

# Measurements of Ice Parameters in the Beaufort Sea using the Nortek AWAC Acoustic Doppler Current Profiler

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**Measurements of sea ice presence, ice keel draft, and ice thickness are important for climate studies and engineering design and maintenance of coastal and offshore structures. Building on the success of upward looking sonar systems for ice measurements, Nortek recently introduced new firmware and measurement methods to make observations of sea ice with the Nortek AWAC acoustic Doppler current profiler. The AWAC employs a dedicated, narrow, upward looking vertical transducer to acoustically measure waves (summer) and ice (winter). One of the first commercial applications of this new measurement capability was a project in 2008 to measure ice parameters in support of the design of an offshore structure and its ice armoring system in the Beaufort Sea, Alaska. An analysis of instrumental and environmental error is described. The AWAC ice measurements are compared to a co-located ASL ice profiler and show a mean difference of less than 0.05 m. Ice formation began in mid-October when air temperatures were routinely below  $-10^{\circ}\text{C}$ . The thickness increased almost linearly until it peaked in mid-May at about 1.8 m. This represents an increase in ice thickness of approximately 0.01 m/day. The near-surface current velocity from the Nortek AWAC was used to estimate the horizontal length scales and the direction of movement of mobile ice blocks.**

## I. INTRODUCTION

Measurements of sea ice presence, ice keel draft, and ice thickness are important for climate studies and engineering design and maintenance of coastal and offshore structures. Climate scientists are interested in knowing when ice-cover first forms and when it breaks up because the roughness parameters are very important for climate numerical models of ocean-atmosphere interactions. Measuring long-term trends in total ice thickness is important for validating climate models and observing trends in climate change. Engineers need to measure ice presence, thickness and movement in order to design coastal and offshore structures and the requisite ice protection for the structures. Measurements of maximum ice keel depths are required for planning installation and maintenance of underwater infrastructure in shallow water such as cables and pipes.

Common ice measurement methods include remote sensing from satellites and aircraft, in-situ ice buoys, and upward looking sonar. Aerial measurements from satellites and aircraft provide maps with good spatial coverage but they cannot resolve ice thickness and subsurface features such as maximum ice keel depths. Ice buoys are typically mounted on the ice surface and must have a hole drilled through the ice to mount a staff extending several meters below the ice bottom with an upward looking sonar for ice thickness measurements. These buoys provide accurate measurements of ice thickness, but they are susceptible to damage and act as Lagrangian measurements; drifting on the same ice parcel as originally deployed. Single beam, upward looking, sonar instruments may be deployed on the seafloor or on a subsurface buoy. These instruments acoustically measure the distance to the bottom of the ice and can estimate ice thickness by subtracting the ice keel location from measurements of water depth (from an onboard pressure sensor). Such sonars have been used widely and successfully for climate and engineering studies.

## II. METHODS

Building on the success of upward looking sonar systems for ice measurements, Nortek recently introduced new firmware and measurement methods to make observations of sea ice with the Nortek AWAC acoustic Doppler current profiler. The Nortek

AWAC has long been used for routine measurements of ocean current profiles and directional waves by using the method known as acoustic surface tracking (AST). The AWAC employs a dedicated, narrow, upward looking vertical acoustic beam to measure the range to the ocean surface [1]. In the traditional “wave tracking” mode, the AST tracks the water-air interface (waves) by locating the peak amplitude of the acoustic echo, typically at a rate of 2-4 Hz. The new capability in the AWAC allows for automatic “ice tracking” by finding the range of the acoustic echo indicating the water-ice interface (ice cover) by locating the leading edge of the peak of the return acoustic signal.

The textural and density complexity of ice means that the water-ice interface does not have the same acoustic return characteristic as the water-air interface (Fig. 1). This means that a new edge detection algorithm had to be implemented in the AWAC to provide simultaneous wave and ice measurements using the AST. The ultimate solution was to implement the standard “max peak” edge detection method for water-air (wave) measurements and a new “leading edge” detection method for the water-ice (ice) measurements.

