The Ice Regime of the Koksoak River at Kuujjuaq, Quebec: Formation and Consolidation Processes

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Abstract

A Shallow Water Ice Profiler (SWIP) instrument was deployed in the Koksoak River at Kuujjuaq, Quebec in late September, 2009. The Koksoak River has very large twice-daily tidal ranges of about 4 m. Located on the river bottom, the SWIP instrument uses an upward looking sonar to measure the range to the underside of the floating river ice, or the water surface when ice is not present. From the acoustic range and pressure sensor data, the draft of the river ice is determined at typical measurement intervals of one or two seconds.

The ice regime at the measurement site is strongly influenced by the very dynamic conditions associated with the large range of tidal heights and currents. Daily ice thicknesses are highly variable due to the tidally driven movement of ice, starting from the initial onset of ice formation (October 15) until the ice consolidates into a stable continuous plate. This continuous plate, established December 13, had an average ice draft of 2.2 m which corresponds to an ice thickness of approximately 2.5 m, which is well above what would be expected from thermal ice growth. These larger ice thickness values are consistent with the occurrence of ice deformation processes (rafting and ridging).

Significant levels of acoustic back-scattering are observed episodically throughout the entire water column under the floating ice pans. These episodes of active back-scattering throughout the water column occur from the time of first ice formation until the surface ice features become stationary and the water surface is completely ice covered. One interpretation of these episodes of water column back-scattering is that they represent the presence of frazil ice. The occurrences of regular episodes of high acoustic back-scatter are related to the stage of tide and water and air temperatures.

Study Area: Koksoak River at Kuujjuaq, Northern Quebec

The study site was located in northern Quebec on the Koksoak River which connects to Ungava Bay. The approximate coordinates of the SWIP deployment were 58° 05' 50.37" N, 68° 22' 29.37" W. Figure 1 shows a satellite image and air photo of the study area.

Figure 1: (A) Satellite image of Kuujjuaq and the Koksoak River, showing the location of the SWIP measurement site.(B) Aerial photo of Elbow Island near the SWIP deployment site.

Shallow Water Ice Profiler Measurement Principles

The upward looking acoustic pings from the SWIP transducer are used to obtain range data from high contrast reflectors such as the open water surface or water/ice interface. The range, or distance of the transducer to the reflector, is calculated by the elapsed two-way time travel multiplied by an appropriate value for the speed of sound in water, divided by two. Water level is an important reference point needed as ice draft is a measure of the ice thickness below mean water level (Figure 2).

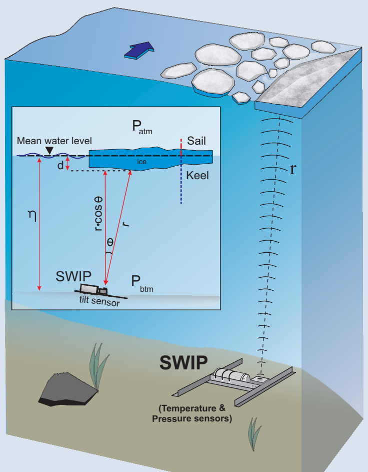

Figure 2. SWIP measurement principles.

In order to calculate water levels, the SWIP has been equipped with a pressure transducer to measure the total pressure exerted by the weight of water above the pressure sensor plus the atmospheric pressure. Calculation of water levels are carried out as follows:

$$\eta = \left(\frac{P_{btm} - P_{atm}}{\rho g}\right) - \Delta D$$

Where:
η – water level, P_{btm} – bottom pressure, P_{atm} - atmospheric pressure, ρ – density of water, g – acceleration due gravity, ΔD – spacing between acoustic transducer & pressure sensor.

As the SWIP is deployed on the river bottom, the orientation of the instrument may not be perfectly level. A tilt sensor is used to measure the angularity of the acoustic beam off vertical. Ice draft is then calculated as follows:

$$d = \eta - \beta \cdot r \cdot \cos\theta$$

Where
d – ice draft
β – calibration factor for sound speed *
θ – tilt angle.
* calibration factor for the actual mean sound speed relative to the initially assumed sound speed used in decoding the raw range data

Large Tidal Range and Dynamic Ice Canopy

All range data were plotted in order to visually examine the raw data to check for anomalies. Upon examination of the plots, it was clear that the data were clipped where ranges of the instrument to the target surface exceeded the user defined set-up limit of 11.5 m. This set-up value was entered before deployment and unfortunately the instrument was deployed in water deeper than expected. Further clipping occurred due to the limits of the pressure transducer such that only water depths of 10 m or less could be used to calculate draft. It was noted that there was a large (~ 4 m) tidal signal in the dataset. Figure 3 depicts 14 days of raw range data.

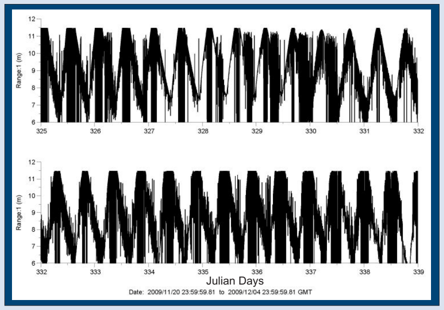

Figure 3. Data plot of 14 days of raw SWIP range data showing the clipping at high water levels.

