Ice crystals in the water column: the view from an Acoustic Doppler Current Profiler (ADCP)

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Ice crystals are observed floating freely in rivers, lakes, seas, and oceans in the cryospheric regions of both hemispheres. In the Southern Ocean their formation may be attributed to the presence of supercooled water, which is found on regional scales in certain locations off the Antarctic coast. During winter, ice crystals that nucleate in supercooled water created through basal melting of floating ice shelves can end up incorporated into adjacent sea ice sheets where they are termed “platelet ice”. One potential outcome of climate change is the warming of ice shelf cavity waters which may lead to enhanced basal melting and increased production of ice crystals, unless the adjacent waters are warmed to a point where they prevent the formation of supercooled water. Freely floating ice crystals are difficult to directly measure \textit{in situ} due to the nature of their environment, particularly once an ice cover has formed at the ice-water interface. This paper reports on the use of backscatter readings from a Nortek 1 MHz Aquadopp ADCP deployed through a sea ice cover as a proxy for measuring ice crystals in the water column at a site adjacent to the McMurdo Ice Shelf, Antarctica during the austral winter of 2003. Ancillary measurements are used to assess its performance. An ADCP at a single frequency can detect the presence of freely floating ice crystals in the water column but is unable to estimate crystal sizes and concentrations.
1 Introduction

The prevalent form of sea ice in McMurdo Sound, Antarctica is columnar ice (Paige, 1966; Gow et al., 1982, 1998; Crocker and Wadhams, 1989; Jeffries et al., 1993; Smith et al., 2001; Jones and Hill, 2001) which is often found below a thin layer of granular ice at the top of the ice sheet. Columnar ice crystals grow down into the underlying water column and this growth is driven by heat flux to the atmosphere. Beneath, and sometimes interspersed within, this columnar ice there is often found an open-textured, random array of dendritic crystals with length scales up to ~150 mm. This layer is said to be composed of platelet ice crystals and has been observed in the Sound since the Discovery Expedition of 1901–1904 (Hodgson, 1904; Wright and Priestley, 1922; Paige, 1966; Gow et al., 1982, 1998; Crocker and Wadhams, 1989; Jeffries et al., 1993; Smith et al., 2001; Leonard et al., 2006; Dempsey et al., 2010). Platelet ice, or ice is that is morphologically similar, is not confined to McMurdo Sound and has been observed in other regions of Antarctica (Moretskii, 1965; Tison et al., 1998; Eicken and Lange, 1989; Kipfstuhl, 1991; Günther and Dieckmann, 1999) in proximity to floating ice shelves. Similar observations in the Arctic are unusual (Jeffries et al., 1995).

The formation processes for platelet ice in McMurdo Sound are not completely understood. The current understanding is that a necessary pre-condition for platelet ice formation at the ice-water interface is supercooled water (water cooled below its in situ freezing point) from beneath an adjacent ice shelf coming into contact with the ice-water interface (see Leonard et al., 2006) for further discussion). Platelet ice growth at the ice-water interface has been observed to be an episodic process (Smith et al., 2001) largely influenced by tidal forcing in McMurdo Sound. A key finding to date is that the presence of platelet ice incorporated in the sea ice cover has been conclusively linked to the time history of the appearance of ice crystals in the water column, monitored using the backscattered signal strength from an Acoustic Doppler Current Profiler (ADCP) (Leonard et al., 2006). The orientation of platelet ice crystals incorporated into the sea ice cover suggests that pre-cursor platelet ice crystals entrained in the supercooled water may be many times smaller than the incorporated crystals observed in ice cores. The in situ growth of incorporated platelet ice at the ice-water interface is believed to be partially driven by a thermal gradient between the ice-water interface and the nearby supercooled layer (Purdie et al., 2006).

One potential outcome of climate change is the warming of ice shelf cavity waters to a point where enhanced basal melting and increased production of ice crystals results. It is therefore necessary to gain a better understanding of platelet ice formation processes in order to improve understanding of sub-ice shelf processes so that potential impacts on floating ice shelves due to climate change can be assessed. This paper reports on the use of backscatter readings from a Nortek 1 MHz Aquadopp ADCP deployed through a sea ice cover as a proxy for measuring ice crystals in the water column at a site adjacent to the McMurdo Ice Shelf, Antarctica during the austral winter of 2003.

