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Ten Years of SWIPS Profiling in the Peace River: Looking Up, Back, Ahead and, Possibly, Down

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Results of 2004-2005 winter measurements in the Peace River, carried out with a single frequency (235 kHz) SWIPS (Shallow Water Ice Profiling Sonar) instrument, were reported (Jasek et al, 2005) at the 13th CRIPE Conference. Although largely qualitative, these results offered previously unavailable information on different components of a consolidated ice cover as well as intriguing observations of early season suspended frazil and anchor ice. Needs for quantitative data, particularly on frazil, motivated development of near-simultaneous backscattering measurement facilities at multiple frequencies. Initial tests of this approach showed capabilities for characterizing frazil distributions in terms of numbers and diameters of idealized, uniformly sized, ice spheres. Nevertheless, in the absence of independent verification data and remaining calibration uncertainties, additional development and laboratory testing were carried out. These efforts utilized a compact four frequency backscattering sonar closely related to ASL's Acoustic Zooplankton Fish Profiler (AZFP) which is currently widely used in monitoring fresh and salt water environments. The laboratory data, obtained on highly controllable and precisely characterized disk-shaped polystyrene pseudo-frazil surrogates, established

operating bounds for multifrequency frazil characterization in terms of idealized spherical particles characterized by probabilistically distributed “effective radii”. Conversions into corresponding fractional volumes were straightforward.

The resulting methodology was applied to 2011-2012 Peace River SWIPS data acquired at frequencies ranging between 125 kHz and 774 kHz to test and extend laboratory-derived operating rules and to obtain the first extensive body of data on river frazil suspension content. Comparisons of these results with a previously employed implementation of the CRISSP simulation model found major discrepancies in both the time dependences and magnitudes characteristic of frazil fractional volumes. In particular, frazil ice presence was, approximately, two orders of magnitude less prevalent than anticipated in CRISSP calculations.

In a subsequent study, the origins of these discrepancies were traced to *in situ* anchor ice growth. Other data, derived from acoustic beam blockages encountered in the same measurement program, provided a basis for quantifying such growth on both the SWIPS instrument and the adjacent riverbed. These results were shown to be quantitatively interpretable in terms of a simple anchor ice growth model. This model ties ice growth on the riverbed to atmospheric cooling rates and accounts for the major features of the 2011-2012 bodies of frazil profile and acoustic blockage data. *In situ* growth and buoyant release of anchor ice into the water column were identified as dominant factors in surface ice cover development. The implications of these results for future river ice monitoring and modelling activities will be discussed.

1. Background

SWIPS (Shallow Water Ice Profiling Sonar) uses upward-looking acoustic beams to "profile" water column content by detecting backscattered acoustic pulses (Fig. 1). This technology was introduced (Jasek et al., 2005) at the 2005 CRIPE workshop largely in the form of semi-quantitative echogram displays documenting typical time series of variations in acoustic backscattering from water column ice constituents. Beyond additional instrumental and methodological advances, most subsequent work on river ice applications have been directed at establishing the relative importance of individual ice constituents and identifying underlying inter-relationships. Key characteristics of SWIPS returns are illustrated in an early season 2006 echogram (Fig. 2) which showed return strength profiles acquired at a moderate, 546 kHz, acoustic frequency. The first 2 hours of the displayed period included:

1) "close-in" returns from water column regions immediately above the transducer (ranges < 0.2 m) which represented, primarily, instrument response time effects (ringing);
2) Strong returns from the often ice-infested river surface (at ranges ≈ 4.0-4.6 m);
3) Weak returns from suspended sediment traces, mostly in the lower water column.

Moderately strong returns from water column frazil began to appear at, roughly, 16:00 Jan. 13 but faded out at 05:00 Jan. 14 before reappearing at 17:30 and vanishing again at, roughly, 00:00 Jan 15. The latter disappearance coincided with major changes in both the close in- and river surface signals. The former signals increased in thickness (range extent) progressively with time: coincident with fading of the surface and water column returns. These effects were classic consequences of anchor ice building up on the surface of the unheated SWIPS transducer: causing temporary loss of profiling capabilities and, eventually, physical destabilization of the entire weighted SWIPS instrument. In subsequent deployments, external heating was applied to almost completely avoid such effects. These blockages did not appear after local ice cover formation, presumably due to the insulating effect of the ice cover which precluded supercooling. Nevertheless, acoustic returns from ice particles in the water column were detectable under a fixed ice cover along with, at low enough frequencies, returns from the ice cover interior. Both types of returns were evident in the two-hour-averaged data spanning the full ice-covered period (Fig.3). The water column frazil returns were distinguishable from their early season counterparts, depicted in Fig. 2, which showed little or no weakening in the lower water column. Instead, frazil returns detected under a stabilized ice cover were largely confined to regions within about 1.5 m of the ice undersurface. An additional feature of ice-covered period data was the presence of strong correlations between time variations in the strengths of returns from water column ice particles and changes in river water levels (a proxy for river flow speed) and other environmental parameters (Fig. 4).

The origins and characteristics of the three generic signal returns (close-in-, water-column- and surface-targets) provided a basis for accessing a broad range of river ice information. Practical exploitation of these returns, slowed by shifts and confusion in priorities, eventually, was achieved by enlightened choices of SWIPS instrument components and methodologies. Choices were most straightforward in applications to surface ice. In the shallow water depths of typical rivers, the time delays of returns from ice undersurfaces could be combined with water sound speed and hydrostatic pressure data to provide quasi-continuous monitoring of ice floe draft (see Fig. 1). Such data could then be combined with river velocity information to provide measures of fractional surface ice areal coverages and floe size distributions. As noted above for Fig. 3, surface layer returns at low acoustic frequencies even allowed detection of strong returns from the interior of the slush ice layer which often comprises the lower portion of a consolidated ice cover. The data in the Figure allow tracking the thickness of this ice cover component: showing the presence of both an overall seasonal thinning trend and sensitivities to river water level/velocity.