Because the AWAC applies both the max peak and leading edge algorithms to the AST echo returns, the AWAC does not need to be programmed to switch between wave measurements and ice measurements at a predetermined date. Thus the AWAC can be deployed bottom mounted, or on a subsurface buoy, to measure the directional wave field during open-water conditions, and also measure ice formation, thickness and max keel draft during ice-cover conditions [2]. The AWAC also functions as a fully capable ADCP to measure the full current velocity profile.

The AWAC measures only ice keel depth directly; not ice thickness. Over a large area, floating ice must be in hydrostatic equilibrium with the water, so the average thickness is only slightly greater than the average keel draft. However, small-scale ice masses, such as pressure ridges, can be partially supported by surrounding floating ice. The thickness of such features cannot be measured and may be greater than the keel draft.

The AWAC’s primary parameters for ice measurements include rapidly sampled time series of the range between the instrument’s transducer face and the underside of the ice, determined from an acoustic travel time measurement, and absolute pressure. In post-processing it is necessary to convert the pressure measurements to an equivalent height of the free water surface, and to apply various corrections to both types of data. Data conversion software provides standard ice measurement statistics such as mean ice thickness and maximum ice keel draft. There are several known sources of instrumental and environmental error associated with this method of upward looking sonar measurements to observe ice thickness.

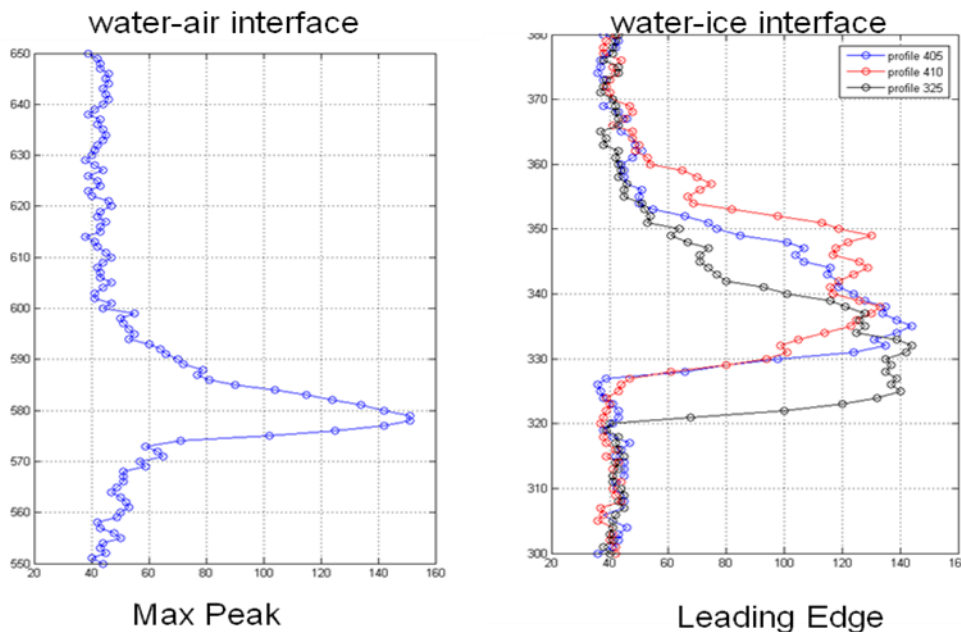


Fig. 1 Acoustic surface tracking (AST) echo returns from water-air (waves) echo (left) and water-ice (ice) echo (right).

### III. ERROR ANALYSIS

#### A. Estimation of Sea Surface Elevation from Pressure Measurements

To determine the free sea surface height above the bottom, which is the same whether or not floating ice is present, the measured absolute water pressure must be corrected for atmospheric pressure fluctuations, and then scaled by the average density of the water column. Adjustment may also be made to account for the effective height of the pressure sensor relative to the AST transducer.