2 Detection of Ice Crystals in the Water Column

The river ice community has long had an interest in observing frazil crystals suspended in rivers. Field observation methods reported at the very first IAHR Symposium on Ice in Reykjavic, Iceland, in 1970 included underwater lights and collection trays (Wigle, 1970) and a device for measuring the electrical resistance between two insulator roads immersed in a river (Kristinsson, 1970). Other techniques developed for laboratory and field environments include instruments based on measuring comparative resistances (Gilfilian et al., 1972; Tsang, 1985), laser Doppler velocimetry (Schmidt and Glover, 1975), piezoelectric transducers (Hanley, 1978), optical instruments (Pegau et al., 1996), electromagnetic-based systems (Yankielun and Gagnon, 1999), calorimeters (Ford and Madsen, 1986; Lever et al., 1992), underwater photography (Daly and Colbeck, 1986), measurement of flow through a simulated trash rack (Daly and Rand, 1990), digital imagery using cross-polarizers (Doering and Morris, 2003) and sonar (Jasek and Marko, 2007). Combinations of acoustic sounding and sample collection using trawl nets have also been used on two occasions in Antarctic waters to confirm the presence of ice crystals with diameters of the range of 10–25 mm at depth in the water column (Dieckmann et al., 1986; Penrose et al., 1994). In general the observation methods developed for the
river ice environment have been specifically designed to measure ice crystals in the water column, while the methods used in the ocean have been made serendipitously by instruments not specifically designed for ice crystal detection.

3 Study Area
All ADCP measurements reported herein were made at Site A (77°48′41.5″ S, 166°26′1.8″ E), which was located within an area of multi-year ice which had been broken up and pushed away to form a fuel tanker turning basin. The area of the turning basin was approximately 61,500 m², while the thickness of the surrounding multi-year ice was 4.30 m on 27 March 2003, with a snow cover thickness of 0.45 m. Site A was chosen as the primary site for the ADCP measurements as it was the only first-year sea ice within the operational range of Scott Base during Feb – Sep 2003 due to the influence on the waters of the Sound by iceberg B15A positioned to the north of Ross Island (Robinson et al., 2010). The depth of water at Site A was approximately 540 m (Davey, 2004). Early winter oceanographic measurements of temperature and salinity measurements made at Site B (77°52′59.8″ S, 166°40′0.7″ E) from mid-March to mid-May as this site was located on multi-year ice and had a viable route to the ice shelf in case of rapid break-out of the sea ice. This S–T instrument chain was later redeployed at Site A once the first-year sea ice in the turning basin was thick enough to support a field camp. The locations of both sites in relation to McMurdo Station and Scott Base are show in Figure 1. For more detail see Leonard et al. (2006).

4 Instruments and Methods
Current measurements were made using a Nortek 1 MHz Aquadopp acoustic Doppler current profiler (ADCP) with its magnetic compass corrected by a declination of 150° ± 10° E (NOAA, 2004). The ADCP was generally deployed just below the ice-water interface with a downward looking orientation, although the particular method of deployment was modified throughout the winter to account for changing conditions. The particular details of the deployments are discussed in the next section. Owing to the clarity of Antarctic waters, the effective range of the ADCP was generally reduced to less than half of the 25 m range stated by the manufacturer. In general the ADCP was
set up to measure three-dimensional current velocities in fifteen 1 m deep bins by averaging signal returns over 1 minute in every 5 minutes. Data retrieved from the ADCP included binned backscatter returns for each of the three beams. The level of backscatter recorded by the instrument is dependant on the number concentration and size distribution of acoustic scatters, and the reader is directed to (Leonard et al., 2006) for discussion with respect to the Nortek 1 MHz ADCP. The raw backscatter values were converted to dB and corrected for beam spread.

Winter-long temperature and salinity measurements, logged at 30 minute intervals, were taken at Site B between 20 March and 9 May, and at Site A between 10 May and 12 September. One Sea-Bird SBE-37 conductivity-temperature-depth (CTD) logger was deployed at 10 m depth between 20 March–23 May, when it was moved deeper by 10 m in order to reduce icing on the instrument. A second identical instrument was placed at a depth of 50 m. Calibration details for these instruments are given in Leonard et al. (2006). Potential temperatures are reported herein, i.e. temperature changes due to pressure have been removed.