2. Recent Progress

Given the widely assumed central role of frazil in river ice cover development, methods for quantitatively estimating frazil fractional volumes have long been judged (Osterkamp, 1978) to be a "most critical need". This belief has driven most recent advances in SWIPS instrumentation and methodology. Specifically, SWIPS measurements of volume backscattering coefficients, S_v, (representative of the fraction of incident acoustic power which is scattered directly back toward its source by a unit volume of spatially distributed targets) at multiple acoustic frequencies were carried out to provide such data. The effectiveness of this approach was largely based upon the extremely strong dependences of small particle backscattering cross sections (the 2-dimensional counterpart of S_v) on particle dimensions and acoustic wavelength. A compact four frequency instrument was developed to provide logarithmic S_v and target strength outputs with selectable range- and temporal-resolutions. User-friendly RUNSWIPS software was designed to use instrument output to extract basic frazil population parameters: numerical particle concentration, median equivalent spherical radius, and the width of an assumed lognormal particle size distribution. This software employs a well verified quantitative relationship to link particle and acoustic measurement parameters to corresponding backscattering cross sections within the limitations imposed by treating particle targets as spheres of equivalent volume. The latter relationship is widely used for acoustic instrument calibrations and requires only inputs of material densities, sound speeds, acoustic frequency and target radii.

The impacts of the spherical target approximation and other simplifications on backscattering data interpretation were tested on disk-shaped and spherical targets in a laboratory tank to establish dependences on particle concentration, particle linear dimensions and acoustic frequency. This testing utilized polystyrene surrogate targets characterized by precisely known individual dimensions (selected to be similar to those of natural river frazil) and concentrations (known to 5% or better accuracy) spanning the anticipated range of river frazil concentrations. The utilized cross section relationship showed its poorest performance corresponding to, roughly, +/-20% uncertainties in applications to disks with dimensions at the upper end of the anticipated range of river frazil particle size. Errors from this source were minimized by carrying out measurements at low acoustic frequencies. Later field tests were consistent with the insignificance of such errors.

The RUNSWIPS program was applied to 10-minute-averaged S_v data gathered in the Peace River in 2011-2012 with a 4 frequency ASL AZFP (SWIPS) instrument during 7 selected major supercooling intervals. Optimal theoretical matching to data from 3 different frequency channels was almost always achieved to within transducer calibration uncertainties. The matching process returned estimates of frazil population parameters and corresponding frazil fractional volumes at multiple user-selected heights in the water column. These results were compared with corresponding mean water column fractional volumes simulated by a CRISSP model optimized to reproduce observed seasonal ice cover volumes and rates of upstream ice advance. As discussed by Jasek et al. (2011), these simulations ignored possible presences of anchor ice.

Comparisons of measured and simulated time series showed major discrepancies. The magnitudes of these discrepancies, illustrated in Figs. 5 and 6 by data from two frazil intervals, were large enough to require separate simulated and measured data plotting scales. Specifically, simulated fractional volumes tended to exceed their observed counterparts by factors varying from, roughly, 10 to 500. Equally strikingly, during periods of progressively decreasing air temperatures typical of supercooling events, observations failed to confirm CRISSP-based expectations that initial sharp rises in frazil content would be followed by ongoing fractional volume increases. Instead water column frazil content tended to either oscillate or decrease with time from peak values down to low baseline levels. These failures in simulating frazil content magnitudes and dependences were suggestive of the model's neglect of a major source of frazil suppression. Anchor ice growth, a potential suppression mechanism, was a component of the full CRISSP model which was intentionally disabled in most Jasek et al. (2011) simulations to avoid unrealistic timings of ice releases. When included, modelled anchor ice growth reduced frazil content by, roughly, a factor of 2 which was incommensurate with the observed SWIPS vs CRISSP discrepancy magnitudes. Model outputs of local water temperature, a critical determinant of ice cover formation, were found to be in close accord with measurements made on a co-deployed ADCP instrument even during extended intervals associated with above-freezing temperatures. This agreement suggested that, irrespective of its failures in simulating frazil content, the CRISSP implementations accurately reproduced the overall energy balance between the freezing river and its external environment.

Analysis of the SWIPS frazil profile data showed that the rates of latent heat input required to account for the initial bursts of frazil growth were very small fractions of estimated contemporary surface heat losses. Moreover, estimates of the upper limits of frazil capture rates were found to be far below those required to account for the anomalously low observed frazil concentrations. Even more fundamentally, it was noted that bottom capture of existing frazil particles would not introduce the additional latent heat required to suppress further frazil growth. Instead, the measured water column frazil content data were found to be explicable only in terms of *in situ* anchor ice growth. Changes over time in the rates of such growth provided naturally varying sources of latent heat input to the water column which could control suspended frazil content. In simplest terms, latent heat from rapid *in situ* growth in a thickening anchor ice layer lowered water column frazil content until sudden buoyancy-driven releases of ice from this layer temporarily lowered the availability of productive anchor ice growth sites. The latter changes reduced latent heat production, favouring increased supercooling and temporary rises in suspended frazil content.

Although this interpretation of frazil backscatter data seems reasonable and self-consistent, the underlying evidence for *in situ* anchor ice growth was indirect and based only on water column frazil content data. Such data are always, in spite of prior verifications (Marko and Topham, 2015), challengeable in terms of possible systematic measurement errors. Fortunately, additional, fortuitous, 2011-2012 SWIPS data provided more direct support for the offered interpretations and some substance for a tentative, semi-quantitative, picture of early winter ice growth processes.

Our above use of the word "fortuitous" reflects the fact that critical data were acquired from acoustic beam blockages on a SWIPS instrument which was intentionally heated to preclude such blockages. These blockages were indicative of anchor ice buildups on the SWIPS transducers resembling those previously deduced from enhanced close-in returns (Fig. 2) detected by unheated instruments. Significantly, the 2012 blockages were both more slowly developing than those observed in the absence of heating and restricted to times subsequent to Jan. 26 in spite of occurrences of earlier, more intense, cooling periods. An echogram of the late January blockage event is presented in Fig. 7. The changes in water column frazil content which preceded this event were previously plotted in Fig. 6. The blockage buildup can be seen to have occurred in two stages: an initial thickening of the close in signals followed by a mid-day thinning and clearance of the blockages; followed by re-thickening and an eventual shutdown of all returns from regions above the transducer's load of anchor ice. This blockage persisted until a major warming event, in the Feb. 3-6 period, cleared all evidence of beam obstruction. On Feb. 6, the return of lower air temperatures re-introduced blockages which remained in place until about 7 days after local consolidation of the seasonal ice cover on Feb. 12.