All pressure sensors have an inherent accuracy limitation, which is typically expressed as a fraction of the full-scale pressure rating. The AWAC pressure sensor has an error of approximately  $\pm 0.5\%$  of full scale (FS), which equates to  $\pm 0.25$  m possible error for a 50 m full scale pressure sensor. While this error is not known in advance of deployment, it is generally manifested as a constant offset so it can be compensated in post-processing by applying an offset to match the free sea surface height measured by the pressure sensor with that measured by the AST.

In addition, pressure sensors like that of the AWAC, which are not temperature-compensated, may experience time-varying errors due to water temperature changes. Nortek has found that the temperature sensitivity of some tested pressure sensors ranges from 0.004% FS/ $^{\circ}$ C to 0.01% FS/ $^{\circ}$ C. For ice measurements in shallow water, the near-bottom temperature becomes relatively constant (typically near  $-2^{\circ}$ C) once ice has formed at the surface. Even at the beginning and end of the ice season, the water temperature does not vary by more than a few degrees, so temperature-induced errors in the pressure data would be less than about 0.025 m in the worst case, and probably much less in typical cases during the period of full ice cover.

The AWAC's pressure sensor measures absolute pressure, but the data are presented relative to a nominal value of atmospheric pressure at the time of sensor calibration (i.e., a constant mean value of atmospheric pressure is already subtracted from the absolute pressure measurements). The data have to be corrected for fluctuations of the actual atmospheric pressure relative to the assigned mean pressure. These fluctuations, which are associated with the passage of high and low pressure zones in the atmosphere, occur on daily to weekly time scales and can have an amplitude equivalent to  $\pm 0.5$  m of water height, if not corrected. A time series record of barometric pressure is required to make this important correction. Since atmospheric pressure variations are associated with large-scale synoptic weather systems, the barometric pressure measurement does not have to be made right at the location of the AWAC. Atmospheric pressure measurements obtained within a few tens of kilometers from the AWAC typically result in residual errors after correction of less than  $\pm 0.05$ m.

After removal of atmospheric pressure fluctuations, the water depth is estimated from the pressure data using values of water density and acceleration due to gravity:  $h=P/(g \cdot \rho)$ , where  $\rho$  is the average water density. Both water density and sound speed in sea water are usually calculated using temperature and salinity data. While the instrument records water temperature, it does not measure salinity, so this parameter has to be estimated from proxy information. For example, when ice is present it may be assumed that the minimum water temperature is near the freezing temperature, which depends on salinity. The salinity can be estimated based on this assumption. A combination of measured water temperature and estimated salinity yields a slowly time-varying estimate of water density and a water depth correction factor related to water density.

Salinity is the most important factor in determining the density of sea water around the freezing point, and the salinity of coastal Arctic waters varies widely with the seasons. In late winter the salinity is high ( $>34$  psu) due to salt brine rejection from the ice, whereas in summer the salinity can be very low (perhaps about 20 psu) due to freshwater runoff from the land. From published density tables it may be estimated that uncorrected temperature variability over the range of  $+2.5^{\circ}$  C to  $-2.5^{\circ}$  C would result in an almost negligible error of 0.003 m in about 10 m of water depth at 34 psu salinity [3]. However, an uncorrected salinity change from 34 psu to 20 psu at about  $0^{\circ}$ C would correspond to a depth error of about 0.1 m in 10 m water depth, so an effort to correct for salinity is warranted. It is reasonable to assume that the water column beneath the sea ice is fairly well mixed, so vertical stratification (less dense water near the surface) probably does not contribute any significant error in the density calculation.