Drafts were calculated for the time series not clipped. The dynamics of this tidally active river produce a highly variable ice canopy. Figure 4 shows a four hour segment of corrected ice draft (2009/12/25 19:59:59 to 2009/12/25 23:59:59). It is interesting to note the large thicknesses of the ice draft at this time of year. Thermally generated level ice would be less than 1 m based on the elapsed freezing degree days since first ice appearance. This would suggest other factors contribute to ice thickness production such as controls to the thermal regime based on river dynamics and possibly ice rafting events that would result in several plies of thermally generated ice.

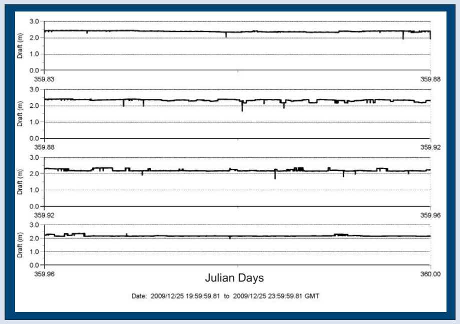

Figure 4. Four hours of ice draft data showing ice block movement and the relatively thick ice draft (>2 m) in late December.

Daily minimum, maximum and mean ice drafts are plotted in Figure 5. The data suggest a mobile pack until a solid ice canopy is formed in mid-December.

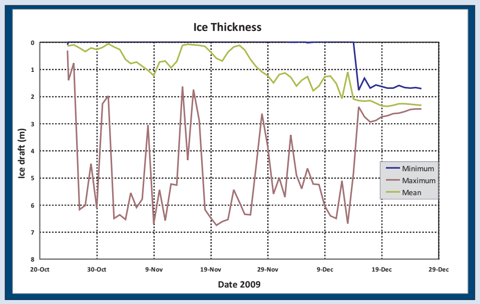

Figure 5. Ice draft minimum, mean and maximum curves for SWIP deployment period. Note the maximum thickness suggests acoustic back-scatter within the water column.

Minimum daily values before the established ice plate suggest glimpses of open water as ice converges and diverges rapidly with the ebb and flow of the high magnitude tides. The maximum values during this time suggest strong back-scatter in the water column as an ice thickness of 6 m is highly unlikely in November.

Possible Episodic Occurrences of Frazil

A possible explanation for the thick maximum daily drafts could be frazil ice production. As frazil ice is typically produced at high thermal gradient air–water interfaces, the strong ebb and flood currents could create turbulence in the water column which would circulate the newly formed ice particles deep into the water column. These particles could create an acoustic target strong enough to reflect the SWIP acoustic beam and therefore be interpreted as a solid surface.

To better understand the nature of these large maximum daily drafts, the data were examined using ProfileView, an ASL software package that plots the acoustic back-scattering amplitudes within the water column. Figure 6 shows the time period where the first ice features appear to move over the SWIP late in the day of October 26. Air temperatures drop to values between -5°C and -10°C and the bottom water temperature drops to just below 0°C for the first time in the fall. This environment could have provided the conditions suitable for the water column supercooling required for frazil formation. On the morning of the 27th, the first band of scatterers appears throughout the water column during the strong ebbing tide. The duration of this event is approximately two hours. These bands appear again during the next three ebbing tides.

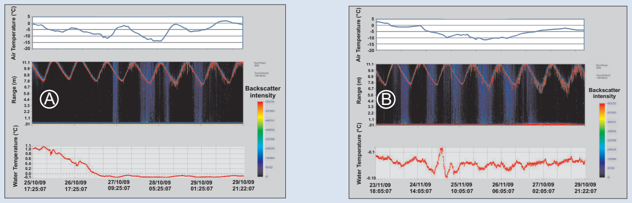

Figure 6. (A) Strong acoustic back-scatter can be seen throughout the water column at the first occurrence of ice drafts. (B) Back-scatter only occurs during the ebbing phase of the tidal cycle.

The bands of water column back-scatter are limited to times of ebbing tide and continue to appear until the continuous ice plate is established. As ebbing flow tends to create ice divergence, it favours the presence of open-water leads which introduce the high thermal gradients needed for frazil production.

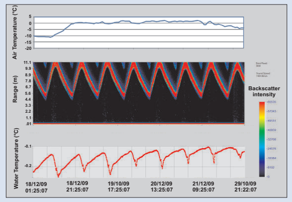

Figure 7. Water column back-scatter disappears once solid canopy has formed.

Once the solid ice canopy has formed, these scatterers completely disappear as seen in Figure 7. The thick (greater than 2 m) ice canopy provides insulation between the water and the cold winter temperatures eliminating the potential for contact freezing, a process often associated with frazil ice production.

Summary

While the results presented here are preliminary, it appears that significant levels of acoustic back-scattering are present episodically throughout the water column under the solid floating ice pans. These episodes of active back-scattering throughout the water column occurred from the time of first ice formation on October 25 until mid-December when the surface ice features became more stationary and presumably completely covered the water surface. One possible interpretation of these episodes of water column back-scattering is that they represent the presence of frazil ice. The acoustic returns from the frazil ice are occasionally sufficiently large that they can be misinterpreted as the bottom side of solid floating ice pans.

The ice at the measurement site was indicative of very dynamic conditions, presumably associated with the large tidal ranges and presumed large tidal currents. The ice pans appeared to develop to considerable thicknesses well above what would be expected from in-situ growth of ice due to heat loss to the atmosphere. The ice cover also appeared to be mobile with different ice thickness values present over the course of the day, which is consistent with the occurrence of ice deformation processes (rafting and ridging). Within two months of the onset of ice formation, the average ice draft of the ice pans had increased to 2.2 m, which would correspond to an ice thickness of approximately 2.5 m.

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