The most immediate benefit of the blockage phenomenon was that it provided a means of estimating anchor ice thicknesses on the transducer face within the approximately +/-30% uncertainties of sound speed in anchor ice. It is to be emphasized that these thicknesses, plotted (Fig. 8) as a function of time for the early portions of each of the two major blockage events represent accumulations on heated transducer surfaces 29 cm above the riverbed. The resulting shorter term accumulation rate estimates of 1-4 cmh^{-1} were indicative of daily layer increments on the order of 25 cm or more. Although, once a complete blockage was in place, further detailed tracking of layer thickening was not possible, the atmospheric temperature data and the qualitative character of the close-in signals were consistent with comparable daily accumulations occurring during all but 3 days of the Jan. 26 - Feb.12 period. Such accumulations would, on their own, provide a sufficient basis for establishing a seasonal ice cover of the observed thicknesses. Consequently, the low frazil fractional volumes inferred from the SWIPS profile data were definitively not inconsistent with seasonal surface ice cover data.

Nevertheless, given the uniqueness of transducer surfaces as anchor ice collection sites, it was relevant to seek equivalent estimates of contemporary accumulations at adjacent, more anchor ice-friendly, sites on the riverbed. Such estimates were feasible within a laboratory-derived (Qu and Doering, 2007) picture of anchor ice layer development wherein thickening anchor ice layers progressively flow over and cover successively higher riverbed obstacles. From this point of view, anchor ice would only appear on the 29 cm high SWIPS surfaces after it attains a similar thickness in immediately adjacent riverbed regions. Assuming prior clearances of anchor ice from the riverbed, blockage onsets in the two observed blockage events would, thus, have had to be preceded by supercooling intervals characterized by durations and intensities sufficient to produce 29 cm of riverbed anchor ice growth. Fortunately, the warming event which preceded the second (Feb.7-19) blockage event was intense and long enough to assure prior anchor ice clearance. This clearance justified assuming that the 8 hour delay between the onset of the observed supercooling interval and initial detection of blockage onset would have produced the required riverbed anchor ice growth. The corresponding accumulation rate (3.5 cmh^{-1}) was compatible with rates subsequently deduced for the SWIPS transducer surfaces. This compatibility, suggesting shared commonalities between riverbed and SWIPS surface anchor ice growth rates, provided an obvious starting point for establishing connections between SWIPS blockages and riverbed ice growth.

These connections were made quantitative by using the pace of the buildup to the Feb. 6-7 blockage to account for both the longer, 15 hour, buildup to the earlier (Jan. 26) blockage event and the absence of earlier 2011-2012 blockages. This effort assumed inverse proportionalities between blockage onset buildup time requirements and contemporary cumulative atmospheric heat loss fluxes. It was found that the latter flux during the 15 hour Jan. 26 buildup was only 15% less than that calculated for the 8 hour Feb. 6-7 buildup. This slight shortfall from a potentially common flux threshold value was not unexpected since supercooling conditions suitable for *in situ* anchor ice growth were present at times as little as 14 hours prior to the start of the buildup to the Jan. 26 blockage event. It was, thus, reasonable to expect that the presence of riverbed anchor ice remnants from this earlier period may have lowered cumulative heat loss requirements slightly relative to the threshold deduced from the Feb. blockage event.

This apparent success in using a common flux threshold to account for differences in the supercooling durations required for two different blockage events encouraged broader use of the overflow concept to explain blockage absences during three earlier 2011-2012 supercooling intervals. In one of these intervals, associated with the Jan. 2-3 period, the short 8 hour duration of supercooling and the accompanying relatively high cooling temperatures limited the resulting cumulative heat loss flux to 22% of the Feb. 6-7 threshold value. It was, consequently, not surprising that, although the basic shape of the fractional volume vs time curve for this interval closely resembled the single peak form (Fig. 6) associated with the two late season blockage intervals, SWIPS blockage did not occur. It was notable that the three supercooling events associated with single peak decays in frazil content (including the two blockage-terminated events) coincided with low cooling rates. Specifically, contemporary air temperatures were mostly in the -5° to -10°C range: never dropping below -14°C. Distinctions between such intervals and the remaining two Jan 14-15 (see Fig. 5) and Nov. 20-21 blockage-free intervals, were readily apparent in that, in the latter cases, air temperatures never rose above -20°C and the time dependences of the estimated frazil fractional volumes were multi-peaked (strongly oscillatory). These results suggest that very low temperatures and their accompanying high rates of cooling introduce similarly oscillatory variations in the amounts of latent heat injected into the water column by *in situ* anchor ice growth.

Applying the common cumulative heat loss flux threshold concept suggests that SWIPS blockages should have been detectable 4.5 hours after supercooling onset in both the Nov. 20-21 and Jan 14-15 intervals. However, within the above interpretation of frazil variability, the prior appearances of deep minima in corresponding fractional volume versus time curves suggest that such blockages were effectively short-circuited by earlier releases of anchor ice from the riverbed. In the Nov. 20-21 interval, a fractional volume minimum and a presumed underlying thinning of the anchor ice layer occurred two hours after the onset of supercooling or 2.5 hours before the expected crossing of the cumulative flux threshold for blockage occurrence. The situation was more complex during the Jan. 14-15 supercooling interval. In that case, the first fractional volume minimum appeared (Fig. 5) about 4 hours after the onset of supercooling or about 0.5 hours prior to the expected breaching of the blockage threshold. Given the uncertainties of our calculations, this proximity to the instability threshold might have been expected to introduce additional complexity. Evidence of this may have been previously detected (Marko et al., 2015) during this interval in terms of anomalous decreases in frazil content with height in the water column: in conflict with observations in most supercooling intervals and theoretical expectations (Ye and Doering, 2003).

