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Acoustic Detection and Study of Frazil Ice in a Freezing River during the 2007-2008 Winter

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An upward looking sonar instrument was deployed on the riverbed in November 2007. The instrument package contained a 545 KHz sonar transducer, as well as temperature-, 2-axis tilt- and pressure- sensors as well an onboard heater and a warm water supply hose to prevent anchor ice formation. The sonar instrument measures the distance to the water surface or the undersides of drifting or stationary ice. By computing the difference between the acoustically-derived distance to the ice and an independently measured water level, the draft of the floating ice can be determined at one second sampling intervals. The instruments can also record the profile of acoustic backscatter returns through the body of the river water column allowing detection of the presence and depth of suspended frazil ice.

Data quantity and quality from prior deployments since November 2004 of this and a lower frequency unit (235 kHz) have been compromised by anchor ice formation on the instrument. This paper describes a new and a much successful design of a mooring system that prevented anchor ice interference.

The location of the underside of the ice cover and the presence of suspended frazil ice as detected both prior to, during and after the formation of the winter ice cover was recorded by this higher frequency instrument for the first time. Relative concentrations of suspended ice and the concentrations and thicknesses of surface ice pans were measured. The ice cover formation (stabilization and shoving events) were also captured for the first time at continuous 1 second full depth-profiling sampling rate.

1. Introduction

Floating frazil ice pans and suspended individual or aggregated crystals of frazil ice in fresh water bodies often have significant impacts upon water supply, hydro electric, fisheries and other management activities. Effective detection and quantitative characterization of such ice can provide direct input to operational decision-making and for formulating numerical river ice and flow models (Shen et al., 1995; Shen, 2006) underlying modern flow management (Jasek, 2006).

The results presented here were obtained in freshwater during BC Hydro's and Alberta Environment's 2007-2008 winter Peace River monitoring programs utilizing SWIPS (Shallow Water Ice Profiler Sonar) instruments developed by ASL Environmental Sciences Inc. from the company's IPS5 Ice Profiler platform. The SWIPS is an upward looking sonar instrument that acquires acoustic backscatter data from, roughly, 1.1 cm deep, horizontal, slices of an insonified water column. Suspended particles such as frazil ice crystals, the water surface, bottom of floating frazil ice pans and the water surface can be detected. The location of the monitoring program and the basic instrument set-up and components are depicted in Jasek et al. 2005. The acoustic traducer is deployed on the river bottom and is linked to an instrument shelter on shore via a communications cable for data transfer. A steel mooring cable and a power supply cable for an onboard heater are also connected to the shore.

Historically, interference from anchor ice ranged from intermittent blockage of the SWIPS signal (a few days or weeks), to movement and tilting of the instrument off the vertical axis, to complete overturning of the instrument, and, in the most severe case, loss of the transducer. mooring system and data cable.

2. Mooring system design and deployment to mitigate anchor ice interference

Up until the fall of 2006, all deployed SWIPS were linked by a single cable to the shore on one side of the river and attached to platforms with submerged weights of about 32 kg. This arrangement was not sufficient to prevent instrument misalignment or overturning by anchor ice (Marko et al. 2006). Therefore in the fall of 2006, the total submerged weight of the SWIPS package was increased to about 68 kg and the platform was moored to both banks of the river. The unfortunate design choice of dual attachment points allowed anchor ice to form on about 400 m of steel cable on the river bottom, which consequently floated upward into the water column where drag from water and ice movement was sufficient to rupture cable connections to both shores (Jasek and Marko, 2007). This loss of a SWIPS transducer and mooring system in the fall of 2006 inspired a mooring system redesign and the inclusion of anchor ice mitigation features into the deployment platform.

The 2007 SWIPS platform consisted of four stacked 6 mm (1/4”) steel plates supporting a steel box enclosure (Figure 1). The enclosure housed the SWIPS transducer head as well as a 500 W electrical heater. Heat was preferentially lost from the top panel of the box due to its lower (3mm (1/8”)) thickness relative to the side walls (6 mm (1/4”)) which, together with the floor of the box, were lined with rubber to reduce heat losses.

The box and plate structure was covered with a steel frame supporting 6 mm (1/4”) Teflon sheeting at 45 degree slopes (pyramid structure). Teflon was chosen as it has the lowest known ice adhesion strength of any readily available coating material (Mulherin and Haehnel, 2003) This arrangement reduced the strength of the bonds between anchor ice and the structure and minimized the perpendicular impacts from moving supercooled frazil ice crystals which cause anchor ice accumulation. There was also a ¼” gap between the top steel plate and the uppermost Teflon sheet which allowed warm water generated by the heater to escape through a circular hole cut to allow emergence of the transducer beam. The steel base plates and steel box weighed about 162 kg (submerged weight of 142 kg, which was more than double the weight used in the previous year). It was calculated that such a weight would maintain stability even with attachment to a mass of anchor ice with dimensions as large as 1.5 m x 1.5 m x 1.25 m. The horizontal dimensions of the steel base plates were 0.74 m x 0.89 m. Given that anchor ice was not believed to grow to thicknesses much more than 0.5 m in the Peace River, lifting of the instrument by added buoyancy was judged to be unlikely although it was recognized that movements driven by drag forces on attached anchor ice accumulations were still potentially possible. A 19 mm (¾”) plastic hose was connected from shore to the pyramid interior to facilitate delivery of warm water should the 500 W heater prove to be insufficient to clear anchor ice. The hose was insulated with 9 mm thick flexible pipe insulation (not illustrated in Figure 1). The pyramid enclosure was sealed at the seams and at the top steel plate to retain the warm water in its interior to maximize the length of time available for radiative heating once the warm water supply was turned off. (Warm water would quickly rise out of the unit due to the buoyancy differential if the mid to upper surfaces were not sealed.) The seals were not fully air tight in order to allow air to escape when the unit was lowered into the river. Air and small amounts of warmer water were able to escape through the bolt holes that allowed attachment of the Teflon sheets to the steel frame. This feature was judged to be a useful one as anchor ice which tends to accumulate around the bolt heads and is likely to be dislodged by the leaking warmer water.

There were 4 “feet” attached to the 4 corners of the platform (not included in Figure 1), one is visible in the gravel at the bottom of the photograph. The feet were used as mounting points to lower the platform and have a convex lower surface to be compatible with the original deployment plan which was to slide the unit out along the gravel to the monitoring location.

There were about 5 m of 10 mm (3/8”) diameter steel cable attached to the upstream foot closest to the river bank. This cable (with the same thickness used in the 2006 deployment) was attached to a much thicker 25 m long steel cable (38 mm (1 ½”) dia.) ,with a dry weight of approximately 155 kg which was believed to be sufficient to minimize lifting under anchor ice growth attachments up to 0.4 m in diameter. The 5 m length of thinner cable attached to the platform was employed to keep the amount of weight that was being lowered from the boat to a manageable level during deployment. The near-shore end of the 38 mm dia. cable was attached to another piece of 10 mm dia. steel cable which made the actual shore connection and was anchored to a tree. Approximately 25 to 30 m of this cable was in the water.

The deployment of the SWIPS went rather smoothly (Figure 2) on Oct 21, 2007. A boat-mounted crane lowered the platform in waters approximately 5 m deep and approximately 50 m from the shore after dragging the heavy 38 mm cable along the river bed. The latter cable acted like an anchor, providing stability for platform placement.

The electrical heater appeared to prevent anchor ice from blocking the acoustic beam until the electrical cable was severed late on Nov 30, 2007. An attempt to send warm water down the insulated hose to allow resumption of acoustic data-taking was frustrated by an apparent kink in the submerged portion of the hose. The greater weight of the platform relative to previous deployments provided physical stability throughout the deployment. There was no indication that the beam ever tilted by a measurable amount from the vertical direction.

Recovery of the unit in the spring went relatively smoothly. A 4x4 truck was used to pull the SWIPS platform and 25 m of the attached 38 mm dia. cable out onto the river shoreline.

2. Suspended frazil intensities, ice pan thicknesses and concentrations prior to the formation of the ice cover - winter 2007-2008

Suspended frazil intensities, ice pan thicknesses and surface ice concentrations have been measured prior to the 2007-2008 ice season (Jasek and Marko, 2007). However, anchor ice interference introduced some uncertainty into measurements after about 24 hours of continuous exposure to supercooling while complete blockage of signals was produced by persistence of about 48 hours of such conditions. A 100 W heater used to mitigate anchor ice formation on the SWIPS platform prior to 2007 proved to be unsatisfactory not only because there was no independent way of ensuring that the heater was functioning but, as well, because the heating was not directly applied to the mooring platform where anchor ice attachment produced dramatic and, sometimes, fatal instabilities. The effects of the internal platform heating during the 2007-2008 season were directly monitored with a temperature sensor attached to the transducer. The data showed that the internal SWIPS temperature stayed at about +9 ^{o}C while the heater was activated even during frazil ice runs on the river. In contrast with our 2005-2006 season experiences, there was no evidence of signal degradation while the heater was functioning.

In addition to suspended frazil return strengths, surface ice concentration and average ice pan thicknesses, t average ice pan durations were also computed. Such durations can be considered as indicators of relative ice pan size if the river velocity can be assumed to be more or less constant. Figure 3 shows a) acoustic profiles, b) post-processed 5-minute averaged values of surface ice concentration, ice pan thicknesses, and suspended frazil return strengths, and c) ice pan duration and air temperature for the Nov 28-29 period. The strengths of returns from suspended frazil were averaged between 1.37 m and 4.28 m ranges above the SWIPS unit in order to be representative of water column values as opposed to returns from suspended sediments or rifting surface ice which are the dominant features of, respectively, lower and higher portions of the water column.

All ice quantity components started to increase gradually from zero values at about 05:00 hours on Nov 28 (Figures 3b and 3c). Unfortunately, the water temperatures recorded during this season were not as accurate as previously since the utilized joint water level/water temperature sensor was deployed in October, 2007 and attached to the water intake structure to prevent movement by anchor ice. This arrangement was ideal for recording water levels but unsatisfactory for water temperatures. There also may have been some groundwater influence precluding adjustment of the absolute values obtained to a relative zero value due to longer term changes introduced by decreasing ground water contribution over time near the river bank. Additional problems could have been introduced by short term fluctuations during periods of rapidly changing water temperatures caused by density driven convection currents.

The gradual increase in ice quantities continued for about 10 hours until about 15:00, Nov 28 after which a very sudden increase was noted in all ice quantity components. This change likely coincided with the maximum latent heat recovery in the water temperature in the main channel of the river but this could not be confirmed from water temperature data obtained near the bed closer to shore.

Ice production over the course of Nov 28 and 29 appeared to be inversely correlated with air temperature and was negligible after the air temperature increased to -15 ^{o}C in the afternoon of Nov 29. Our confidence in the relative quantities of suspended and surface ice present is high for the Nov 28-29 frazil ice run period as the heater was functional.

3. Heater Failure on November 30, 2007

Unfortunately, the heater failed at about 21:30 hrs on Nov 30 as indicated by the internal SWIPS temperature which dropped from +9 to +1 ^{o}C in Figure 4b. Acoustic profiles for the period of Nov 29 to Dec 4 are shown in Figure 4a along with the corresponding air temperatures in Figure 4c. By 02:30 on Dec 2 the SWIPS signal was sufficiently attenuated by anchor ice to entirely eliminate returns from suspended frazil (which according to air temperature data should have still been present). By 08:00 hrs the same morning the SWIPS beam was completely blocked. On Dec 3, the SWIPS signal returned probably due to routine shedding of anchor ice but started to fade rapidly again with resumed anchor ice buildup. The internal SWIPS temperature did increase to about +2 to +3 ^{o}C but far shy of the + 9 ^{o}C attained previously. When the SWIPS unit was recovered in the spring of 2008 the industrial grade extension cord wire lead to the heater was found to be worn through in several locations and severed completely at one location, probably due to anchor ice action. Similar problems were not encountered with the much more abrasion resistant Polyurethane-protected data cable. Plans for a Fall, 2008 deployment include use of a Polyurethane heater cable.

4. Comparison of manually and acoustically measured ice pan thicknesses

Since the winter of 2004-2005 manual ice pan thickness measurements have been collected with the aid of a video camera suspended on an L-shaped graduated boom (Figure 5). The submersible camera is an off-the-shelf recreational fishing camera employing a monitor at the end of an 18 m cable. To obtain frazil ice thickness measurements, one field team member looks into the video monitor and lets the boom operator know when the bottom of the camera is even with the bottom of the ice pan. The boom operator then reads the graduation marker on the vertical portion of the boom and the video monitor viewer then writes down the ice pan thickness value. Normally, 30 readings are taken at a particular location over the course of 15 to 40 minutes. The variations in total measurement time were determined by the surface ice concentration which governed the frequency of passing measurement opportunities.

Such information has been used to calibrate ice models such as CRISSP and PRICE on the Peace River. Attempts have been made since 2004 to obtain coincident SWIPS-derived frazil ice pan thicknesses for comparisons with these measurements: an effort which has, until the past season, been frustrated by anchor ice interference.