#### B. Estimation of Sea Surface Height from the Acoustic Surface Tracking (AST) Range Measurements

The AWAC's acoustic range measurement technique uses an estimate of the vertically-averaged speed of sound to convert acoustic travel-time measurements into distance estimates. The speed of sound is calculated in the instrument from user-input salinity and measured temperature at the location of the instrument. Salinity plays a relatively minor role in sound velocity (about 1.4 m/s/psu at  $0^{\circ}$ C), so the uncertainty in salinity is not expected to contribute significantly to errors in the acoustic range data [3]. For example, uncorrected salinity variations over the range of 30 -35 psu would contribute errors in calculated water depth of only about 0.05 m. Temperature is important for sound velocity (4.34 m/s/ $^{\circ}$ C) so an uncorrected temperature change of  $-2.5^{\circ}$ C to  $+2.5^{\circ}$  C would result in a depth error of 0.15m. By using the measured AWAC temperature to correct the speed of sound, combined with an estimate of salinity based on the assumption that the water column is near the freezing point, it is possible to reduce the residual error due to density uncertainty to less than  $\pm 0.05$ m. Again, it is reasonable to assume that the water column is not highly stratified during ice conditions.

Also, it is necessary to correct the AWAC's AST range data for instrument tilt, as this affects the range to the sea surface. An uncorrected tilt of  $5^\circ$  would result in a range error of 0.2 m in 50 m water depth, or 0.04 m in 10 m water depth. Tilt errors will be negligible if the AWAC is deployed in a gimballed mount, but in many cases the instrument is not gimballed and can experience substantial tilts when the bottom platform is deployed in soft bottom sediments. Moreover, the tilt can change over time as sediment erodes and the platform settles into the sea floor. Time series data from the AWAC's pitch and roll sensors are used to correct the slant range to estimate true vertical distance from the instrument to the water or ice interface, and any residual uncertainty due to this cause is negligible.

In summary, there are various sources of static and time-varying error in the determination of water depth and the location of the ice edge, even after application of the correction factors. However, an approximate value of the residual error may be estimated by comparing the pressure-based and AST ice draft measurements during times when there was clear water, for example, just before ice formation or after ice breakup. An offset can be applied to the pressure-based sea surface height estimate to zero out any difference at this time, leaving only small time-varying errors. With this approach, if the environmental conditions remain unchanged throughout the measurement period the accuracy of the ice draft measurement would only be limited by the vertical resolution of the acoustic echo profile, which has a native resolution of 0.024 m. As a practical matter, a residual uncertainty (among all variables) of 0.05 m to 0.1 m remains and this limits the ability of the acoustic sensor to reliably detect and estimate the thickness of thin new ice.

#### IV. DATA

##### A. Applications of the AWAC for Ice Measurement

One of the first commercial applications of this new measurement capability was a project to measure ice parameters in support of the design of an offshore structure and its ice armoring system in the Beaufort Sea, Alaska. The goals of the project were to measure ice thickness during stationary fast ice periods and ice block thickness and size distribution during partial ice coverage periods.

Two Nortek 1MHz AWAC's with ice measurement capability were deployed in the Beaufort Sea in August 2008 in about 12 m water depth (Fig. 2) and recovered one year later. At one of the sites an ASL Ice Profiler, Model IP-5, was also deployed for comparison. The AWAC's were configured with enough internal memory and external batteries to measure current velocity, surface wave height and direction (during open water) and ice thickness, every half hour for a one year period. The AWAC AST sampled the ice/water interface at a rate of 1 Hz for 512 samples (~8.5 minutes) every 30 minutes for the 1-year deployment, and recorded the entire high-resolution echo amplitude profile for each ping. This high-resolution burst measurement provided information about the mean ice thickness, maximum ice keel draft, and ice block movement. The measurement of ice thickness is made by subtracting the location of the leading edge of the AST peak from the mean depth determined from a pressure measurement (also made onboard the AWAC) after all the corrections. The near-bottom water temperature was very stable under the ice and was near  $-1.7^\circ\text{C}$ , suggesting the salinity was near 32 psu throughout the entire winter. These measurements of ice thickness were based on recorded high-resolution single-ping echo amplitude profiles. In addition, the AWAC's also collected normal wave data (4 Hz AST measurements, 2 Hz wave velocity measurements) in 512-second bursts every 30 minutes, so ice and wave measurements were interleaved for the entire 1-year measurement program. The AWAC's collected four 1-minute current profiles during each hour.