The 2011-2012 SWIPS profile and blockage data suggest that observed tendencies for frazil fractional volumes to remain below 10^{-4} (0.01%) are consequences of massive releases of latent heat from *in situ* anchor ice growth. Rates of this growth, which apparently accompanies all supercooling intervals, are on the order of a few cmh^{-1} and sensitive to atmospheric heat fluxes. Use of standard empirical relationships between air temperatures and such fluxes suggests that layer porosities are, roughly, at the upper end of the 71%-84% range estimated by Parkinson (1984) for detached slabs of anchor ice in the St. Lawrence River. Layer growth appears to suppress water column frazil contents to levels as low as 10% to 20% of peak interval values. Buoyancy-driven layer depletion reduces anchor ice growth rates and inputs of latent heat to the water column: triggering quasi-periodic, usually short lived, increases in frazil content. Frequencies of depletion events appear to be correlated with cooling rates. Rapid cooling, corresponding to temperatures ≤ -20°C, appears to favour less stable anchor ice layers and more frequent transfers of ice mass to the river surface. Slower cooling, at temperatures primarily between -5°C and -10°C, tends to enhance ice stability and allow anchor ice growth to thicknesses large enough to impact upon SWIPS measurements. Physical evidence for the presence of large fragments of detached anchor ice in the water column was detected in echogram data coincident with clearances of SWIPS blockages. Acoustic returns from such fragments appeared as moderate to high strength targets highly localized in time (on single acoustic pings) in the lower and middle water column. These targets were largely confined to periods characterized by detectable thinning of close-in anchor ice returns and strengthening of returns from water-column- and river surface-targets (see Fig.9). Blockage and anchor ice thickness sensitivities to freezing rates are schematized in Fig. 10.

Independent evidence of significant anchor ice deposits on the Peace River has recently been obtained by Jasek et al. 2015 which supports the argument in this paper that anchor ice is being produced in preference to suspended frazil ice.

3. Conclusions and Looking Ahead

It is hard not to interpret these results as evidence of a greatly diminished role for frazil ice as a direct contributor to seasonal changes in ice cover composition. In particular, the frazil content of the water column appears to be much less important in this regard as opposed to its changes over time in sign and magnitude. Such changes appear to be closely tied to contemporary variations in a river's more influential, but less visible and quantifiable, anchor ice constituent.

The strengths of such linkages open possibilities for re-thinking SWIPS usage. Specifically, the future utility of SWIPS frazil profiling may now lie in tracking and characterizing anchor ice changes which directly impact upon surface ice. Exploiting such connections for monitoring or calibrating river ice models requires initial acquisition of data on relationships between variations in frazil content and contemporary anchor ice growth and release rates. Conventional SWIPS profiles provide access to detailed suspended frazil content data. Data on anchor ice thickness as functions of: water and air temperatures; water depth and velocity; riverbed composition and frazil content are not as easily obtained. Bottom-fixed thermistor chain measurements at a small number of sites, coincident with SWIPS profiling, could provide initial insights. More comprehensive data could be accessible from downward-looking multifrequency SWIPS measurements which exploit the tendency of anchor ice to become more acoustically transparent with decreasing frequency. This tendency previously (Fig. 3) allowed deep (235 kHz) acoustic penetrations of slushy lower portions of consolidated ice covers. Other evidence for low frequency transparency includes the fact that complete extinctions of 2011-2012 Peace River acoustic returns at 125 kHz and 235 kHz required two additional days of anchor ice accumulation (equivalent to at least 50 cm of growth) after the onset of high frequency (774 kHz) blockages. Such results suggest that downward-looking measurements at the lower end of the current SWIPS frequency range (i.e. frequencies between 35 kHz and 125 kHz) would acquire ranging data from riverbeds covered by 1 to 2 m of anchor ice. Ranges to the upper and lower boundaries of such ice can be established using the upper and lower ends, respectively, of the SWIPS frequency range: offering accurate measures of layer thickness. Measurements at intermediate SWIPS frequencies would provide additional information relevant to layer porosities, stabilities and cooling rate sensitivities. Bottom-fixed instruments at 3 or 4 locations across the width of a river could provide the initial database needed for incorporating anchor ice into upgraded ice models. Greater advantages could be offered by short term surveys utilizing a single mobile downward-looking instrument mounted on a small boat and/or an ROV or other contrivance controlled from a shore station or river infrastructure. Repeated mapping of layer properties at intervals of a few hours could quantify anchor ice growth and release rate dependences on atmospheric and river parameters, at least during supercooling periods occurring prior to major accumulations of hazardous border and surface ice. Additional survey site candidates could include the controlled flows immediately downstream of hydroelectric dams which are, typically, characterized by less dynamic surface ice conditions.

Much of this presentation has focused on SWIPS applications in periods preceding ice cover formation. This bias reflects both the naively assumed "simplicity" of early season processes and widespread interest in verifying models applicable to such periods. Nevertheless, the experiences outlined above and limited reviews of in-hand data suggest that similar, relatively fundamental, "re-adjustments" may be needed in present understandings of processes occurring subsequent to ice cover consolidation. Specifically, SWIPS data show the slush-, anchor- and frazil- (active and passive) ice forms to be present in varying amounts and at various times extending into the ice clearance period. Quantitative data on these individual presences would offer obvious possibilities for upgrading model performance in all stages of ice cover evolution and dispersal.