Figures 3b and 6 show the first comparisons of measured and SWIPS-derived frazil ice pan thickness data. Since the pan measurements were not conducted directly over the SWIPS instruments, it is more appropriate to make comparisons with manual measurements using the 5-minute averages of the SWIPS data. The two independent types of measurements compared very well on Nov 28 and 29 but the manually measured ice pan thicknesses were significantly greater then the SWIPS derived values on Jan 5. On the latter date, the ice pans were significantly thicker, larger in size and associated with higher surface ice concentrations than previously. One possible reason for the manual/SWIPS discrepancy on this date could have been that outer edges of the ice pans were significantly deeper than the middle portions of the ice pans due to increased frequencies of collisions between the ice pans. Since the camera can only see the edges of the ice pans these edge effects would have introduced a bias toward higher ice pan thicknesses.

Note: The 5-minute average SWIPS derived ice pan thicknesses shown in Figure 6 are calculated by considering ranges that only intercept an ice pan. (i.e. zero ice pan thicknesses are not included in the averaging.)

5. Surface ice quantities on Jan 4 to 10, 2008.

After the heater failure on Nov 29 and before the formation of the stationary ice cover on Jan 11, 2008, confidence in the estimated suspended ice quantities was low and not worthy of further analyses. However, ice pan thicknesses and surface ice concentrations were only affected by the most severe anchor ice SWIPS blockages and useful data for these surface ice quantities were obtained during this period. Figure 7 shows the SWIPS acoustic data for the period of January 4 to 12 and Figure 8 shows the derived 5-minute average surface ice quantities for Jan 4 to 9, just before the stabilization period.

The Jan. 4-6 period was relatively warm (Figure 8b, with air temperatures between -10 and 0 ^{o}C) facilitating release of anchor ice from the unit and allowing resumed acquisition of ice draft data in the afternoon of Jan 4. The measured surface ice quantities were still substantial at this time (Surface Ice = 94%, Ice pan thickness = 0.46 m and ice pan durations 10 to 35 seconds) due to a previous cold spell that lasted from Dec 30 to Jan 3. However, by Jan 6 this ice had travelled downstream past the SWIPS and the same measured quantities were down to 40%, 0.32 m and 2 sec respectively. Cold weather (temperatures between -22 and -15 ^{o}C) returned on Jan 7 with a sharp increase in the surface ice quantities. By the end of Jan 8, the ice quantities reached more or less equilibrium values of 86%, 0.6 m and 10 sec respectively. The increase in the surface ice quantities indicate that surface concentration and ice pan duration (size) respond quickly to the arrival of cold weather while increases in pan thicknesses occur more gradually. The first two of these changes are likely due to the formation of frazil pan rafts while the slower process of pan thickening may be indicative of a dependence on increasing collisions between rafts and additional frazil coming out of suspension underneath these rafts. This Jan. 4 to10 data set provides one example of the surface frazil evolution process. Combining this with data collected in the future at different air temperatures and in different river hydraulic regimes may be useful in coming up with a theory of surface ice evolution which includes the ice pan size component usually not included in computer river ice models.

6. Ice stabilization process on Jan 10 to 11, 2008

Figure 9 shows the acoustic profiles, surface ice quantities and water levels during the river stage-up process associated with the arrival of the ice front late on Jan 10. It appears that the river stage-up had significant effects on surface ice. Changes such as the increase of surface ice concentration have been observed previously from the air and are due to the slowing down of velocity in the deeper backwater upstream of an ice front which allows the ice pans to come closer together and start the process of rafting. Evidence for the rafting process was apparent in the observed large increases in ice pan durations. Such increases are the combined product of increased rafting and the slowing of river velocity in the backwater upstream of the ice front.

Other quantities such as ice pan thickness which change with time as the ice front approaches have never been previously quantitatively monitored. From a thermal perspective, one should not expect increasing pan thickness in the backwater as the expanding surface coverage further insulates the water column, preventing additional supercooling and thereby reducing contributions from suspended ice flocculation. On the other hand, higher collision frequencies in the presence of greater surface concentrations should produce larger ice thicknesses. An additional potential agent of ice thickening could arise from reduced turbulence in the slower moving back water which could allow finer frazil (or even un-flocculated) ice particles to come out of suspension. Figure 9 shows some evidence for this possibility in that frazil pan thickness was the first surface ice quantity to begin to rise following the first arrival of the back water increase at about 04:00, Jan 10. The ice pan thicknesses increased from about 0.6 to 0.7 m prior to a significant change in surface concentrations. Thus, this first 0.1 m increase was likely not a consequence of additional frazil pan collisions but reflected frazil ice coming out of suspension due to the lowered backwater turbulence levels. This addition of 0.1 m of frazil removed from the 4.4 m deep water column depth implies an initial concentration of frazil on the order of 0.7% (assuming a frazil pan porosity of 0.7) in accord with estimates suggested by CRISSP modeling on the Peace River (Jasek, 2008). There is also video data recorded during the stage-up period which could allow velocity estimation. Figure 10b shows suspended ice intensities or return strengths which show significant reductions as the backwater increases. Some of the variability prior to the backwater may be attributable to variations in anchor ice blockage of the SWIPS acoustic signal. However, supercooling should no longer be occurring in the Jan 9 – 10 period due to the additional insulation from the atmosphere which accompanied higher surface ice concentrations. Consequently, most or even all anchor ice should have released at the start of this period. Some of the sharp increases in suspended ice on Jan 7 – 8 may have been due to an anchor ice release as there are some coincident sudden changes in the (red) intensity near the bottom line in Figure 10a.

Another noteworthy feature of the backwater period data is the significant increase in rafting implied by the ice pan duration estimates. In particular, there was a sudden increase in thickness from 0.8 to 1.2 m (Jan 10, 16:00hrs) shortly after the first sustained 100% ice concentration coverage (Jan 10, 15:00hrs), (Figure 9b). This event was the effective start of the consolidation (thickening) process.

Figure 10 shows the final stabilization processes at the SWIPS site. The ice first stabilized on Jan 11 at about 00:00hrs and was about 1.4 m thick. The ice cover remained stable overnight but at about 12:00 hrs the ice cover shoved again and thickened to 4 m. Higher resolution acoustic profiles of this event are shown in Figure 11. Figure 11b shows that about 45 seconds prior to the remobilization of the ice cover, the suspended ice content increased significantly. Once the moving surface ice run arrived this suspended ice disappeared and then reappeared for a few minutes following the last stabilization (Figure 11c) before disappearing again 10 minutes after the ice cover re-stabilized. This behavior is consistent with the relative velocity (or shear) between the ice cover and water during these highly dynamic events.

After the consolidation event on Jan 11, the river ice cover stabilized as depicted in Figure 12. It was evident that rougher ice occupied the left third of the channel where the SWIPS was located. This was confirmed by surveys (Figure 13) and was a result of the consolidation process as the right two-thirds of the channel continued to run for some time after the left third stabilized. The right two-thirds then formed a relatively smoother cover consisting of juxtaposed frazil ice pans. This was likely the result of low surface ice velocities in the back water upstream of the consolidation that was now about 1.5 m higher than a normal freeze-up water level. Unfortunately, this consolidation also caused high water levels 4 km downstream that resulted in seepage into some basements in the Town of Peace River over the duration of the winter.

7. Suspended frazil intensities and deposition/erosion of the underside of the ice cover, Jan - Mar, 2008.

Figure 14 shows the elevation of the bottom of the ice and the water surface during the stable ice-covered period between Jan 11 and Mar 28. There was a rapid deposition of frazil on Jan 16 a more gradual deposition from Jan 16 to 20 (Figure 15). This may had been due to the atypical low velocities at the relatively isolated SWIPS location (due to the rough ice at the SWIPS site) which allowed rapid frazil deposition from flow entering this now isolated area of the main channel. The other alternative is erosion of ice from upstream that arrived suddenly such as a large frazil “bedform” originating from thick ice upstream of the SWIPS (Figure 12). On Jan 20 the bottom of the stabilized ice cover reached its minimum elevation of the winter, only 1.2 m above the SWIPS. Figure 15 does show increased frazil in suspension that is coincident with the depositional rate. It is somewhat of a mystery what triggered this sudden deposition but was most likely just a local phenomenon as such a deposition river-wide would have caused significant water level increases which were not observed during the Jan 16 to 20 period. The river discharge at this time was constant as releases from Peace Canyon Dam under agreement between Alberta Environment and British Columbia were steady as not to contribute to possible ice cover disruptions or consolidations.

On Jan 26 the thermal ice cover was deemed competent enough to resist any further secondary consolidations and BC Hydro was allowed to increase flows. This was not an easy decision as river level increases could exasperate the seepage into basements. However, it was reasoned that although there would be temporary increases in water levels, the higher flows would erode the frazil ice and increase the conveyance capacity of the river channel and eventually decrease the water levels. This was especially critical to realize such a result prior to the potential dynamic break-up of the Peace River triggered by the Smoky River which was anticipated in April. A series of weekly pulses of high flows were conducted through the month of February. Figure 14 does show that the bottom of the ice did erode at this site during this period.

From Feb 3 to a week before break-up on Mar 29, Figure 14 shows that the ice cover eroded by about 2 m at the SWIPS location and the water level had dropped by about 1 m. It appears that the weekly pulsing flows eventually aided in reducing water levels. However, further analyses need to be carried out to discern the thinning effects of individual discharge pulses.

8. Suspended frazil intensities during the ice-covered season, Feb - Mar, 2008.

8.1 Past Results

The preceding paper showed that, in 2005-6, frazil-related returns from the water column after ice cover stabilization rose from initial very low levels before declining to low levels again just before breakup. This pattern resembled less frazil-sensitive 2004-5 SWIPS1observations. 2005-6 connections between return strength and environmental factors were most apparent at diurnal and higher frequencies and, then, with respect to the speed of the river which controlled water levels (Figure 16). At times near peak returns, well over 50% of the high frequency variance was accounted for by water level/speed variations.

The high sensitivity of return strength to small (< 5%) water level/speed changes was tentatively linked to a critical speed sensitivity in the rates of transfer into the3 water column of ice particles moving along or resident at ice cover undersurface.

8.2 2007-2008 Results

Previous observations of depth independence and 2008 SWIPS positioning in shallower water and thicker ice forced focus in our studies on return strength variations in a single layer 0.9 to 2.0 m above transducer. Processing used averaging over this layer and low pass filtering based on 4- and 24-hour running averaging as in earlier analyses. Data are presented here for the middle and latter portions of the ice covered season associated with our most intense monitoring efforts. Comparisons of 24-hour filtered return strengths with similarly processed water level and air temperature series showed, as in 2005-6, detectable, but inconsistent ,linkages on time scales longer than diurnal (Figure 17).

As before, more definitive linkages were observed between the diurnal and shorter term return strength changes (= differences between the 4- and 24-hour filtered series) and corresponding water level series.

Correspondences are again strong, with the larger sudden drops (rises) in water levels tending to line up with decreases (increases) in high frequency return strength (Figure 3). However, smaller diurnal return strength variations are also apparent which have no counterparts in the water level record but can be seen (Figure 19) to be linked to the suitably scaled (by subtraction of 24 °C for visual clarity) high frequency air temperature series. The diurnal components of the 2 series are closely aligned with negligible lag. The relationship with air temperature was not detected in the 2005-6 data due the obscuring effects of the more diurnal character of that year's variations in the more influential water level/speed parameter. It should be noted that equivalently good matchups were obtained between the return strength and solar radiation intensity series. However while the noted linkages to air temperature and water level were found to persist even in the periods of very low return strengths immediately following stabilization and immediately preceding breakup, a similar persistence of connections to solar radiation was not observed. Tentatively, we would conclude that the two strongest empirical linkages connect suspended frazil returns to (strongly) high frequency variations in water level/speed and (more weakly), to similar variations in air temperature.

Moreover, these linkages are such that increases in both water level/speeds AND air temperature INCREASE suspended frazil content. In the first case, such a dependence is consistent with expectations from a suspended sediment-like model of frazil content variability. The air temperature result is counter-intuitive for mechanisms based upon contemporary frazil growth (for example, in upstream open water or at the ice cover). In fact, the observed temperature correlations provide a strong argument for the locality of the processes that drive water column frazil variability. It is hard to visualize alternatives such as upstream air temperature sensitive processes which maintain synchronicity between air temperature and acoustic return strengths at our particular downstream monitoring site.

In our view, these results support development of models of frazil variability along the line of those applied to suspended sediment transport whereby, in this case, rapid changes in water flow and, to a lesser extent, air temperature enhance suspension and movement of ice particles from an adjacent reservoir. The critical velocity concept by which increasing flow rates above a threshold produces observed disproportionate increases in water column frazil concentrations arises naturally. The challenging complication is that the properties of the postulated reservoir must vary drastically over the course of the ice covered season to account for observed changes in the apparent effectiveness of the water level/speed and air temperature-dependent suspension mechanisms over the lifetime of a stabilized ice cover. Specifically, three years worth of observations have detected only low levels of frazil target concentrations in periods near the beginning or the end of the ice covered season, irrespective of contemporary high frequency variability in the relevant environmental parameters. Furthermore, the 2004-5 acoustic penetration studies of the only viable candidate as a local frazil reservoir, the slush layer at the bottom of the ice cover, have shown penetration to be negligible after stabilization but that it slowly grows in time to its maximum thickness before slowly thinning again and virtually disappearing a few hours before breakup. This trend in penetration thickness is identical to that which would be required of the availability of frazil in the reservoir of a suspension-based frazil model such as that outlined above.