Fig.2 Three Nortek AWAC's in fiberglass bottom frames with acoustic pop-up floats were deployed in the Beaufort Sea for one year.

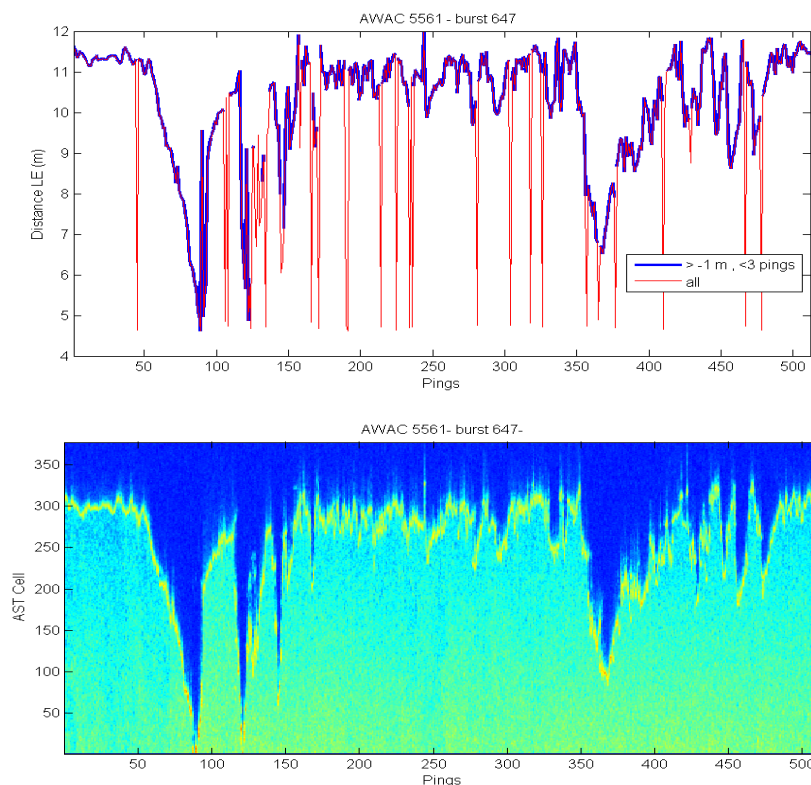
## B. Quality of Ice Keel Draft Measurements

Although the AWACs provided extensive, highly detailed data on ice keel draft, inspection of individual diagnostic sampling bursts revealed the presence of large-amplitude “spikes” characterized by apparent ice keel elevations around 5 mab (meters above bottom). Such spikes are clearly evident in the example shown in Fig. 3 (upper panel, red trace). The ASL IP-5 Ice Profiler did not exhibit such spikes. Echo intensity profiles from the AWAC’s diagnostic data (Fig. 3, lower panel) reveal that the spikes occurred when there was a rapid transition of ice keel depth, such as would occur when the edge of an ice block passed over the AWAC. At such times, the strength of the acoustic echo from the steeply sloping bottom of the ice apparently became too low and the Nortek software sought a maximum in echo intensity elsewhere in the water column. The leading edge detector employed by Nortek’s software apparently latched onto the bottom of the AWAC’s preset range window (5-14 mab for this deployment), where the echo amplitude due to scatterers in the water column was relatively strong. This accounts for why the spikes in ice thickness always exhibit the same elevation (slightly higher than the bottom of the range window).

Because of the unique characteristics of these spikes, it is possible to screen them out in post-processing using a rate-of-change criterion to identify the leading edge of each spike. An iterative multi-step procedure was applied to determine the optimum set of screening criteria. The spikes are brief (usually only a few pings) allowing interpolation across the gap where spikes were removed. Finally a 7-point running mean filter was applied to further smooth the edited data. The result is shown in Fig. 3 (upper panel, blue trace). It is seen that the filter process is effective at removing the spurious spikes without otherwise affecting the characteristics of the ice keel depth time series.