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Figures

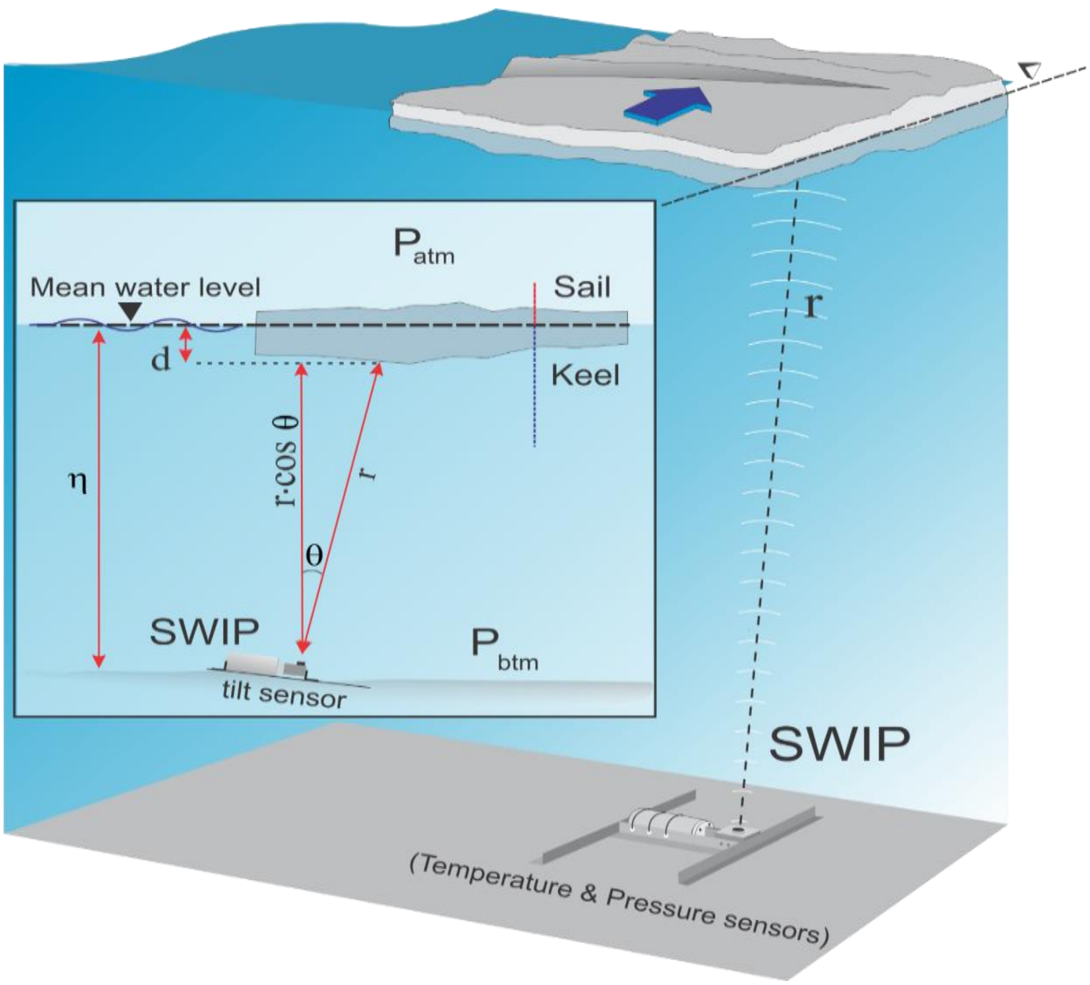

Fig. 1 Simplified sketch of deployed (single frequency) SWIPS unit and standard range measurement parameters

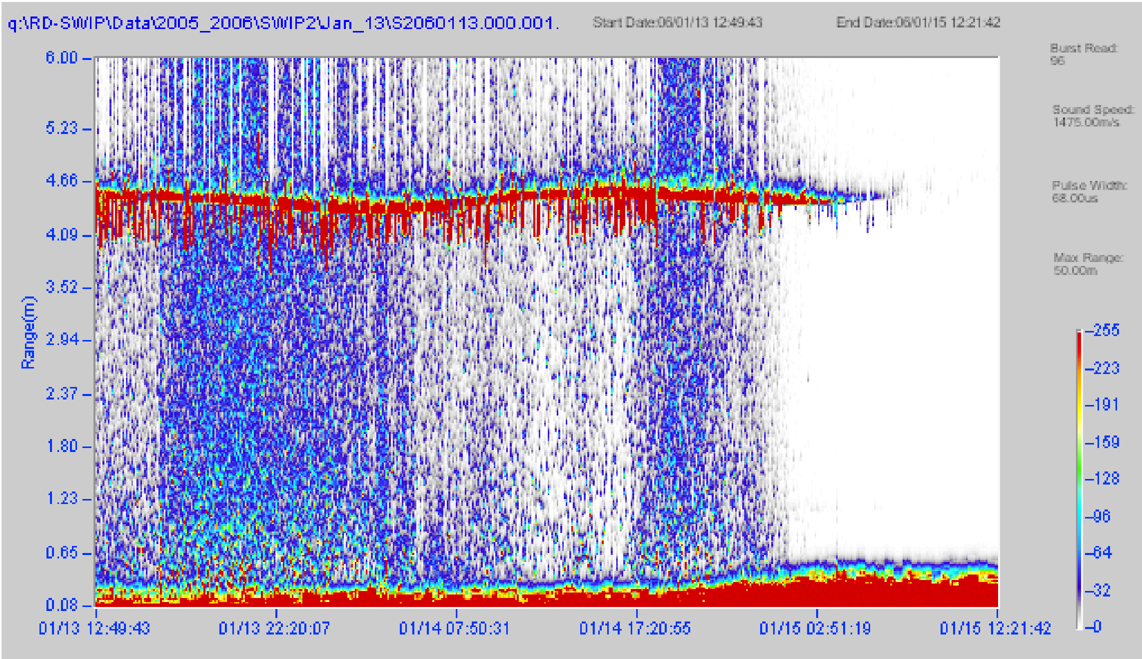

Fig. 2. SWIPS Profile return strength data acquired at 546 kHz prior to and during a Jan. 2006 frazil interval.

