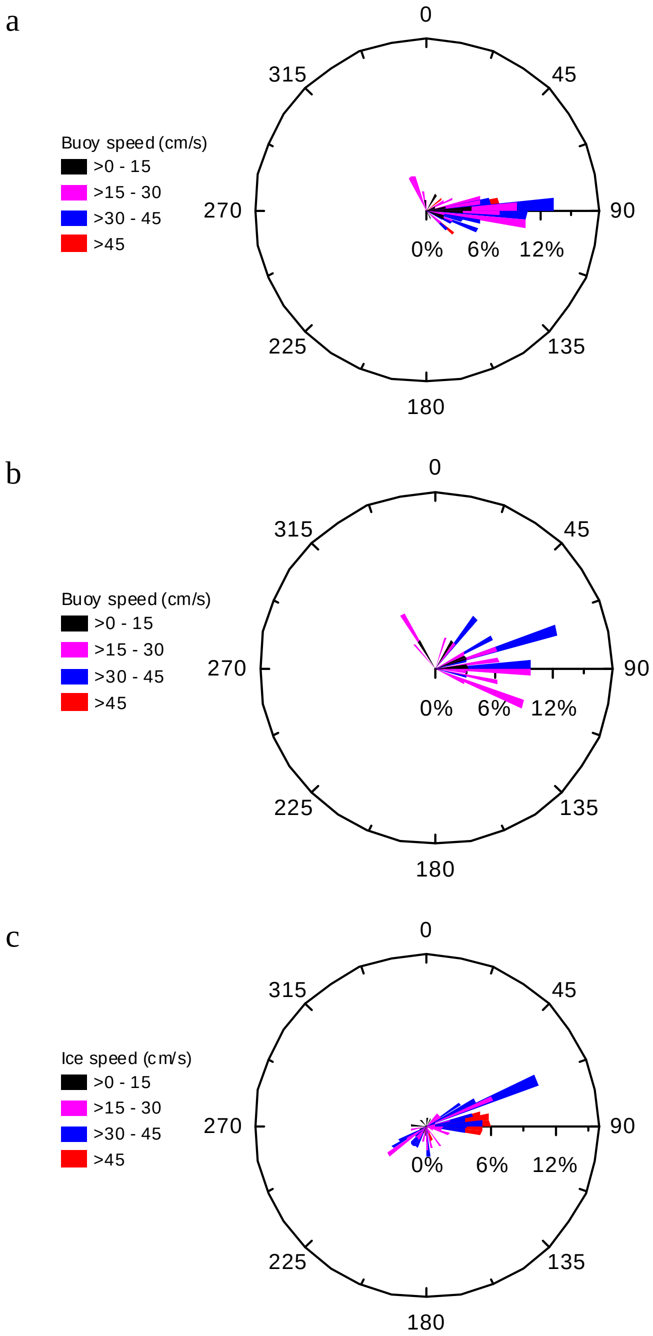


Figure 5. Ice sub-period C polar histograms of (a) buoy 6 drift direction and scaled drift speed (4 classes, cm/s), (b) buoy 5 drift direction and scaled drift speed and (c) ADCP-measured ice drift direction and scaled ice drift speed.

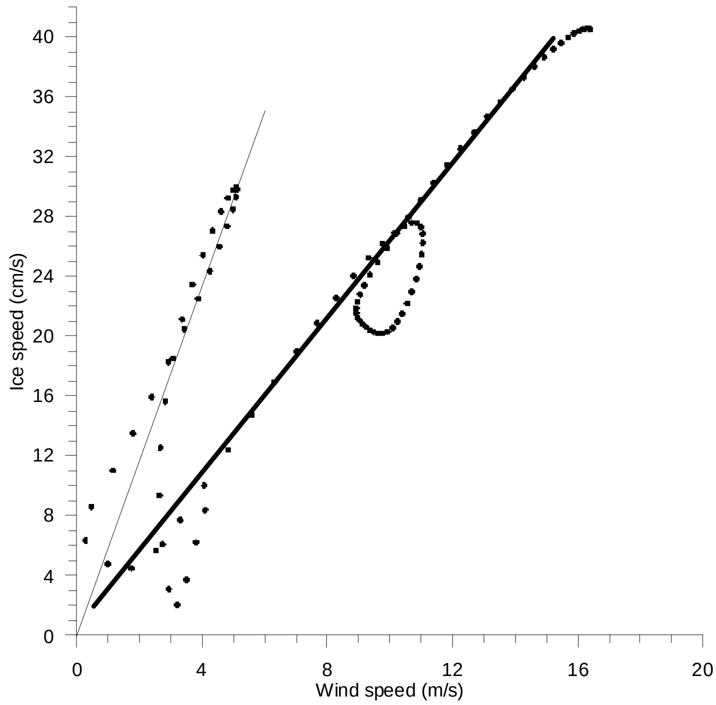


Figure 6. Scatter-plot of the low pass-filtered (filter cut-off: 36 hours) ice drift and wind speeds for ice period C. The thin line is the linear fit for the early part of the ice cover period and the bold line for two later consecutive periods with rising winds (wind speeds of up to 16 m/s).