An ASL Model IP-5 Ice Profiler was deployed near the AWAC for reference ice thickness measurements. The ASL IP-5 uses an upward-looking acoustic echo sounding technique similar to that of the Nortek AWAC, but with a narrower beam and lower acoustic frequency (420 kHz). A comparison of ice thickness during the period of stationary fast ice shows excellent agreement between the two similar acoustic measurement methods, with no bias (Fig. 4) and a mean difference of less than 0.05 m.

It was important to understand whether ASL and AWAC ice data agreed in regard to identification of individual ice blocks during time intervals when the conditions were characterized by floating ice. Such a comparison is vital for a better understanding of the impact of instrument noise on ice measurements on a ping-by-ping basis. In particular, one of the objectives of the measurement program was to compare characteristics of floating ice at different locations, for which AWAC ice data are available. However, it was not immediately clear if the results of ice block identification are stable enough for such a comparison.



**Fig.3 Example of removal of erroneous ice keel detects from the AWAC diagnostic data for Burst #647, using criteria of a 1m ping-to-ping decrease in range to the ice bottom that persisted for 3 or fewer pings. Upper Panel: raw (red) and corrected (blue) AST range. Lower Panel: echo intensity profiles for Burst #647.**

The largest ice block was observed at about 09:30 a.m. on October 23rd. Time series of ice drafts for the ASL and AWAC bursts around that time are shown in Fig. 5. The data reveal a good agreement between the high-resolution ASL and AWAC data. The only minor disagreement is that the AWAC data are noisier than the ASL data. Although the noise magnitude is small, a seven-point running average was later applied to the AWAC AST time series to smooth the high resolution data.

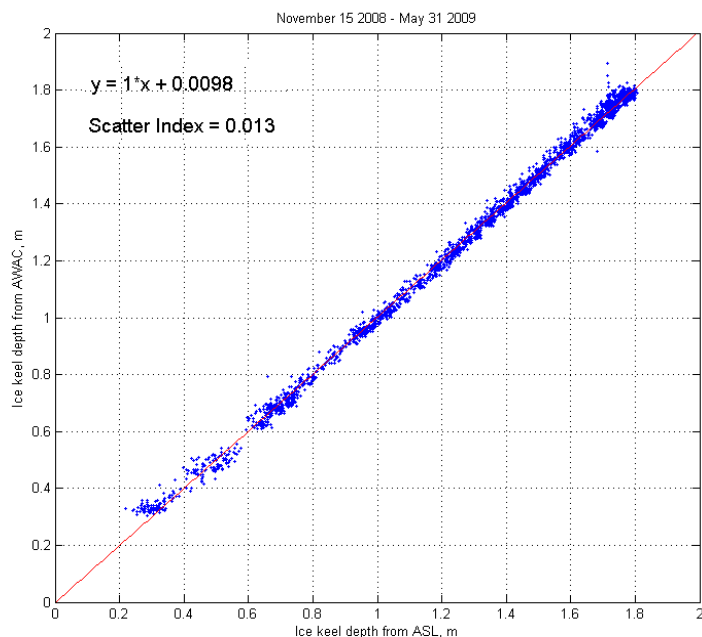


Fig. 4 Comparison of ice thickness from Nortek AWAC and ASL Ice Profiler.