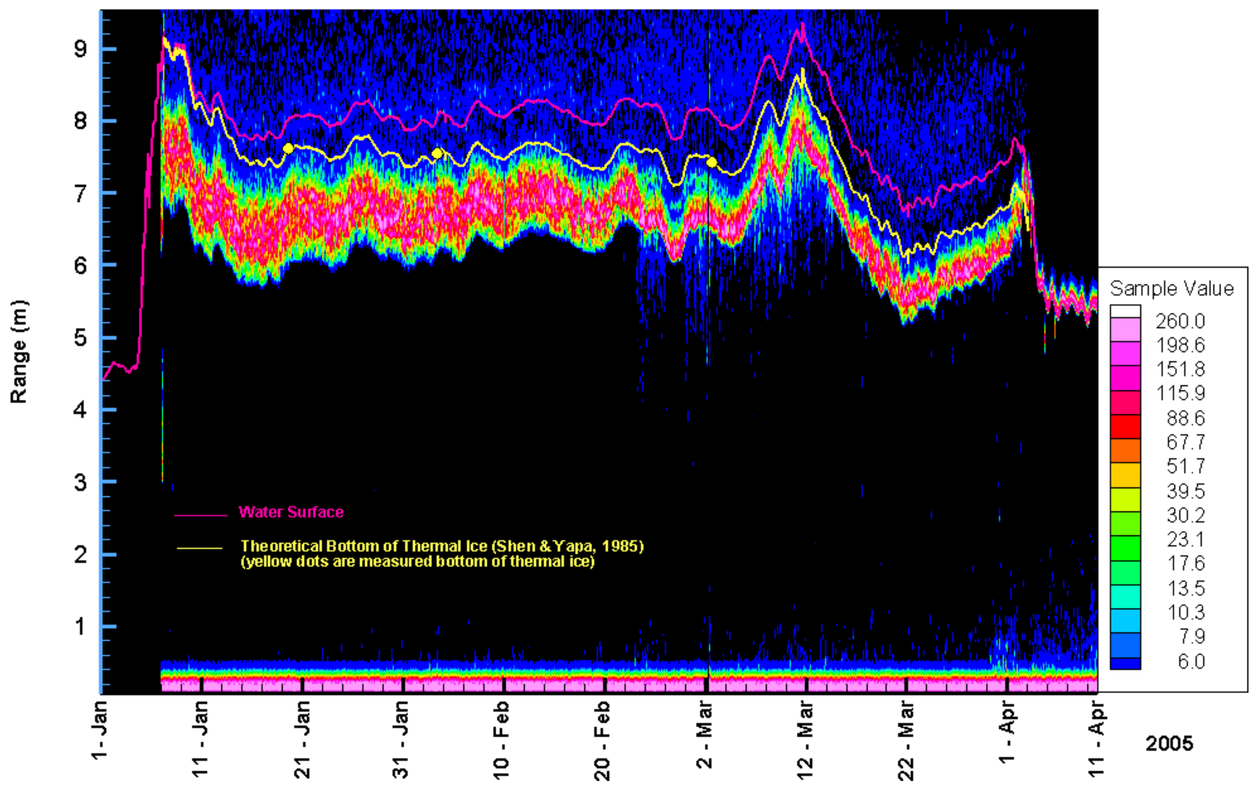

Fig. 3. Two-hour averaged SWIPS Profile return strength data acquired at 235 kHz over the mid-winter, January-April, 2005, stationary ice covered period. Also shown are local water levels and positions of the modelled, and measured (on 3 dates) lower surface of the thermal ice.

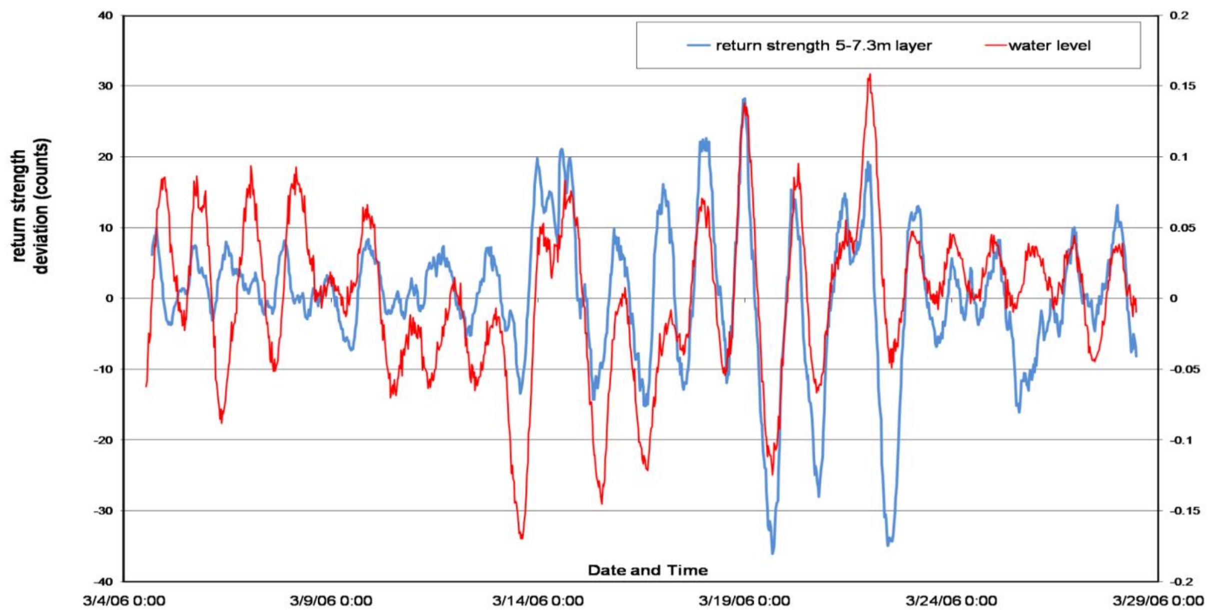

Figure 4. Deviations from mean March, 2006 SWIPS return strengths averaged over heights (relative to the riverbed) between 5m and 7.3 m and local water levels after filtering to remove variability on time scales > 24 hours.