At least two important issues remain to be addressed involving the mechanisms which:

1) Govern the postulated seasonal changes in the reservoir; and
2) Convert diurnal and more rapid air temperature change signals into essentially un-lagged changes in suspended frazil.

In the first case, continued accumulation of frazil drifting downstream ice from upstream open water growth areas and, then ,as temperatures rise and such growth ceases, progressive erosion could account for most of the seasonal cycle leaving only the initial “emptiness” of the postulated reservoir as the puzzle. Two explanations of the latter feature appear to be worth examining. One of these attributes the initial dearth of a mobile slush layer to the sudden change in the relative motion between the river water and the drifting ice floes which become stabilized into the new ice cover. Potentially mobile ice in the lower portions of these surfaces is exposed to drastically increased shears which establish a new equilibrium characterized by greatly reduced frazil particle availability which only slowly grows again over time by accumulation from upstream portions of the water column and ice cover. The second possibility recognizes that the newly stabilized ice cover was largely formed out of flocculated frazil particles large enough to overcome turbulence and rise to the surface to create frazil ice pans. While initially strong to resist erosion by the moving river water, weakening of the bonds in the interlocking lattice of these particles begins to occur over time with the increasing physical separation from supercooled upstream water which accompanies continued seasonal advance of the ice front. In both instances, the rate of recovery should be sensitive to annual variations in ice front advance/retreat and overall air temperature trends. Such variability has been observed but has not yet been examined in detail.

The anomalous coupling of air temperature to water column frazil poses a greater puzzle but similarly almost certainly involves the largely unknown but active dynamics of the slush layer. Substantial slow movements of acoustic targets in this layer have been noted in a previous report on the Peace River studies Jasek et al., 2005), largely based upon the same SWIPS1 penetrations studies cited above. The character of this layer is depicted (Figure 20) in 36 days of 3-hour averaged profile data from the Jan. 21- Feb. 25, 2005 period depicted below along with the modeled (and verified) position of the bottom of the thermal ice layer. An abundance of coherent, diurnal and other higher frequency, structures are detectable along with evidence (at the extreme right) that the thinning of this penetrated layer coincides with the sudden appearances of detectable water column frazil (even at the low SWIPS1 acoustic frequency). It is particularly notable that Feb. 19 video observations from the ice cover reported qualitatively larger numbers of ice particles in the upper 1 m of the water column relative to March 2 observations when water column frazil was detected acoustically with intensities similar to those evident in the Figure at the end of the displayed period. The failure to observe water column acoustic returns at the time of the Feb. 19 observations suggests that the acoustic visibility of frazil on March 2 (and, presumably on Feb. 24-25) was due to the larger sizes of the suspended particles (scattering cross-sections are proportional to the 6th power of particle diameter). The implication here is that erosion of slush layer proceeds with progressive increases over time in the size of particles put into suspension and that this trend coincides with reduced acoustic penetrations of the slush reservoir layer. Understandings of these changes and, more generally, of the dynamics of the slush layer would appear to be essential in making further progress toward quantitative models of water column frazil variability.

Such progress toward is likely to be assisted in the near future by studies underway in Canada involving both laboratory calibration and continued field measurements employing simultaneous measurements at two or more acoustic frequencies. Results from this work should facilitate conversion of target strength data into the particle concentration and size information needed for quantitative process modelling.

9. Thermal Break-up March 2008

Figure 21 shows the acoustic profiles during the thermal break-up on Mar 28-29, 2008 and Figure 22 shows the underside of the ice cover, water level and water temperature at the SWIPS site. It is evident that there was rapid erosion of frazil ice on Mar 28, about 3 m in 6 hours. This was coincident with a dramatic increase in suspended ice targets and positive water temperatures which begs the question as to whether the frazil ice was being, alternatively, eroded or melted away. It seems most likely that both processes make important contributions to frazil dissipation. In any case, the data do suggest that increases in heat input to the water column can help mobilize frazil transport in accord with the implications of the mid-winter data discussed in the previous section.

After the effective disappearance of the suspended frazil layer at about 15:00 hrs on Mar 28, the thermal cover remained in place until complete breakup occurred at about 14:00hrs on Mar 29. The solid ice thinned only marginally during this time is compared with the previous thinning of the frazil layer. This could be taken as evidence that the preceding frazil depletion event was primarily driven by hydraulic erosion or alternatively a there is a large disparity between the ice-water transfer coefficients descriptive of heat exchanges between the water column and the bottoms of, alternatively, the slush layer and the thermal ice cover.

Figure 23 shows the full time resolution acoustic returns of the thermal break-up of the thermal ice over the SWIPS location. Notable is the apparent rubble ice at the head of the ice cover that came to within almost 1 metre of the SWIPS unit. The apparent weak returns of the water surface following break-up are thought to be caused by absorbed acoustic signal by high bed-load sediments just following break-up.

10. Conclusions

The larger mass of the SWIPS platform deployed in the Fall of 2007 compared to previous deployments facilitated keeping the SWIPS in its deployed position and orientation throughout the 2007-2008 ice season despite anchor ice adherence. Based on previous submerged deployment masses, it is likely that a submerged weight somewhere between 68 and 142 kg is optimal for this purpose. However, it is unclear what role the sloped Teflon surface plays in reducing the necessary platform mass.

It is also likely that the increased mass of the steel mooring cable, 6.2 kg/m compared to 0.7 kg/m used in previous years also contributed significantly to resisting platform movement.

The use of warm water for removing anchor ice from the SWIPS platform poses a difficult challenge since the delivery hose can easily get kinked in a river environment.

The use of the 500W heater appeared to be successful in preventing anchor ice from blocking the SWIPS acoustic beam. However, the utilized standard electrical cord was insufficiently abrasive resistant to last throughout the winter. It is therefore recommended that a polyurethane coated cable (similar to the data cable) be used for the heater cable in the future.

With the arrival of supercooling events, the SWIPS data showed all measures of suspended ice and surface ice quantities rose in a few hours from near-zero values to equilibrium values. These quantities then varied inversely with air temperature as expected. The exact timing and value of the supercooling was not measured accurately during the 2007-2008 deployment as the water temperature sensor was mounted too close to the river shore. It is recommended that a water temperature sensor be mounted on the SWIPS unit or further out into the river for next year's deployment.

SWIPS derived average ice pan thicknesses and manually (camera) measured ice pan thicknesses compared well for thinner (0.1 to 0.2 m) ice pan thicknesses and medium ice concentrations (40 to 60%). For higher ice pan thicknesses (0.4 to 0.6 m) and higher ice pan concentrations (70%) the manually measured thicknesses were significantly greater than SWIPS derived values. This was likely due to the downturned edges of the ice pans resulting from more frequent collisions. This deformation was not discernable from the horizontal perspective of the camera which lacked the vertical perspective of the SWIPS beam. The SWIPS derived ice thickness values are therefore deemed to be more accurate than the camera measured values for higher ice pan concentrations.

Frazil ice pan evolution was quantitatively monitored successfully by the SWIPS. The measurements indicated that surface ice concentration, frazil ice pan thickness and size (approximated by duration) stayed constant when the air temperature remained relatively constant. A temporal equilibrium was reached in which these quantities changed primarily with longitudinal river distance but stayed constant at the SWIPS location. When the air temperature cooled from one temperature regime to another, the surface ice quantities increased at different rates. The increase in the surface ice quantities indicate that surface concentration and ice pan duration (size) respond quickly (one to two hours) to the arrival of cold weather while increases in pan thicknesses occur more gradually (over the course of about a day). The first two of these changes are likely due to the formation of frazil pan rafts while the slower process of pan thickening may be indicative of a dependence on the frequency of collisions between rafts and upon additional frazil coming out of suspension beneath these rafts. Ice pan rafting appeared to suddenly occur when the surface ice concentration was greater than about 60 or 70%.

Increases in surface ice concentration, ice pan size (by rafting) was measured by the SWIPS in the slower moving and rising backwater caused by an approaching ice front. Several mechanisms of ice pan thickening in the ice front backwater could be deduced from the SWIPS data. The first increase in ice pan thickness preceded the increase in surface ice concentration indicting that perhaps suspended frazil ice was coming out of suspension due to the slower moving and less turbulent backwater reach. Subsequent and slightly more rapid thickening occurred with increasing surface ice concentration indicating that frazil ice pan collisions were responsible. Finally, very rapid thickening occurred when the surface ice concentration approached and reached 100%, indicative of thickening caused by shoving of the bank to bank ice run.

The SWIPS successfully quantified the ice cover formation process in that it recorded the initial thickness of the stable ice cover and tracked a subsequent shoving event that thickened it further. Re-suspension of frazil ice during the shoving event was consistent with relative velocity (or shear) between the water and ice layers during the highly dynamic event.

Post-stabilization ice cover thickness was recorded by the SWIPS over the entire ice season and showed a rapid thickening event shortly after ice cover stabilization followed by a gradual thinning (erosion) over the remainder of the winter. The sudden rapid thickening occurred about 5 days after ice cover formation and was more than likely a local phenomenon as there was not a corresponding water level increase and no known accompanying triggering mechanism. These results do suggest that sudden and unpredictable local changes in frazil thickness can occur which may be important for water intake considerations.

Following the initial rapid thickening, the frazil slush layer thinned over the course of the winter and appeared to be thinned more rapidly over the period of discharge fluctuations (frazil flushing operations) aimed at increasing the conveyance capacity of the river channel in order to relieve seepage flooding of basements in the Town of Peace River. Further analysis needs to be carried out however to discern the effect on thinning by each discharge pulse.

Data on the mean return strengths from the water column during the stabilized ice cover period showed predominant dependences on changes in water level/speed and air temperature which occur on diurnal and faster time scales. By far, the closest linkages of return strength were to water levels and speed but the air temperature linkage was also clearly evident and in both cases the connections were local in the sense that they showed no evidence of the time lags one would expect if they represented responses to changes in, for example, distant upstream open water areas. Descriptions of the observed changes were consistent with a mechanism in which increases in water speed and air temperature facilitate (increase) movements of ice particles from a reservoir in the slush portion of the lower ice cover much in the way that increases in river flow raise concentrations of suspended sediments above a silted river bed. Compatibility of this picture with the observed changes in return strengths throughout the season requires additional changes in the nature of the lower portion of the ice cover throughout the stabilized ice cover period. Such changes are consistent with those observed in SWIPS measurements made at acoustic frequencies low enough to penetrate and produce returns from this portion of the ice cover. Detailed quantitative matching of the data with such models will almost certainly require simultaneous measurements and calibrations at multiple acoustic frequencies and the conversion of corresponding return strengths into particle size distribution and concentration characterizations,

The SWIPS recorded the thermal break-up of the Peace River. The eventual break-up of the ice cover over the SWIPS site was preceded by about 23 hours by the rapid erosion of 3 metres of slush. The erosion was coincident with the rise of water temperature that made its way under the ice from the nearby and approaching ice front from upstream. It was unclear how much of this rapid erosion was due to melting and how much was due to mechanical erosion.

It may be beneficial for the future to include a current profiler to be deployed at the SWIPS site in order to expand on the data analysis of frazil pan sizes, frazil ice erosion/deposition and transport throughout the winter and at break-up.