5 Results and Analysis
The nearly contiguous winter-long ADCP record revealed several episodes where the recorded backscatter values departed from a background level. The nature of the signal was changeable from episode to episode throughout the course of the winter. For each of four selected time periods ADCP backscatter is correlated with respect to potential drivers to determine if changes in signal can be explained by them. The potential drivers are the vertical migration of biological matter in the upper water column due to seasonal and daily changes in solar elevation, the ocean current speed along its principal axis, and the observed temperature variation at 10/20 m and 50 m depths. The solar elevations were computed using the USA National Energy Research Laboratory’s Solar Position Algorithm (Reda and Andreas, 2008). The current’s principal axis is determined by applying principal component analysis to the East-West and North-South current velocities (corrected for magnetic declination) recorded by the ADCP. Each signal was zero-meaned and normalised by its standard deviations before cross-correlations were computed.

5.1 24–29 March
For this time period the ADCP was attached via an aluminium arm to a ring buoy and placed through a hole in the first-year ice (See Figure 2). This proved to be an effective method for deploying the instrument, although it was necessary to retrieve the ADCP every 3–4 days to ensure that icing did not interfere with current measurements (see Figure 3a).

The ADCP backscatter returns averaged over bins 4 through 7 (approximately 5–8 m depth) are shown in Figure 4 together with the solar elevation, principal current speed and 50 m temperature time-series. The 10 m temperatures were not available for this time period. The ADCP backscatter for

![ADCP on ring buoy ready to be deployed.](a)
![ADCP on ring buoy after deployment.](b)

Figure 2. ADCP deployed through the first-year ice using the short aluminium arm at site A. Photos taken on 7 March.
Figure 3. Examples of icing on the ADCP. (a) shows ice growing down from the ice-water interface after a 3.85 day deployment on the ring buoy. (b) shows the ADCP attached to a stainless steel bracket which is suspended on a winch wire above a hole in the ice which has been completely filled by ice platelets that have been knocked off the wire as the ADCP was retrieved from a 15 day deployment at a depth of 10 m. The white structure seen in the right of the photograph is the edge of the hut’s dive platform.

beams 1 and 2 in Figure 4 a have been offset for clarity from Beam 3 by 25 and 50 dB, respectively. Figure 4 clearly shows daily increases in ADCP backscatter in all three beams of approximately 6–9 dB, with the peak centred around 12:00 UTC. This compares well with both the track of the sun above the horizon and tidally driven oscillations in current speed, as evidenced by the cross-correlations shown in Figure 5. The correlation between signal strength and solar elevation peaks at 0.769 at a lag of -0.017 days (i.e. the backscatter signal lags the solar elevation signal). The current speed also correlates with the backscatter with a correlation of 0.512 at a lag of 0.055 days. The bearing of the current principle axis is 356.05° (see Table 2), so that the ADCP backscatter signal is generally peaking when the tidally driven current is flowing out of the Sound to the north. However, the precise nature of the 24-hour period observed in the backscatter favours changes in solar elevation as a driver, as the diurnal tidal period in McMurdo Sound is longer than 24 hours, at around 24.8 hours (Leonard et al., 2006). There is no clear evidence of a correlation between backscatter and 50 m temperatures.

5.2 15–26 May

By this time the first-year ice in the turning basin had thickened to the point where huts could be deployed onto it. The ADCP was now deployed through the ice from within a heated hut and was attached to a longer version of the aluminium arm shown in Figure 2. It was located just below the ice-water interface and was positioned in a downward-looking orientation. The ADCP backscatter returns averaged over bins 4 through 7 (approximately 5–8 m depth) are shown in Figure 6 together with the principal current speed and 10/20 and 50 m temperatures. The solar elevation is not shown as the sun had set below the horizon. It can be seen that the periodic signal in the ADCP backscatter observed in March is no longer present in May. The most notable features in the backscatter signal are episodes of increased intensity in the latter half of the time series. These increases are matched by corresponding decreases in the 10/20 m temperature, which can be seen by viewing the cross-correlations presented in Figure 7. It can also be noted in Figure 6 that the two temperature signals are similar from the middle of 22 May onwards, indicating that the mixed layer below the growing ice sheet has reached a depth of at least 50 m (Leonard et al., 2006). The correlation between the ADCP backscatter and 10/20 m temperature is the only significant correlation for this time period, with a cross-correlation coefficient of -0.808 at a lag of 0.017 days.
Figure 4. Time series data for the first time period. (a) ADCP signal strength, with Beams 1 and 2 offset from Beam 3 by 25 and 50 dB, respectively, (b) solar elevation angle, (c) principle current speed and (d) 50 m potential temperatures.