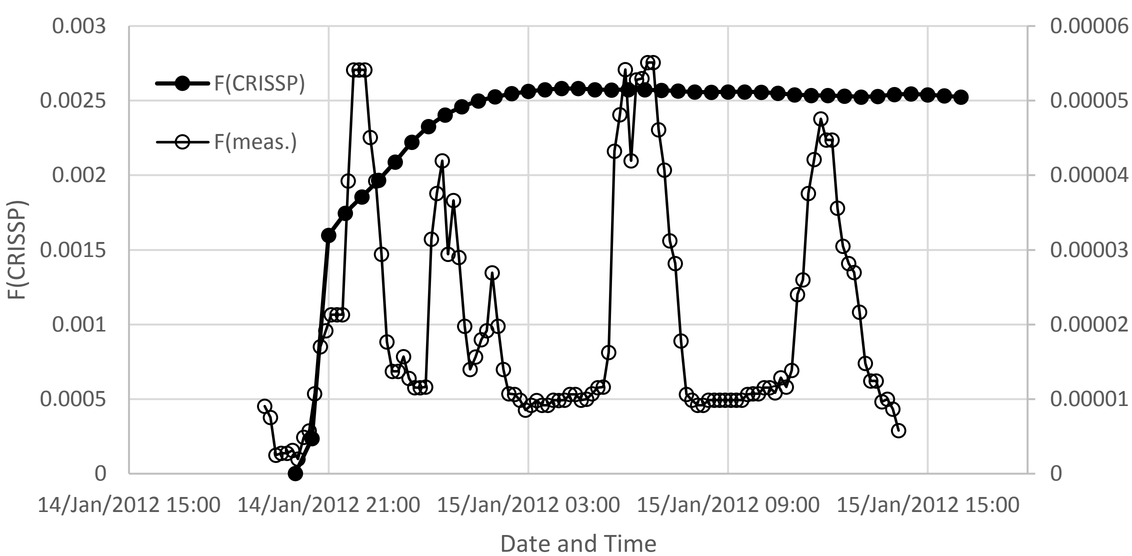

Fig.5. Comparisons of Interval 3 fractional volumes (Marko et al., 2015) as measured (F(meas.)) and simulated as described in the text (F(CRISSP)). The simulation results denote water column mean values while measured data represent mid-water estimates 2.3 m above the SWIPS instrument.

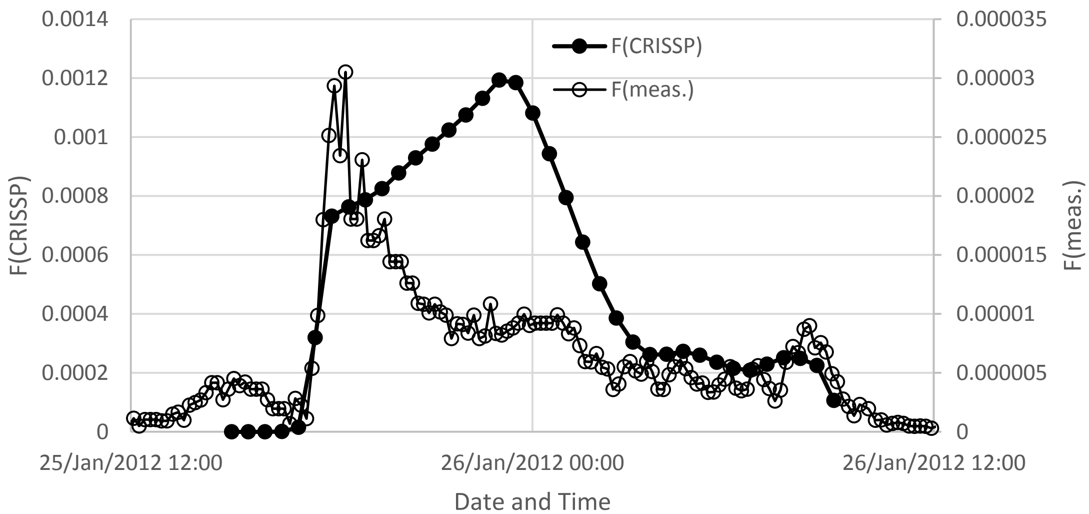

Fig. 6. Comparisons of Interval 4 fractional volumes (Marko et al., 2015) as measured (F(meas.)) and simulated as described in the text (F(CRISSP)). The simulation results denote water column mean values while measured data represent mid-water estimates 2.3 m above the SWIPS instrument.

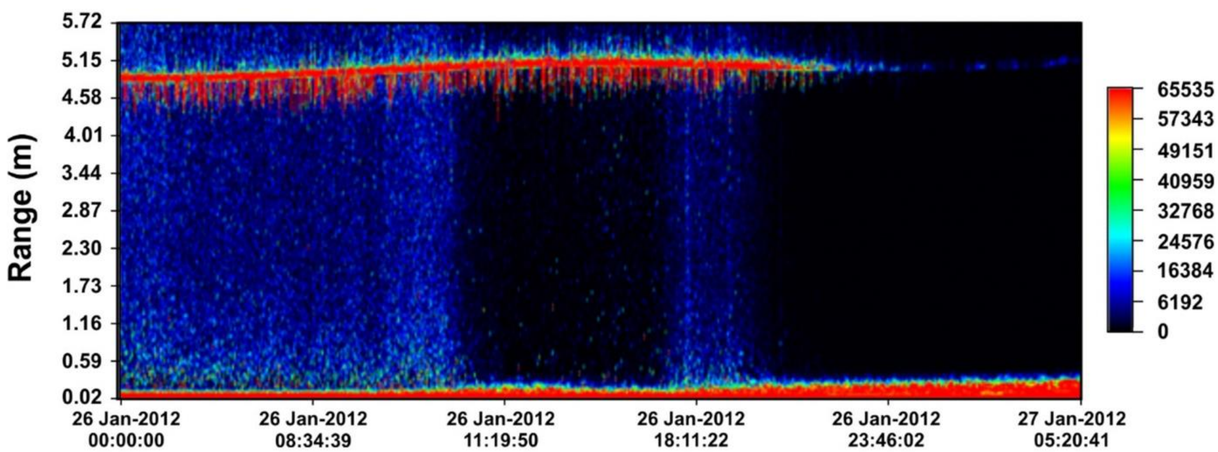

Fig. 7. Echogram of the 774 kHz SWIPS returns in the first blockage event of the 2011-2012 Peace River Study Program.