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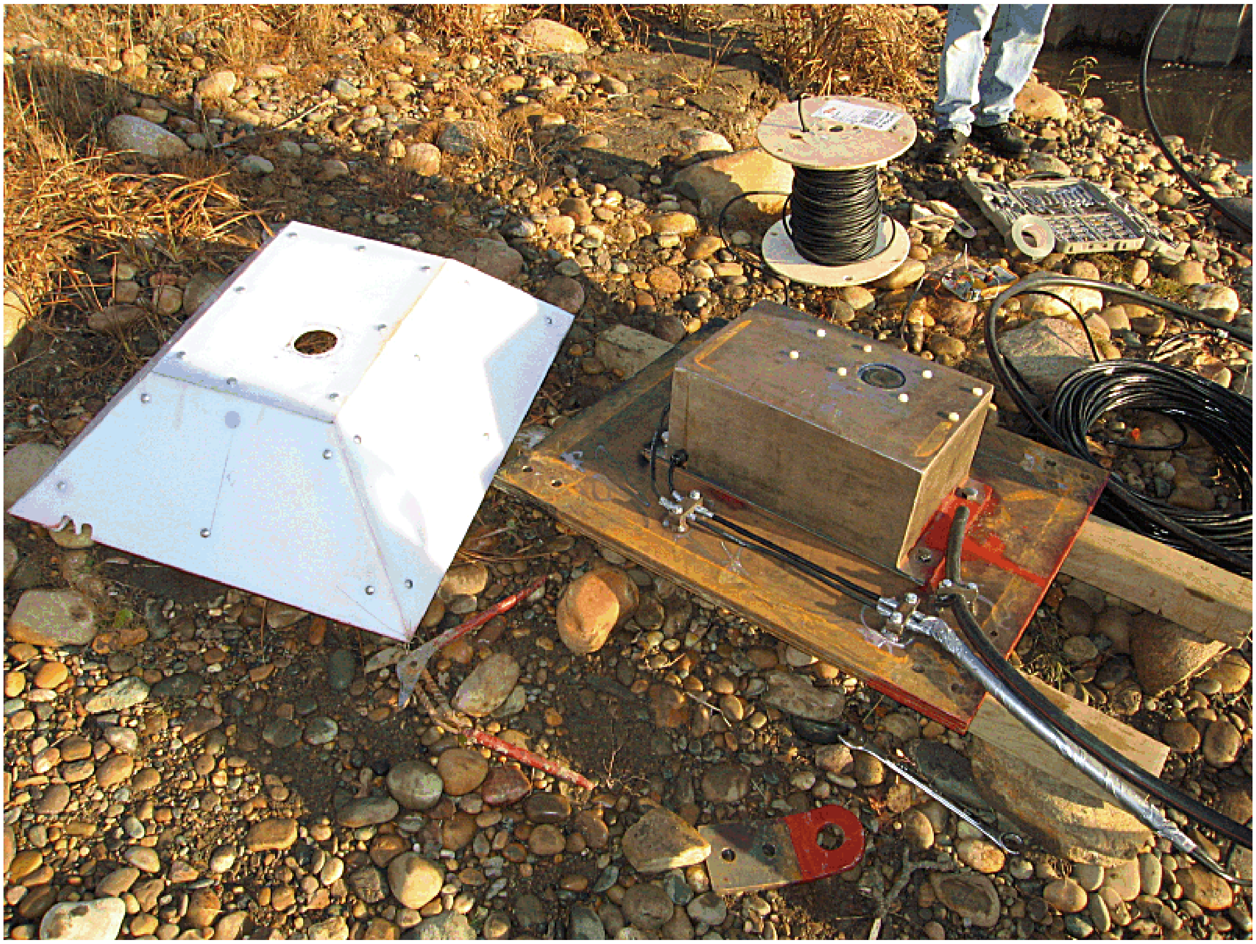

Figure 1. SWIPS housing in process of being assembled on site.

Figure 2. Deployment of SWIPS on October 21, 2007.

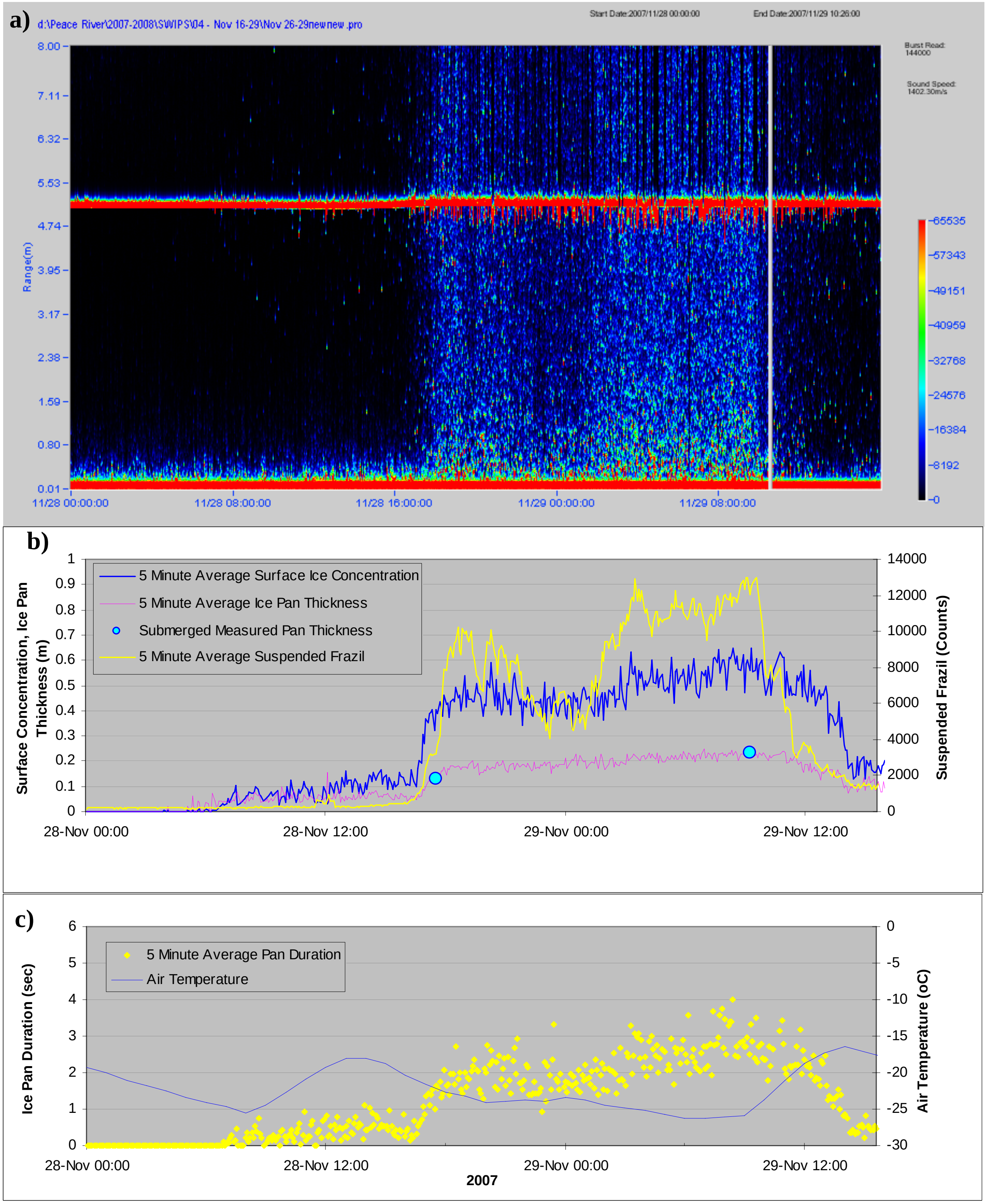

Figure 3. a) Acoustic Profiles (The data interruption at about 10:00 hrs on Nov 29 is due to a data download) **b)** 5 minute averaged ice quantities, **c)** ice pan duration and air temperatures.

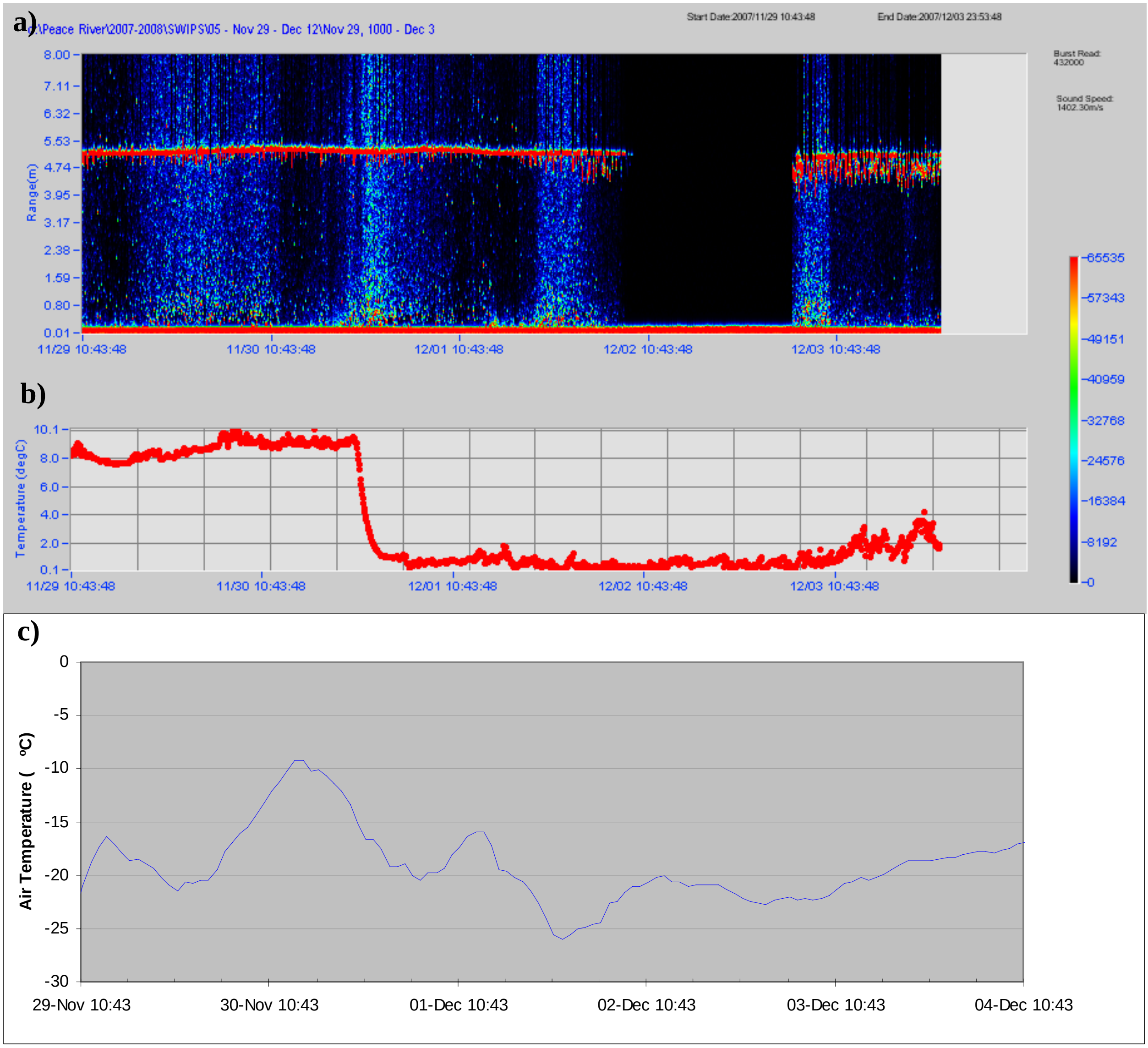

Figure 4. a) Acoustic Profiles **b)** internal SWIPS temperature and **c)** air temperature from Nov 29 to Dec 4.

Figure 5. Frazil Ice Pan Measurements on Jan 12, 2005, photo by Dan Healy, nhc.

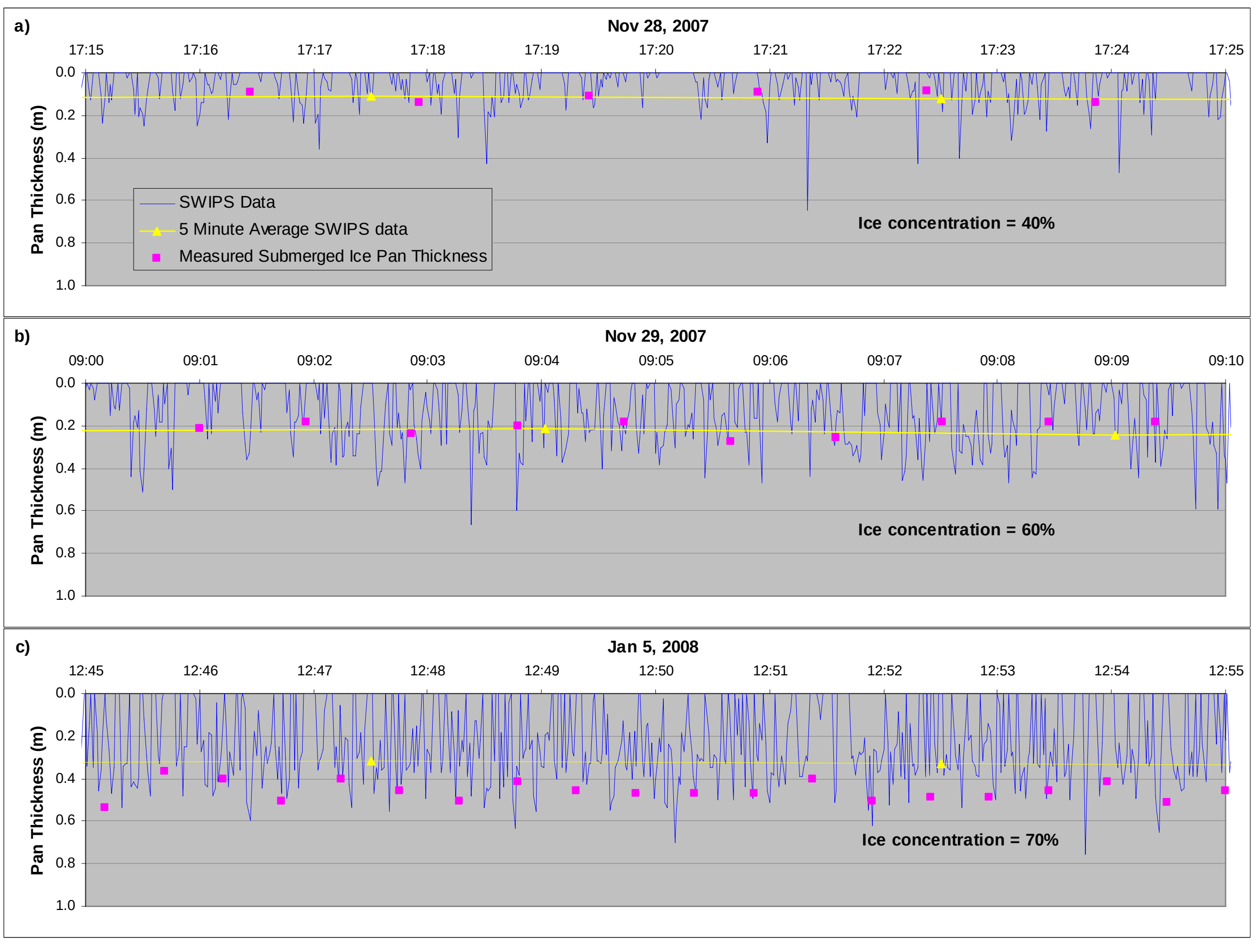

Figure 6. Comparison of SWIPS derived ice pan thicknesses and measured ice pan thicknesses on a) Nov 28, 2007, b) Nov 29, 2007 and c) Jan 5, 2008.