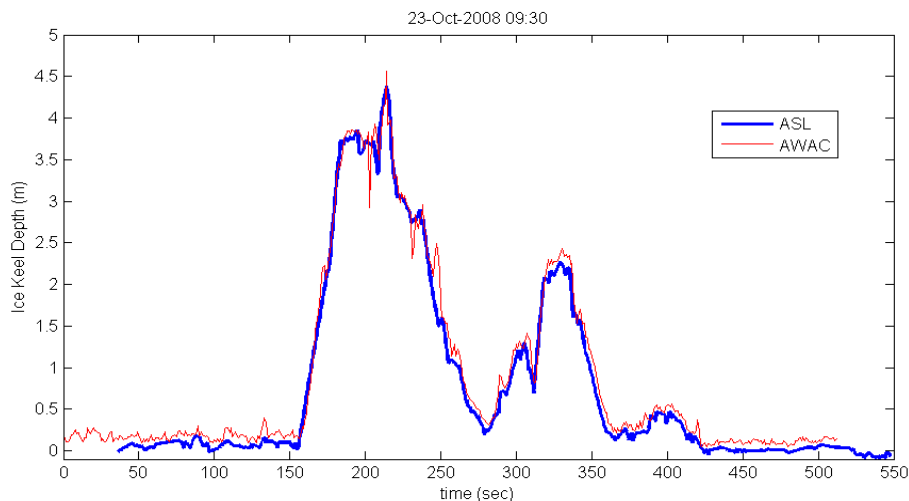
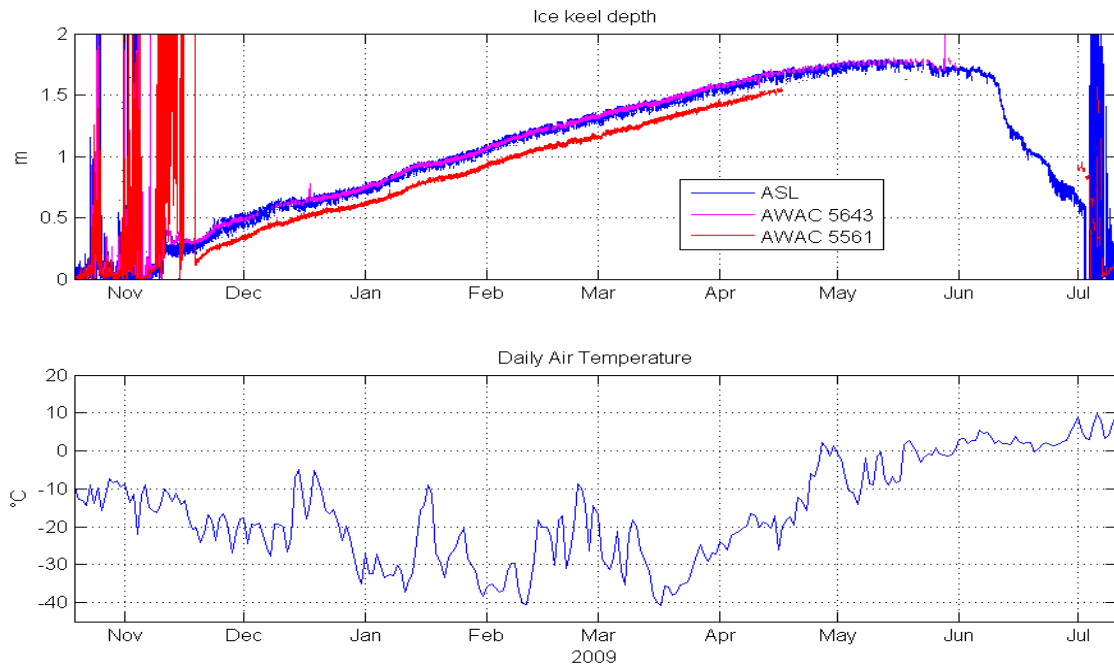


Fig. 5 Time series of ice draft for the AWAC and the ASL within a sample burst.