CONCLUSIONS

The use of the bottom-track function of the ADCP became popular during the last couple of decades (Belliveau *et al.*, 1990; Visbeck & Fischer, 1995; Strass, 1998; Shcherbina *et al.*, 2005) as, laying on the sea bed, it is protected from direct influences occurring on the water's surface and (most importantly) from the impact of the ice itself. Another advantage of this method is that it makes it possible to obtain measurements of ice dynamics with high temporal resolution. The analysis of ice movements using three different datasets simultaneously (MODIS satellite images, drifting buoys and ADCP ice drift data) in a relatively small sea area allowed us to conclude that the ADCP bottom-track facility is a reliable tool in detecting ice cover periods and its main dynamic properties, such as drift speed and pattern of movements. The main focus of this study was the application of combined *in situ* measurement technology consisting of ADCP, drifters and satellite data in the Gulf of Finland conditions, in a sea area with intensive winter traffic of ships and ships frequently becoming stuck because of ice compression. As ice compression has a local scale, we concentrated on fine scale ice dynamics able to be derived from the methods used. The analysis of experiment data revealed the nature of ice dynamics characteristics in the middle of the Gulf of Finland. Namely, the frequent alternation of ice cover periods with open water periods was possible due to the presence of leads on the north and south coasts of the Gulf of Finland and frequent changes in relevant wind direction. A total of five periods of ice cover with a duration of 6-12 days were determined at the measurement location. During ice cover sub-period C three instruments (buoy 5, buoy 6 and the ADCP) showed the most frequent ice drift direction as coinciding, indicative of homogenous ice drift in the middle of the Gulf of Finland. The speed of ice movement was well correlated with the wind data measured nearby. For the ice cover period in March (sub-period C) the correlation coefficient between wind speed and ice drift speed was as high as 0.91. The averaged ratio of the ice drift speed to the wind speed was 0.037, which is about two times higher than the usually estimated ratio of current speed to wind speed, but still in accordance with other ice studies (Björk *et al.*, 2008; Leppäranta, 2005). As the width of the Gulf of Finland is not large, the mean deviation of ice motion to the right of the direction of the wind vector being 26° was lower than the reported 30° for free drift (Thorndike & Colony, 1982). The study concludes that the bottom-track option of the ADCP applied in detecting ice cover is a reliable tool for high resolution monitoring of ice conditions. Ice-bound drifters provide a wider spatial dimension to the dynamics of ice conditions.

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REFERENCES
Alenius, P., Myrberg, K. and Nekrassov, A., 1998. Physical oceanography of the Gulf of Finland: a review. Boreal Env. Res., vol. 3, pp. 97-125.

Belliveau, D.J., Bugden, G.L., Eid, B.M. and Calnan, C.J., 1990. Sea ice velocity measurements by upward-looking Doppler current profilers. J. Atmos. Oceanic Technol., vol. 7, pp. 596-602.

Björk, B., Nohr, C., Gustafsson, B.G. and Lindberg, A.E.B., 2008. Ice dynamics in the Bothnian Bay inferred from ADCP measurements. Tellus, vol. 60A, pp. 178-188.

Granskog, M., Kartokallio, H., Kuosa, H., Thomas, D.N. and Vainio, J., 2006. Sea ice in the Baltic Sea – a review. Estuarine, Coast. Shelf Sci., vol. 70, pp. 145-160.

Kundu, P.K., 1976. Ekman veering observed near the ocean bottom. J. Phys. Oceanogr.,vol. 6, pp. 238-242.

Leppäranta, M., 2005. The Drift of Sea Ice. Springer, Helsinki.

Leppäranta, M., Sun, Y., and Haapala, J., 1998. Comparison of sea ice velocity fields from ERS-1 SAR and dynamic model. J. Glaciol., vol. 44, pp. 248-262.

Leppäranta, M. and Hakala, R., 1992. The structure and strength of first-year ice ridges in the Baltic Sea. Cold Regions Sci. Technol., vol. 20, pp. 295-311.

Leppäranta, M. and Omstedt, A., 1990. Dynamic coupling of sea ice and water for ice field with free boundaries. Tellus, vol. 42A, pp. 482-495.

Leppäranta, M., 1981. On the structure and mechanisms of pack ice in the Bothnian Bay. Finnish Mar Res., vol. 248, pp. 3-86.

Pärn, O. and Haapala, J., 2011. Occurrence of synoptic flaw leads of sea ice in the Gulf of Finland. Boreal Env. Res., vol. 16, pp. 71-78.

Shcherbina, A.Y., Rudnick, D.L. and Talley, L.D, 2005. Ice-draft profiling from bottom-mounted ADCP data. J. Atmos. Oceanic Technol., vol. 22, pp. 1249-1266.

Soomere, T., 2003. Anisotropy of wind and wave regimes in the Baltic Proper. J. Sea Res., vol. 49, pp. 305-316.

Strass, V., 1998. Measuring sea ice draft and coverage with upward-looking moored sonar. Deep-Sea Res., vol. 45, 795-818.

Thorndike, A.S. and Colony, R., 1982. Sea ice motion in response to geostrophic wind. J. Geophys. Res., vol. 87(C8), pp. 5845-5852.

Uotila, J., 2001. Observed and modelled sea-ice drift response to wind forcing in the northern Baltic Sea. Tellus, vol. 53A, pp. 112-128.

Visbeck, M. and Fischer, J., 1995. Sea surface conditions remotely sensed by upward-looking ADCPs. J. Atmos. Oceanic Technol., vol. 12, pp. 141-149.