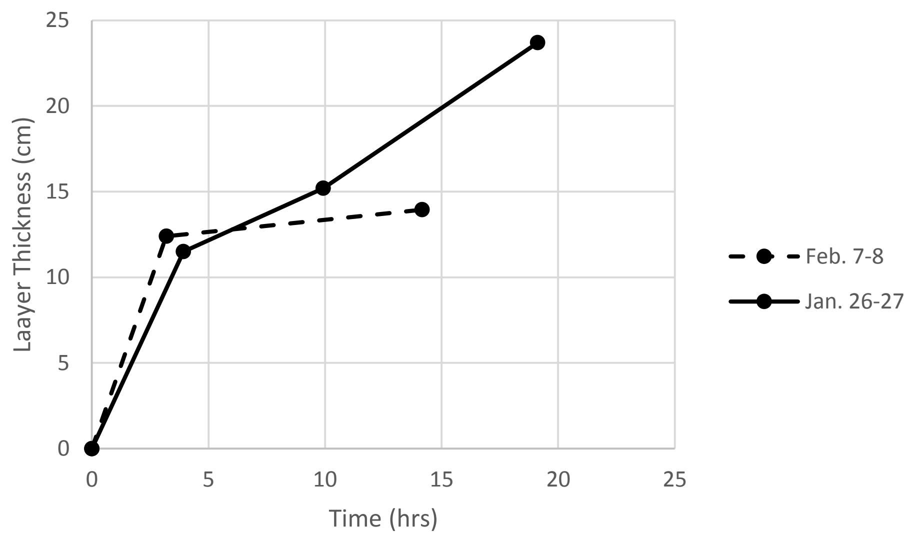

Fig. 8. Anchor ice accretion estimates during the Jan. 26-27 and Feb. 7-8 blockage events as a function of time since event onset.

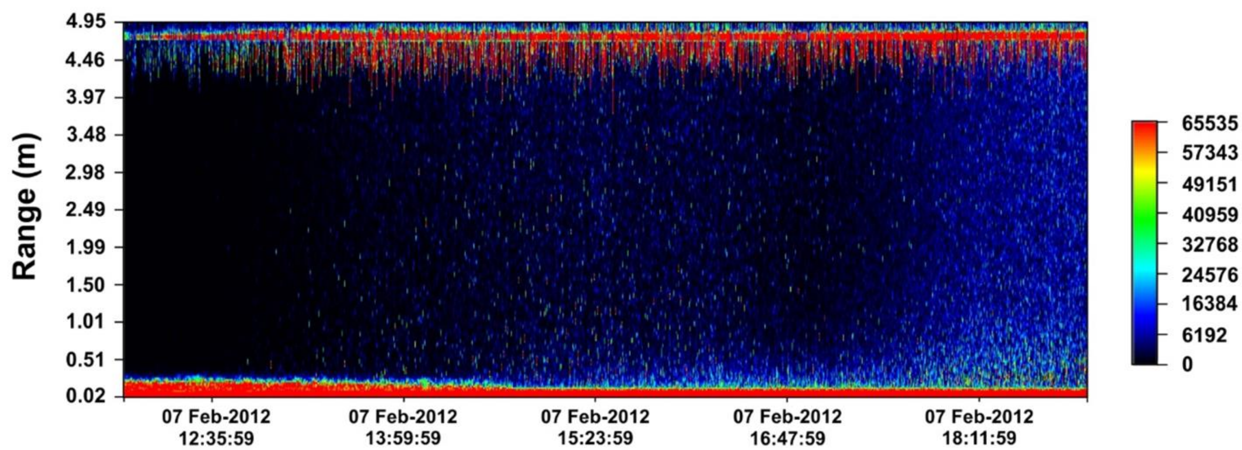

Fig. 9. Echogram depicting events following the last stage of the initial, partial, fadeout of the 774 kHz SWIPS returns during the second 2011-2012 Peace River blockage event. Blockage clearance began at about 13:15 followed at 18:00 by reappearance of high concentrations of water column frazil leading to eventual complete signal extinction. The notable feature of the data was the presence, at times between 14:00 and 17:00, of isolated, localized medium- and near-maximum-strength water column returns from released anchor ice fragments.

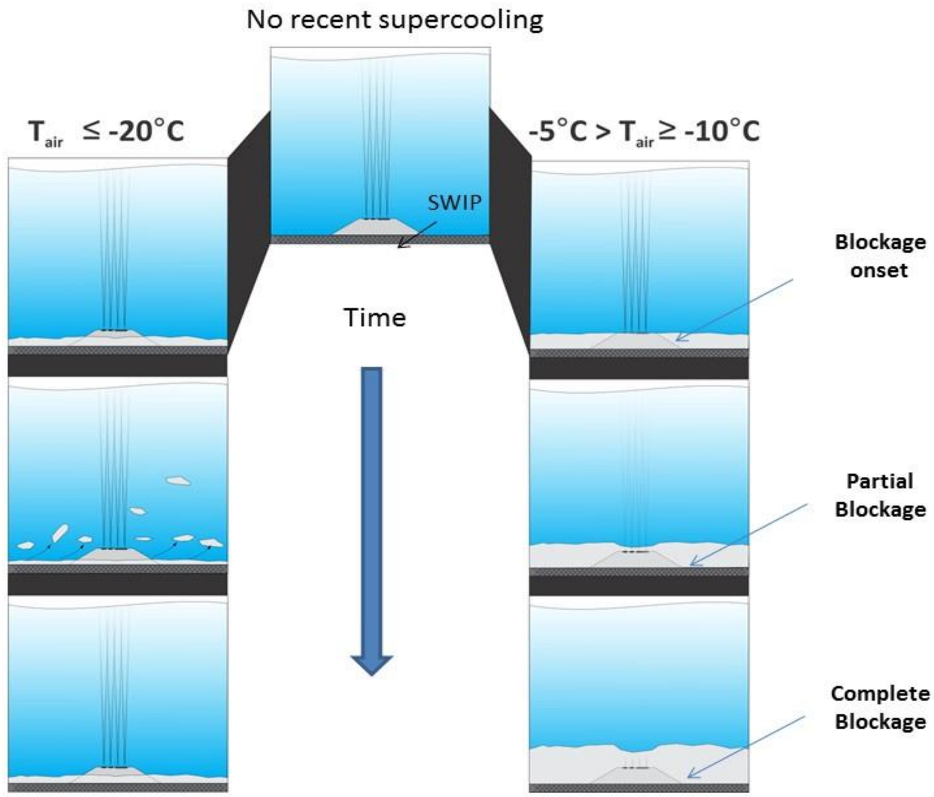

Fig. 10 Schematic illustrations of proposed anchor ice layer evolution processes under alternatively strong (T < - 20°C) and weak (T > - 10°C) supercooling conditions.