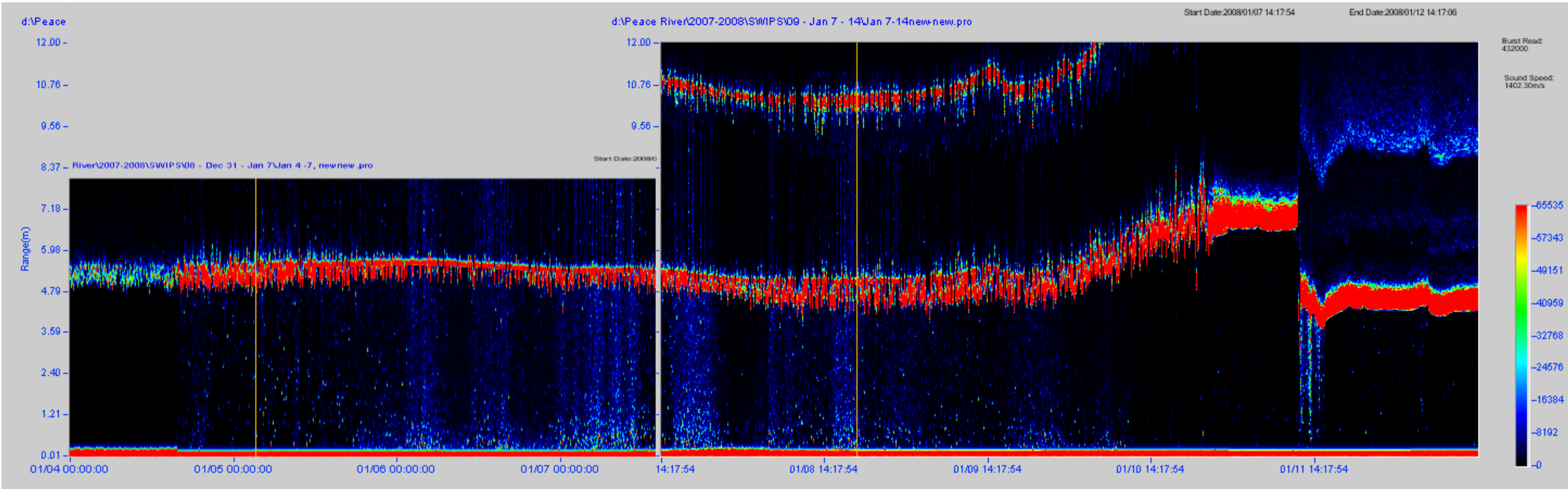

Figure 7. SWIPS acoustic data, Jan 4 to 12, 2008. The composite plot had to be pieced together from two separate data sets since the data collection range was increased on Jan 7 in anticipation for the river stage-up associated with ice cover formation.

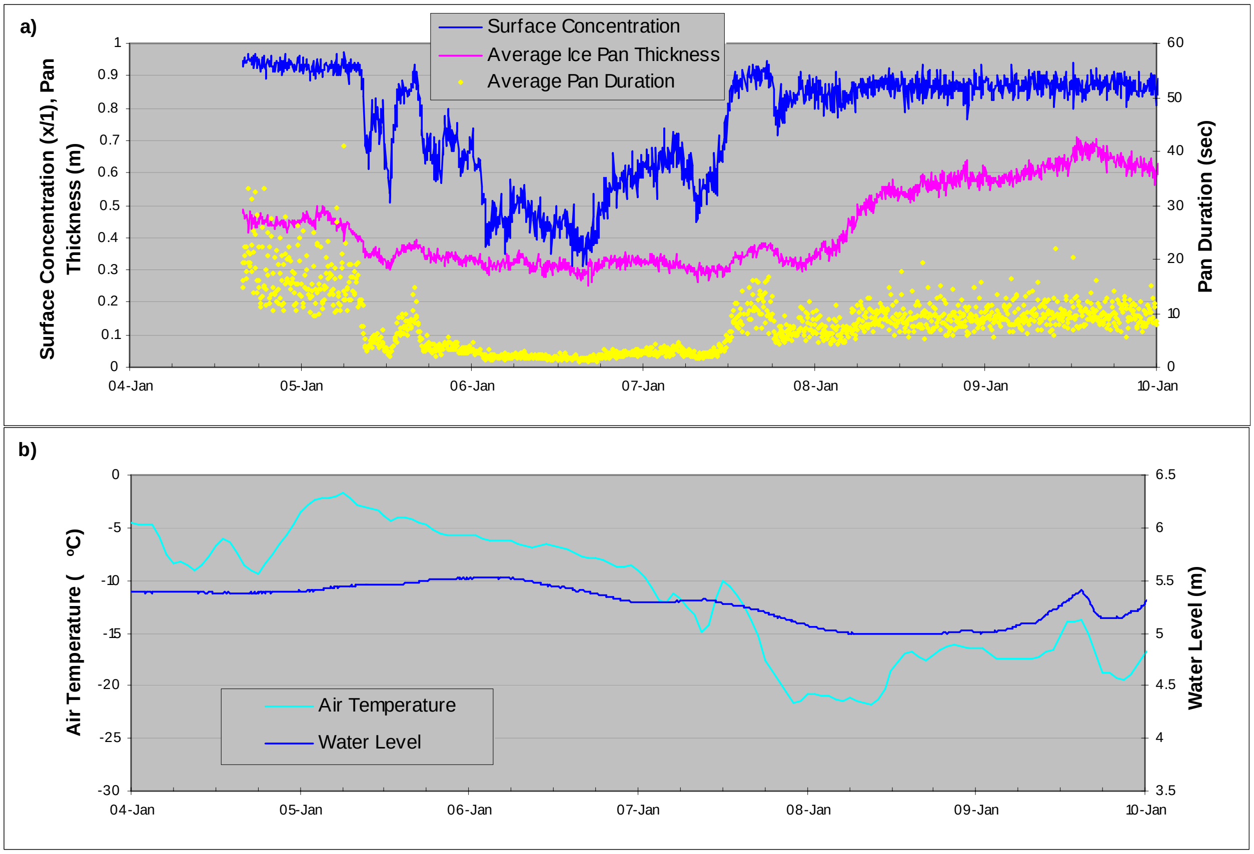

Figure 8. a) Five-minute averaged surface ice concentrations, frazil ice pan thicknesses and durations, **b)** air temperatures and water level.

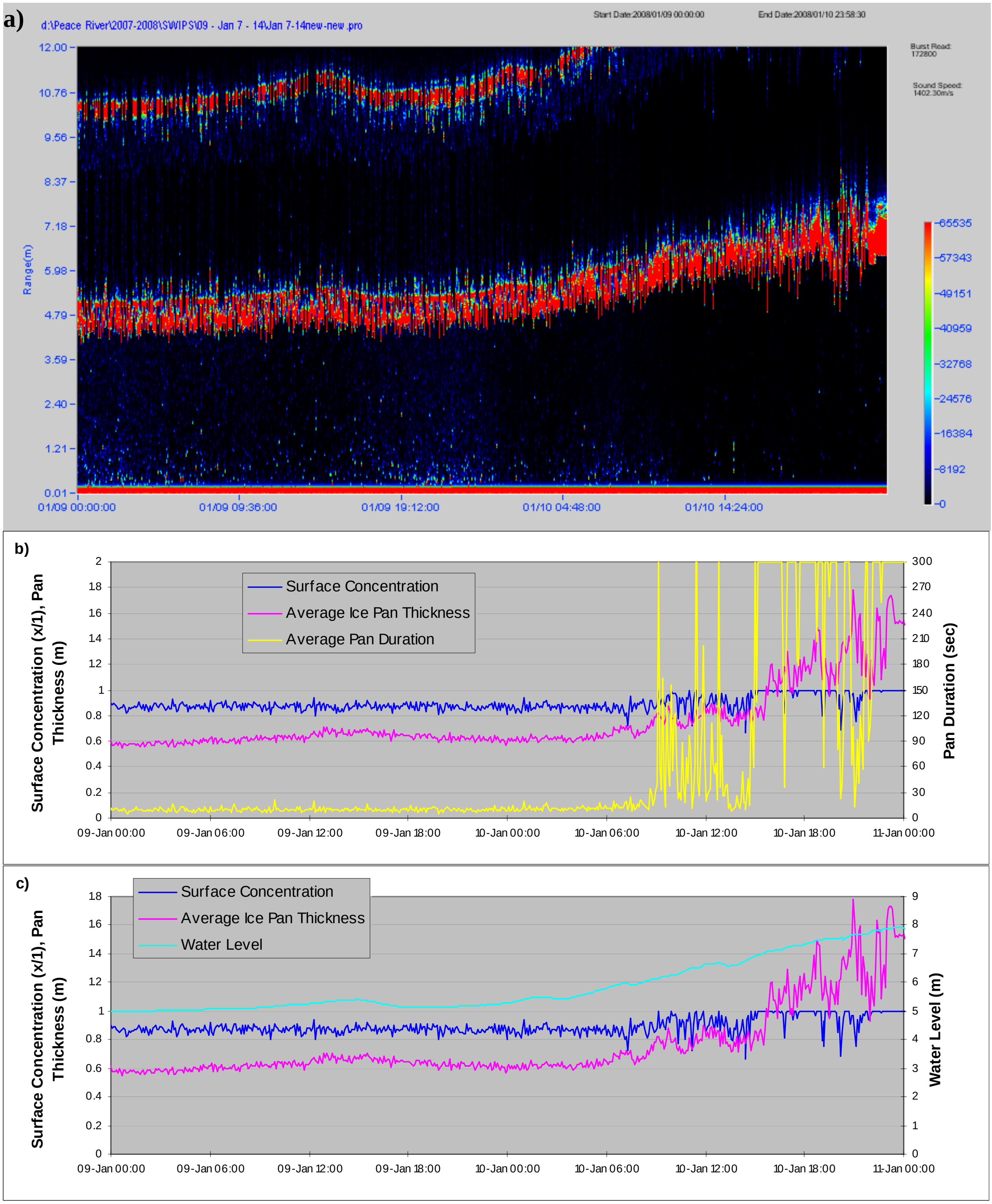

Figure 9. a) Acoustic profiles, **b)** five-minute average surface ice concentration, frazil ice pan thicknesses and durations, and water levels Jan 9 – 10, 2008. The average air temperature during this period was about -16 ^{o}C and ranged between -19 ^{o}C and -13 ^{o}C.