Figure 5. Lagged ADCP backscatter cross correlations for the first time period.

5.3 22–31 July
For this time period the ADCP was deployed from within a hut on a propylene rope or steel winch wire, and was positioned at an approximate depth of 10 m and oriented upward. The ADCP backscatter from bins 4 through 7 (now ~6.5 to 4.5 m depth due to the upward orientation) are shown in Figure 8 together with the principal current speed and 20 and 50 m temperatures. Again there is no periodic signal within the ADCP backscatter, and episodes of increased ADCP signal generally correspond to decreases in the temperature signals at 20 and 50 m, although the only significant
correlation is once again with the 20 m temperature, which is now weaker (-0.548 at a lag of 0.024 days) than the May time period. The principal current speed is tidally driven and not correlated with ADCP signal strength. The end of this time period was notable for enhanced platelet ice growth as evidenced by ice accretion on ropes, wires and instruments suspended in the water column. An example of this is when the ADCP was recovered from the 15-day deployment at 10 m depth on 7 August (see Figure 3b), it was found to be completely encased in platelet ice. Analysis of the ADCP backscatter revealed that icing probably began to affect the instrument from early on 1 August.

5.4 5–11 September
For the final time period the ADCP was once again deployed in a downwards orientation through the ice on an aluminium frame from within the hut. The ADCP backscatter from bins 4 through 7

Figure 6. Time series data for the second time period. (a) ADCP signal strength, with Beams 1 and 2 offset from Beam 3 by 25 and 50 dB, respectively, (b) principle current speed and (d) 10/20 and 50 m potential temperatures.

Figure 7. Lagged ADCP backscatter cross correlations for the second time period.
Figure 8. Time series data for the third time period. (a) ADCP signal strength, with Beams 1 and 2 offset from Beam 3 by 25 and 50 dB, respectively, (b) principle current speed and (d) 20 and 50 m potential temperatures.

Figure 9. Lagged ADCP backscatter cross correlations for the third time period. (~5.5 to 8.5 m) are shown in Figure [10] together with solar elevation (the sun first rose back above the horizon in mid-August), principal current speed and 20 and 50 m temperatures. A peak in backscatter strength in Beam 1 on 6 September is not seen in the Beam 2 and 3 signals, indicating interference in the Beam 1 backscatter by some unidentified object. Although the periodic signal in the solar elevation angle is evident as it was in March, there is no clear periodicity in the ADCP backscatter. The dominant feature remains the correlation between episodic increases in backscatter and 20 and 50 m temperatures decreases, as evidenced in Figure [11] Beam 1 signal strength was not included in this correlation due to the previously mentioned signal transient in the Beam 1 time-series. The correlations with the 20 and 50 m temperatures are very similar in this record, with peak correlation coefficients of -0.865 and -0.757 at a lag of 0.007 and 0.017 days, respectively.
Figure 10. Time series data for the fourth time period. (a) ADCP signal strength, with Beams 1 and 2 offset from Beam 3 by 25 and 50 dB, respectively, (b) solar elevation angle, (c) principle current speed and (d) 20 and 50 m potential temperatures.

Figure 11. Lagged ADCP backscatter cross correlations for the fourth time period.