## V. RESULTS

Ice formation began in mid-October (Fig. 6) when air temperatures were routinely below  $-10^{\circ}\text{C}$ . Following a 3-week period when floating thick blocks of multi-year ice were present, the ice became solid and its keel draft varied only slowly. This suggests that the solid ice was land-fast and consisted of a solid sheet of more-or-less uniform thickness, which is taken to be approximately equal to the ice keel draft and ice thickness, as the density of sea ice is only slightly less than water density. The thickness increased almost linearly until it peaked in mid-May at about 1.8 m. This represents an increase in ice thickness of



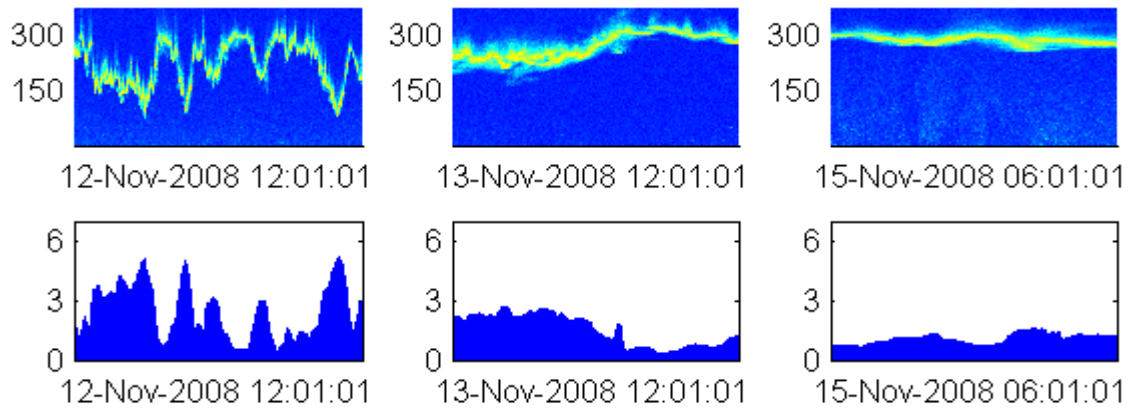
**Fig. 6 Ice thickness from two Nortek AWAC's and one ASL Ice Profiler (top). The ASL and AWAC 5643 were deployed in the same bottom frame, while AWAC 5561 was deployed about 2 km away in slightly different water depth. Ice thickness integrates daily air temperature (bottom).**

approximately 0.01 m/day. The ice began to thin rapidly in late May and ice breakup occurred in early July, with the breakup and transition to open water lasting only a few days.

The 512 point time series of ice thickness in each ice sampling burst provided detailed information on keel draft (examples shown in Fig. 6), from which information on individual solid ice block size and frequency could be derived. An ice block analysis was performed to study the time interval for block passage and average thickness. The near-surface current velocity from the Nortek AWAC was used to estimate the horizontal length scales of the ice blocks in the direction of movement. This information was used to calculate the distribution of ice block size and mass, assuming symmetrical shape in the horizontal. Finally, the probability of occurrence of various ice block masses was estimated. Individual ice blocks and their parameters were identified in the AWAC and ASL data using an ice thickness threshold of 0.5 m. This threshold serves to distinguish ice blocks from thin ice pancakes floating at the surface.

## VI. CONCLUSIONS

Results from the first long-term, commercial deployment of the Nortek AWAC under the ice in the Beaufort Sea, and comparison between the AWAC and a co-located ASL Ice Profiler, have demonstrated that the AWAC provides high-quality ice keel draft measurements. With proper data processing and corrections for atmospheric pressure, temperature, salinity, and tilt, the AWAC's independent estimates of free sea surface height when ice is not present agree with the AST to within typically +/- 0.1 m or better. Detailed time series of ice keel depth, in combination with the AWAC's current profile data, permit estimates of the size and movement of floating ice blocks to be made. The AWAC's combination of current & directional wave measurements and accurate, detailed ice keel draft measurements makes it a valuable sensor for ice studies.



**Fig. 6** Acoustic echo amplitude from AWAC vertical Acoustic Surface Tracking (AST) from three measurement bursts (each 512 samples over 8.5 min) in November 2008 (top) during ice formation. High-resolution (2.4 cm bin size) echo amplitude profiles were collected for each ping. Lighter color represents higher acoustic echo strength and indicates the ice/water interface (ice keel). Analysis of AST echo provides calculation of ice thickness (blue area in bottom panels, depth in meters).

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