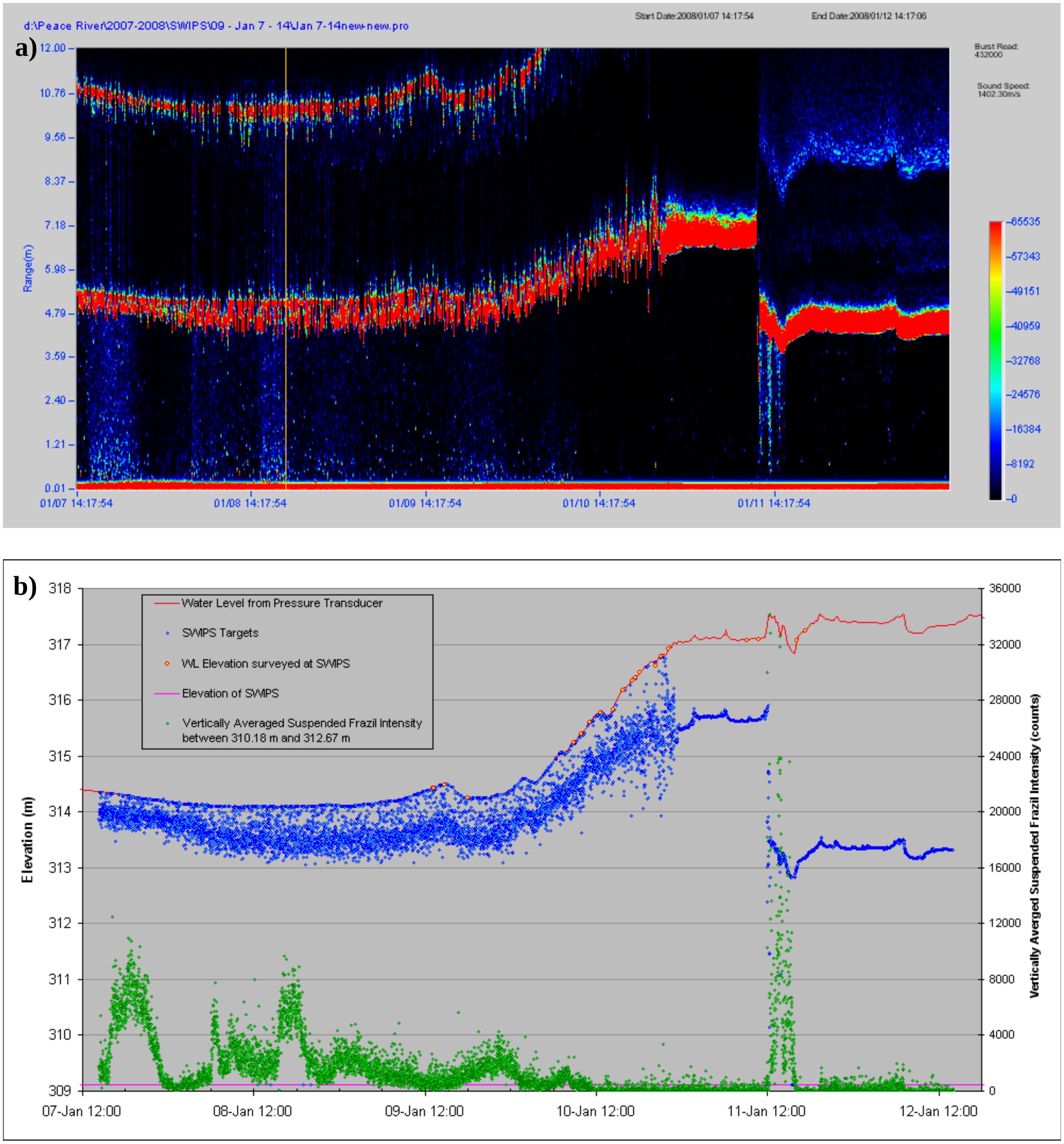

Figure 10. a) Acoustic profiles and **b)** water level, surface targets and suspended frazil intensities during the ice stabilization process.

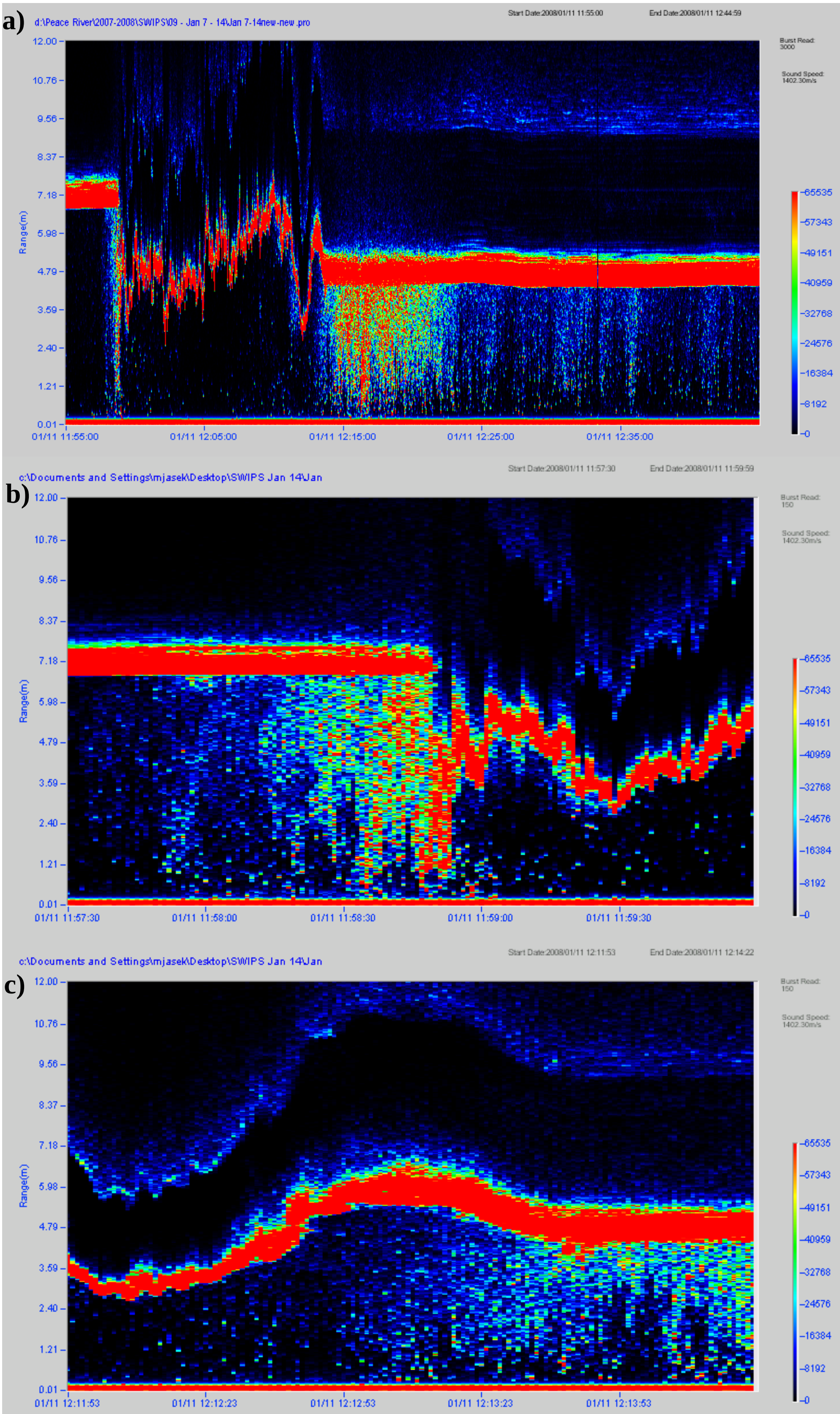

Figure 11. Acoustic Profiles during final consolidation event on January 11, 2008.

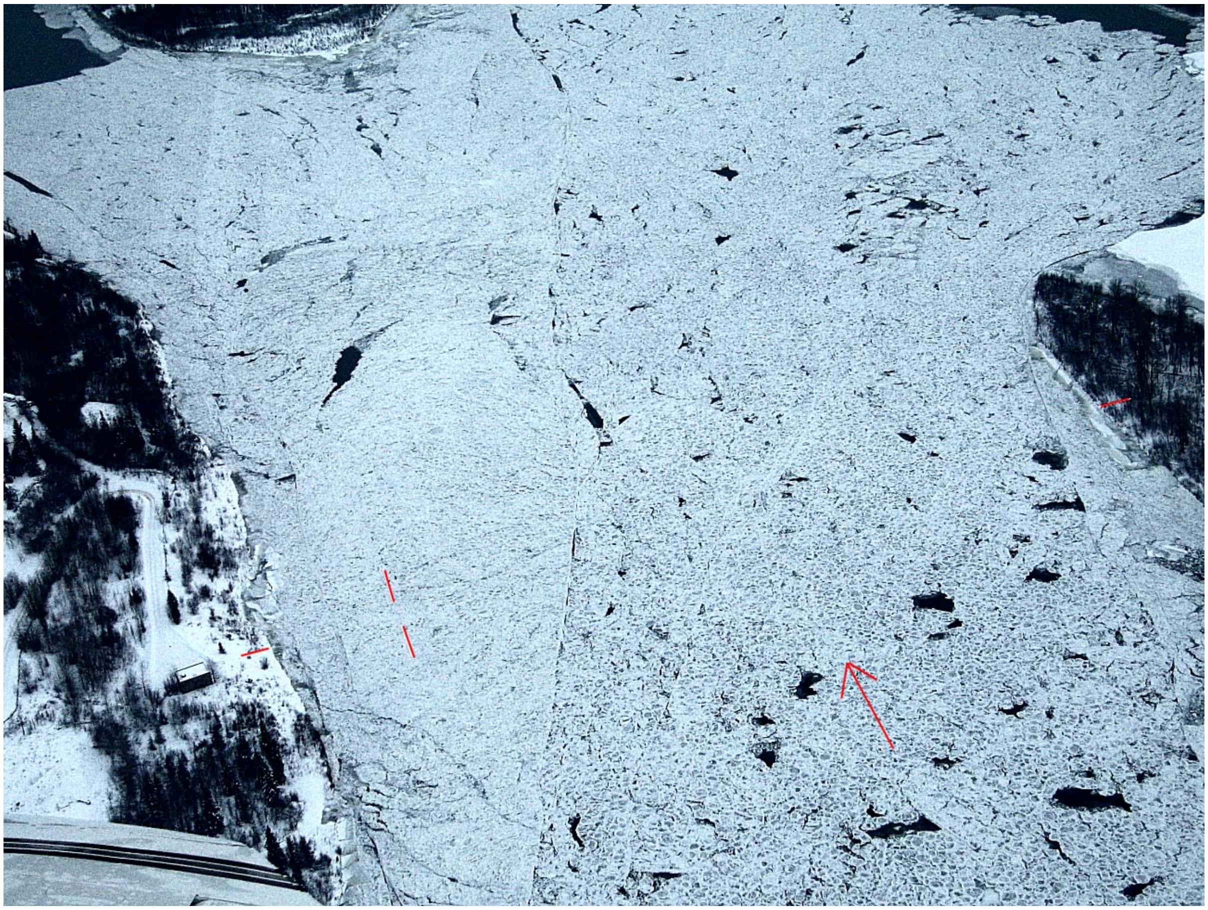

Figure 12. Photograph of Peace River at SWIPS location on Jan 12, 2009 looking downstream. Red marks indicate ice cross section measurements and SWIPS location.

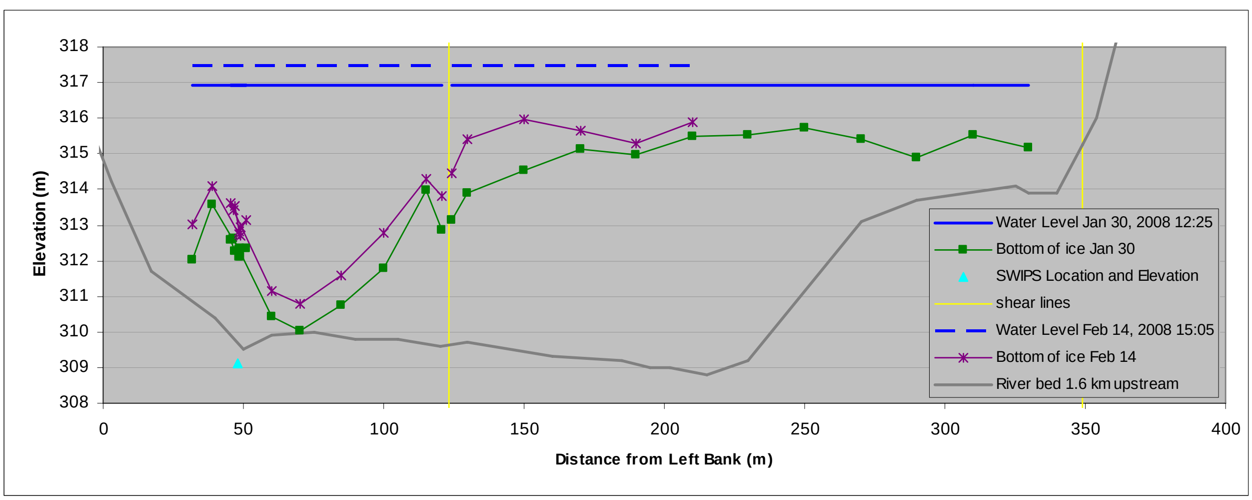

Figure 13. Ice cross sections at the SWIPS location on Jan 30 and Feb 14, 2008. River bed cross section is from a nearby cross section 1.6 km upstream.