6 Discussion
Analysis of ADCP signal strength from March to September 2003 in McMurdo Sound, Antarctica, indicate that backscatter increases periodically above a background level in March, while it tends to vary episodically from May to end of the observational record in September as first reported in (Leonard et al., 2006). Leonard et al. (2006) surmised that the periodic signal observed in March was due to daily migration of organisms upward through the water column in response to a circadian rhythm governed by the solar elevation, followed by a descent beyond the range of the ADCP (∼12 m)
when the sun drops below the horizon. This is supported herein by the strong correlation between backscatter and solar elevation angle for the March time period (see Table 1). Although backscatter also correlates significantly with the variation in the tidally driven principal current speed, the current is not thought to be a driver of the variation in the backscatter signal due to the 24.8 hour period of the diurnal tides versus the precise 24 hour period in the ADCP signal.

Table 1. ADCP backscatter cross correlation coefficients and corresponding lag times.

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</tr>
</thead>
<tbody>
<tr>
<td>24–29 March</td>
<td>0.769</td>
<td>-0.017</td>
<td>0.573</td>
<td>-0.056</td>
<td>-</td>
<td>-</td>
<td>0.230</td>
<td>-0.746</td>
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<tr>
<td>15–26 May</td>
<td>-</td>
<td>-</td>
<td>0.250</td>
<td>-0.045</td>
<td>-0.808</td>
<td>0.017</td>
<td>0.534</td>
<td>0.764</td>
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<tr>
<td>22–31 July</td>
<td>-</td>
<td>-</td>
<td>-0.188</td>
<td>-1.764</td>
<td>-0.548</td>
<td>0.024</td>
<td>-0.283</td>
<td>-0.080</td>
</tr>
<tr>
<td>5–11 September</td>
<td>0.234</td>
<td>0.010</td>
<td>-0.587</td>
<td>0.438</td>
<td>-0.865</td>
<td>0.007</td>
<td>-0.757</td>
<td>0.017</td>
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The periodic nature of the ADCP backscatter signal has disappeared by May, which coincides with the setting of the sun in late April. From May to early September the ADCP backscatter signal is dominated by episodic increases of up to ∼30 dB over a background level which has been shown to correlate with decreases in temperature in the upper water column. The direction and nature of the principal current shows some variance during this time (see Table 2), but is predominantly influenced by the diurnal tides flowing into (South) and out of (North) of the Sound, although the strength of the current along its principal axis is reduced in July as evidenced by the decreases in variance along the principal axis as shown in Table 2. This analysis leads to the same explanation reached in the (Leonard et al., 2006), namely that episodic increases in ADCP signal strength are likely due to ice crystals of some indeterminate size which appear episodically in the water column in tandem with a reduction in the local temperature. These episodic decreases in temperature often resulted in the water at 10 and 20 m below the water surface becoming supercooled (Leonard et al., 2006).

Table 2. Principle current bearings and variances for the four time periods.

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Principal Current Bearing (°)</th>
<th>Variance along Principal Axis (%)</th>
<th>Length of time period (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24–29 March</td>
<td>356.05</td>
<td>88.63</td>
<td>4.86</td>
</tr>
<tr>
<td>15–26 May</td>
<td>340.46</td>
<td>75.49</td>
<td>11.18</td>
</tr>
<tr>
<td>22–31 July</td>
<td>11.42</td>
<td>65.63</td>
<td>9.85</td>
</tr>
<tr>
<td>5–11 September</td>
<td>6.30</td>
<td>70.13</td>
<td>6.74</td>
</tr>
</tbody>
</table>

7 Conclusions

The results presented herein indicate that an ADCP operating at a single frequency is capable of detecting acoustic scatterers in the water column, be they of biological or ice crystal origin. Sensors capable of measuring acoustic scatterers at different frequencies are necessary in order to estimate their number concentration and size distribution. One such platform, an upward looking sonar instrument, has been developed for measuring frazil ice in Peace River in Northern Alberta, Canada (Jasek and Marko, 2007). Jasek and Marko (2007) state that the quantitative measurement of variations in the size distributions of suspended frazil ice would appear to be accessible through near-simultaneous profiling at several acoustic frequencies, although, to the authors’ knowledge, such measurements have not been reported in the literature. It is suggested, based on the observations reported here, that a measurement platform comprised of ADCPs operating at different frequencies may be capable of
providing estimates of number concentration and size distribution of ice crystals in the water column. The frequency of the ADCPs would need to be chosen such that they are capable of resolving particles within the size range of interest. Such measurements are currently being planned for future ice crystal measurements in McMurdo Sound, Antarctica.

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