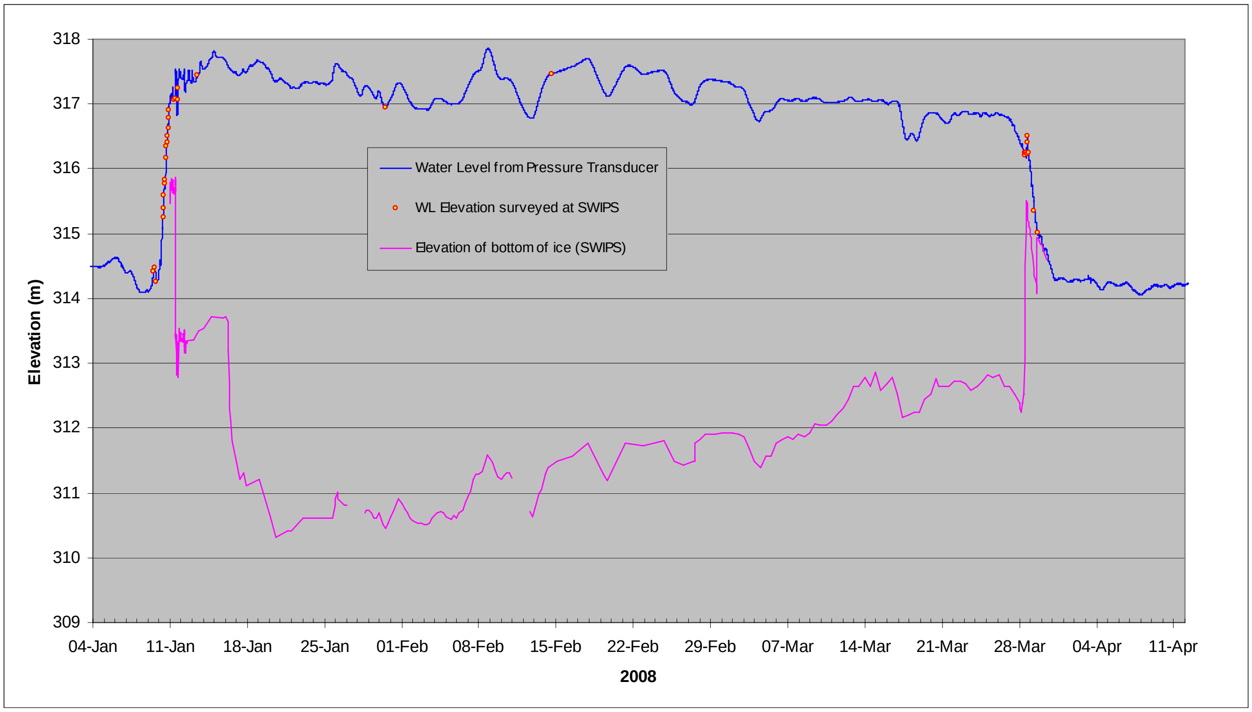

Figure 14. Water level from pressure transducer and bottom of ice elevation for the entire 2008 ice-covered season.

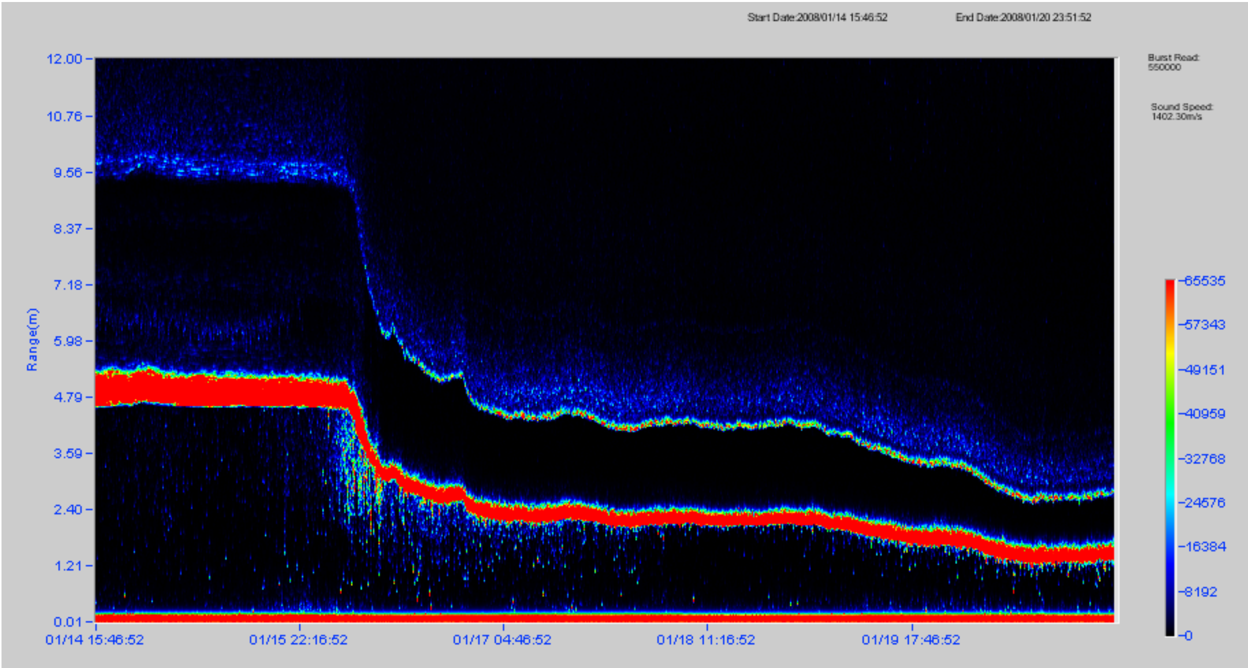

Figure 15. SWIPS acoustic profiles showing the Jan 15 to 20 depositional event.

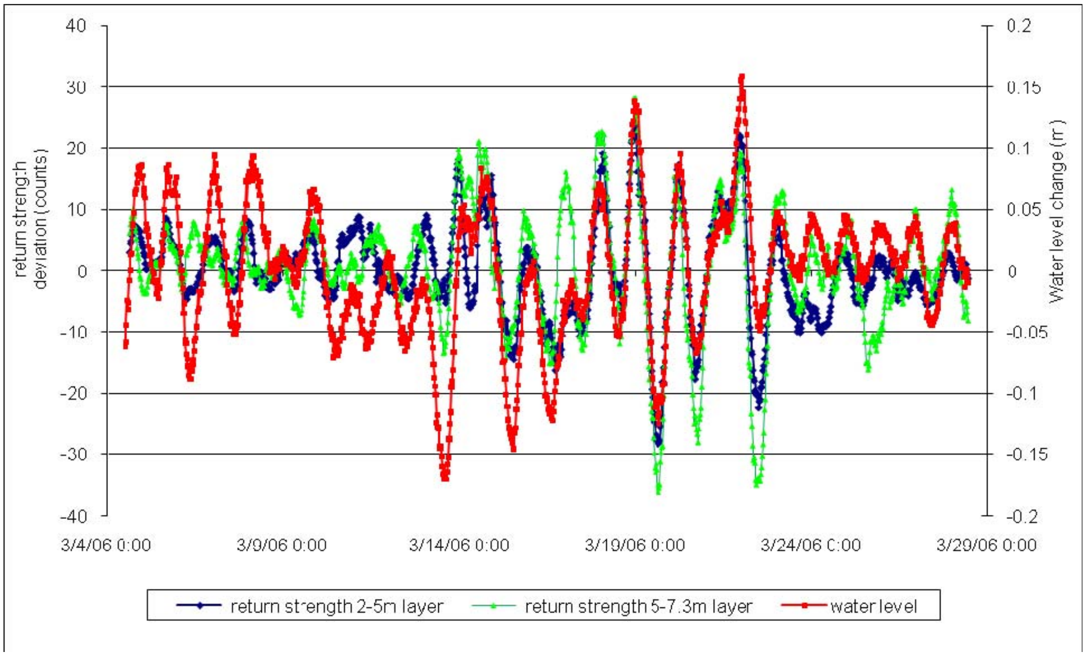

Figure 16. Time series plots of 2005-2006 high frequency components of variability in local water level and mid- and upper-water column average return strengths.

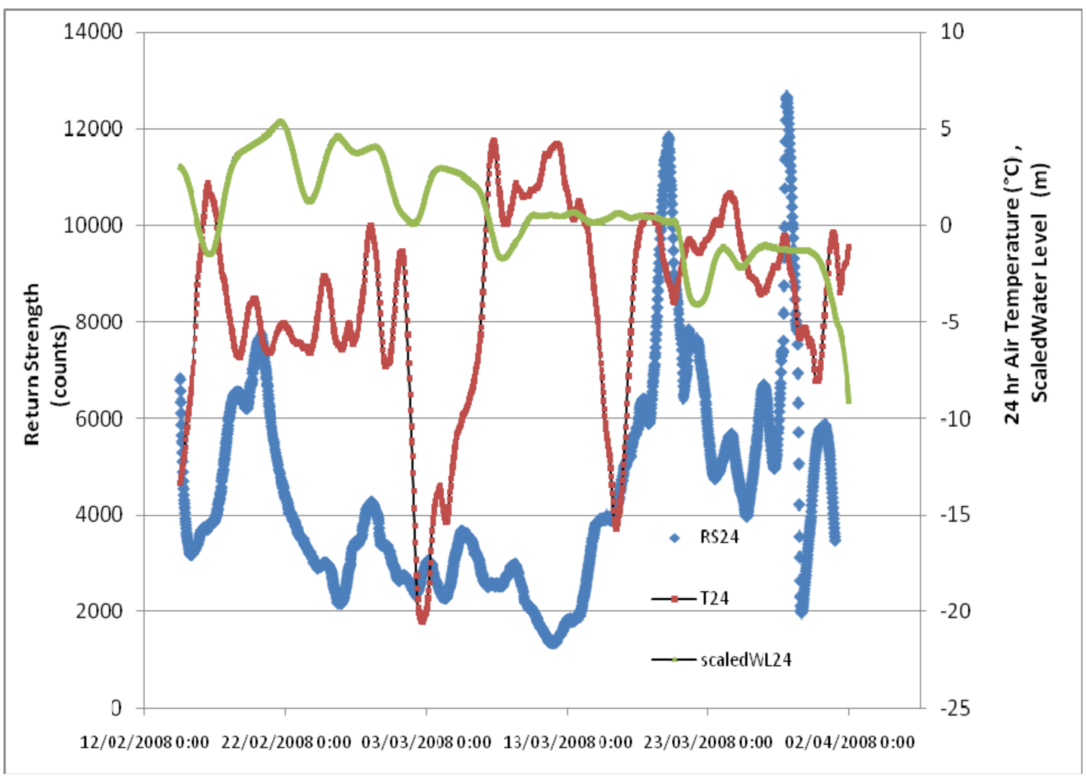

Figure 17. Plots of 24 hr-running averaged time series of return strengths (RS24) in the layer 0.9 to 2.0 m above the transducer, local air temperature (T24) and water levels (scaled WL24) calculated from the Solinst hydrostatic pressure sensor on the deployed SWIPS platform. For convenience in the plotting, the water level data have been scaled such that scaled water level = 8 × (water level-317) in m.

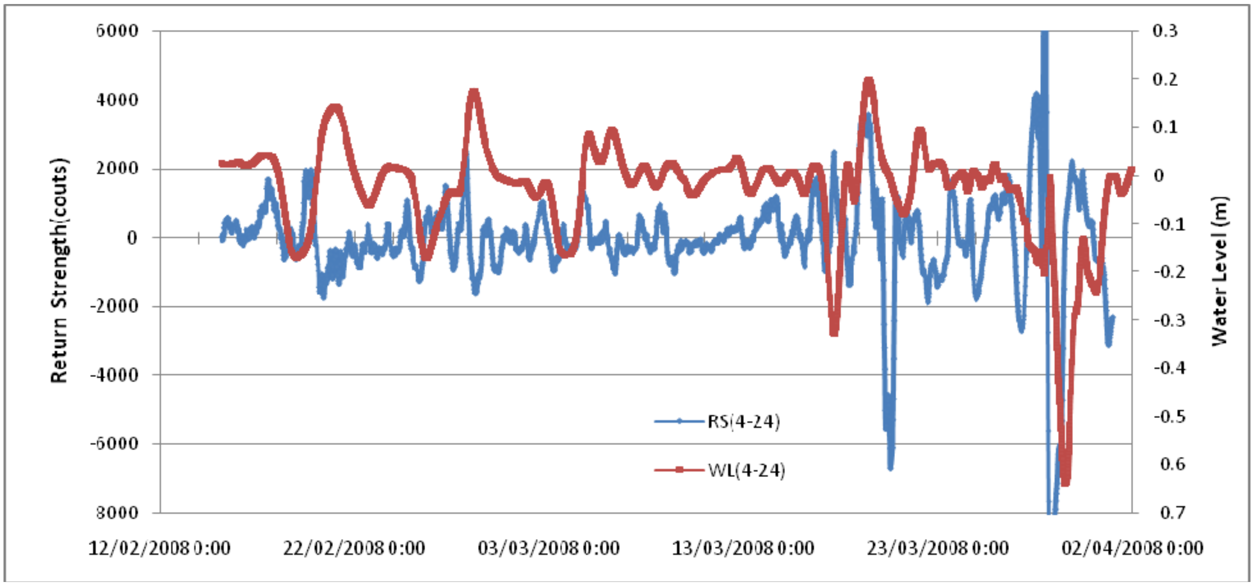

Figure 18. Differences in the 4- and 24-hr running average time series as computed for the mid-water layer return strength (RS(4-24)) and water levels (WL(4-24)) derived from Solinst hydrostatic pressure data gathered on the SWIPS instrument.

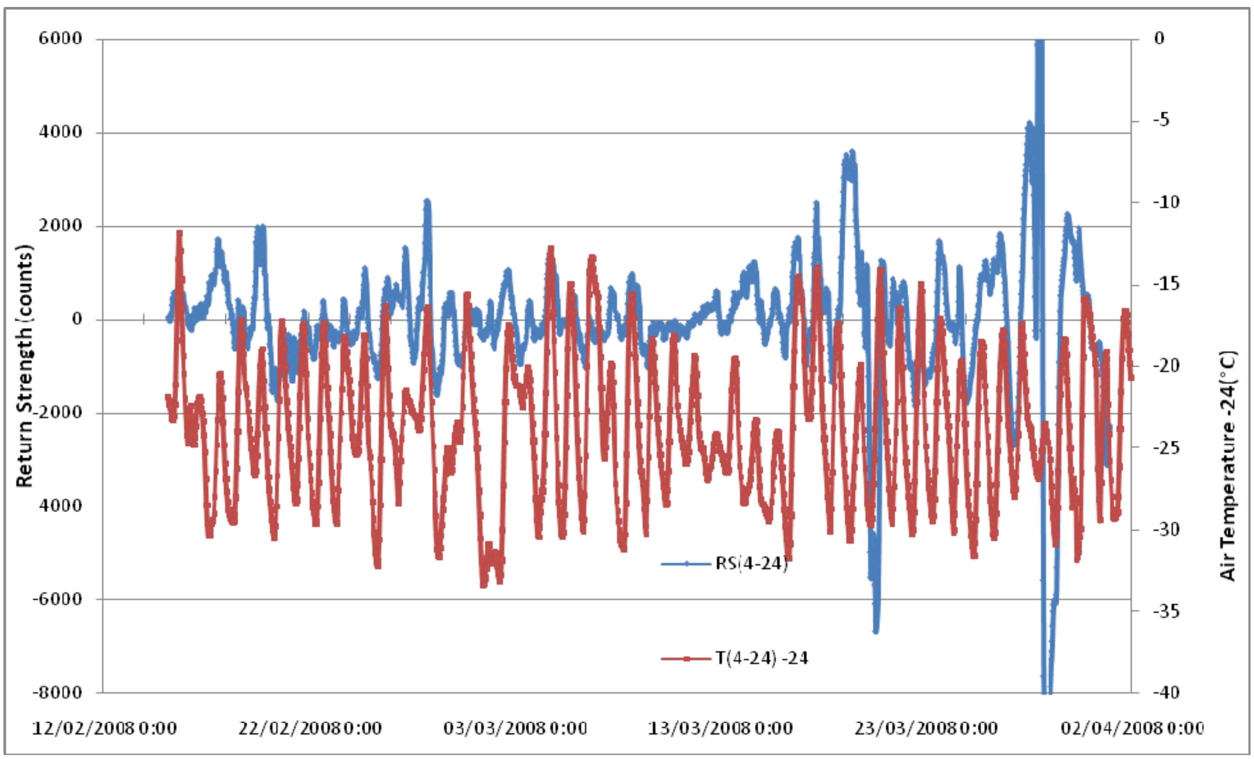

Figure 19. Differences in the 4- and 24-hr running average time series as computed for the mid-water layer return strength (RS(4-24)) and a local air temperature (T(4-24)) which is offset by subtraction of 24°C. The offset was introduced only to allow easy comparisons of the peaks in the two series. The temperature data were gathered in the Town of Peace River, 7 km downstream of the SWIPS site.

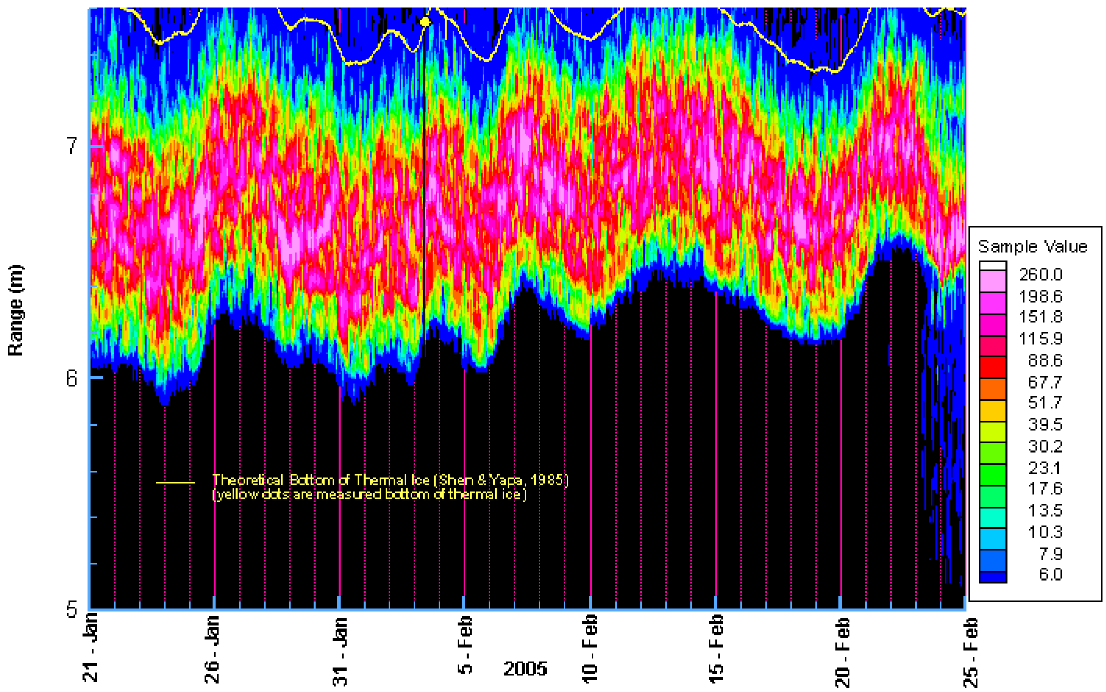

Figure 20. A blow up of the Jan 21- Feb 25 portion of 3-hour averaged SWIPS1 plots presented originally in Jasek et al. (2005) and in (Marko and Jasek, 2008). The plotting is focused on returns from the lower portion of the stabilized ice cover. The yellow curve and added field measurement point represents the estimated bottom surface of the thermal ice cover. The extent of acoustic penetration of the slush layer is probably less than that represented because of the anomalously low speeds of sound propagation noted by Jasek et al. (2005).

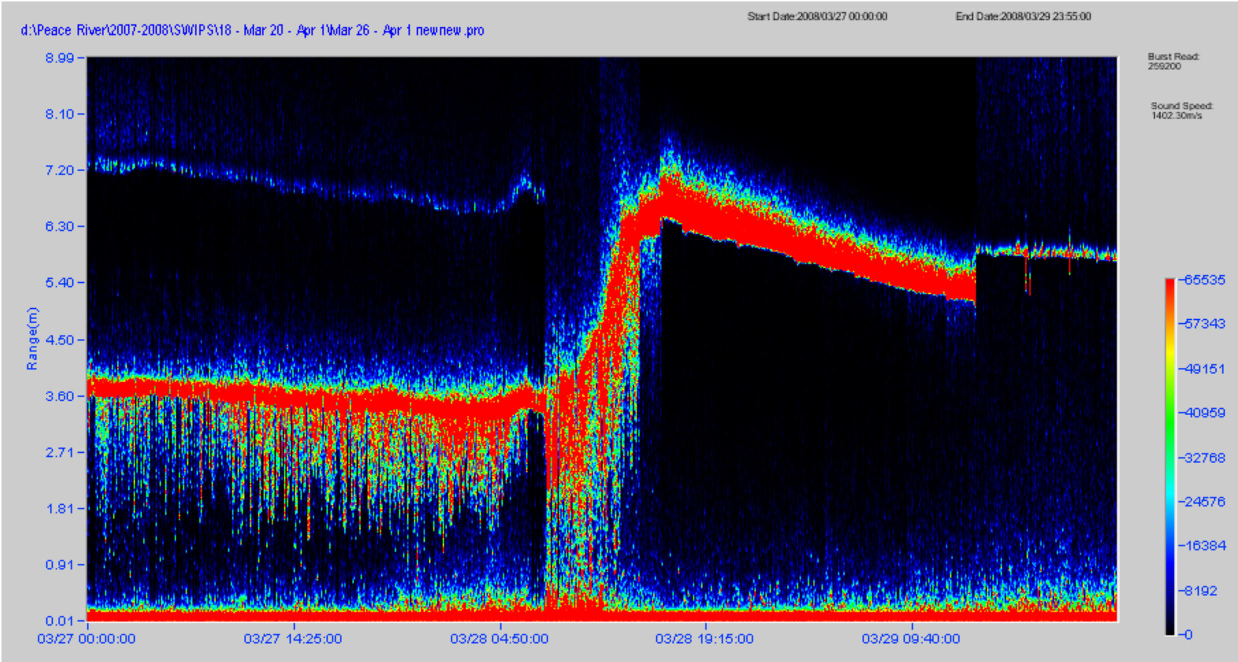

Figure 21. Acoustic profiles during the thermal break-up on Mar 28-29, 2008.

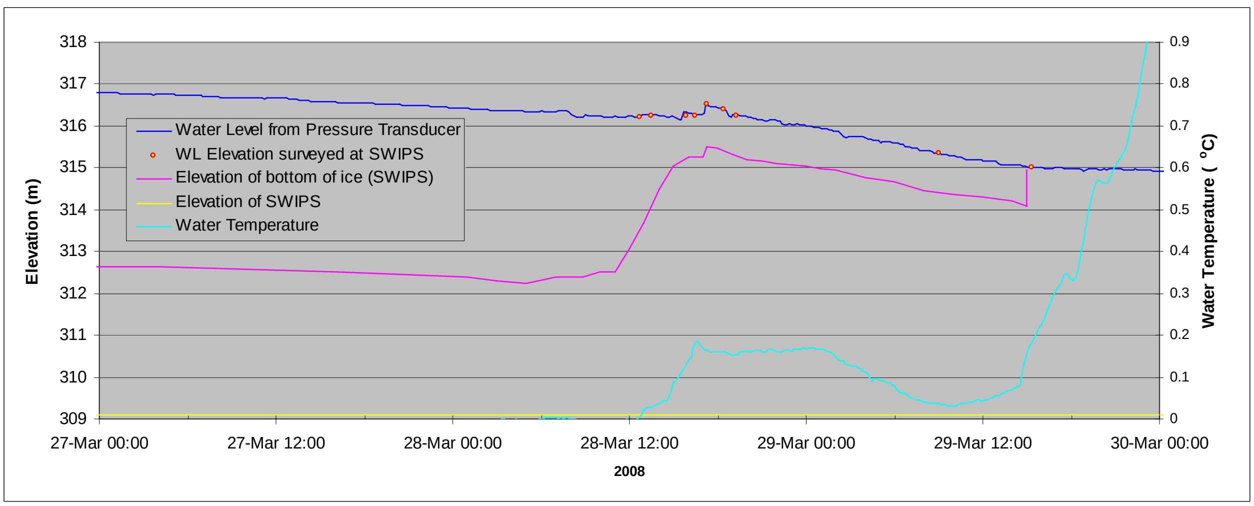

Figure 22. Water Temperature and the elevations of **w**ater level and the bottom of the ice cover at the SWIPS site during the thermal break-up on Mar 28-29, 2008.

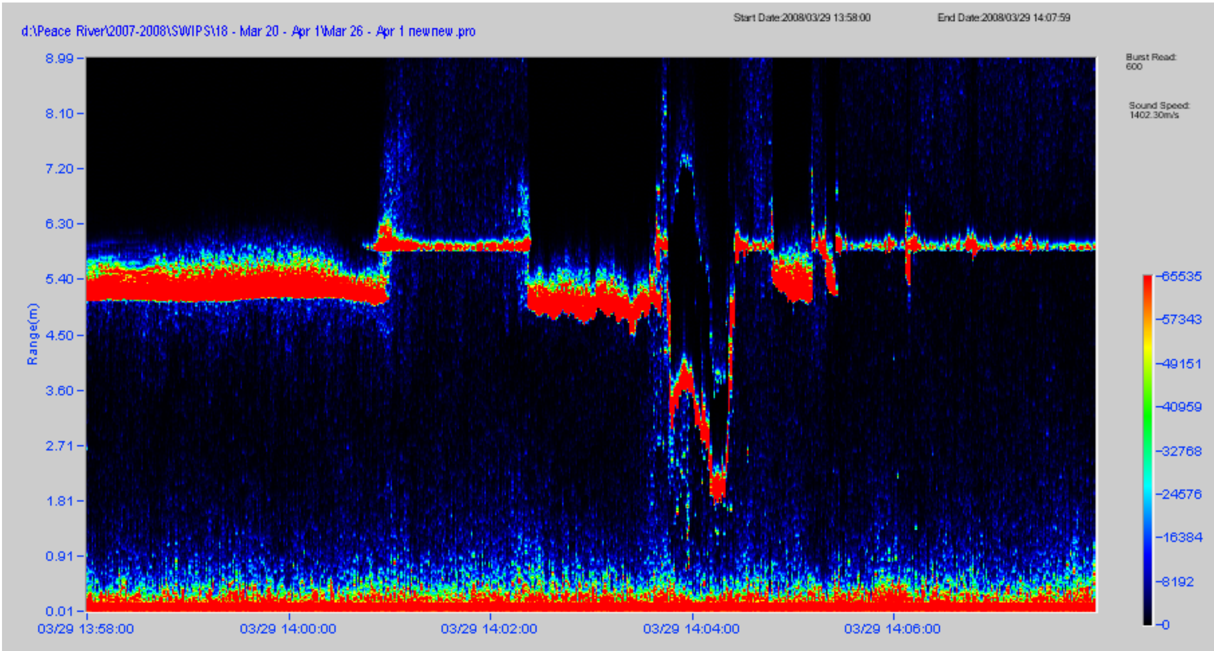

Figure 23. Full resolution acoustic returns of thermal break-up of thermal ice.