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Estimation of Frazil Particle Size and Concentration from SWIPS Measurements in the Peace River: an Assessment of Options and Prospects

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Requirements and procedural alternatives are discussed whereby quantitative parameters descriptive of populations of suspended frazil ice particles can be extracted from SWIPS acoustic water column profile data. It is shown that, on their own, acoustic measurements have to be made at more than one acoustic frequency to allow separate extraction of particle size and concentration information. Nevertheless, a simple method is described and tested which obtains concentration profile and mean particle size estimates from single frequency SWIPS data with the aid of a simple inverted suspended sediment-type model. Conditions for applicability of this approach are discussed prior to presentations of results obtained from application to data collected under the stabilized Peace River ice covers in 2006 and 2008. Research needs are identified for both verification of these results and explication of observed anomalies prior to discussions of methodological refinements available for applications to multifrequency data sets.

1. Introduction and Background

Examinations of results from BC Hydro's ongoing SWIPS (Shallow Water Ice Profiling Sonar) Peace River monitoring programs (Jasek and Marko, 2008) (Figure 1) have focused on observed strong, un-lagged, correlations between environmental factors and high frequency components of backscattered acoustic returns from frazil ice detected under stabilized ice covers. The presence of frazil and its environmental linkages, illustrated with respect to water levels in Figure 2, are of obvious importance to river ice transport and management issues. The conclusion that the amounts of such ice beneath the ice cover tend to increase with river flow rates has already been tentatively incorporated into river management practices (Jasek and Trevor, 2009).

Although we have proposed simple models (Jasek and Marko, 2008) for interpreting these results in terms of a dynamic local equilibrium with the lower ice cover, quantitative understandings have been inhibited by the absence of data characterizing frazil in useful terms such as particle size and concentration. Such data are essential for understanding frazil ice variability and, eventually, for use as inputs to improved river ice models. To date, however, analyses have focused on the return strength output of the SWIPS instrument (in digital "counts"). Although interpreted, in at least one case, as particle concentrations in arbitrary units (Morse and Richard, 2008), the SWIPS output is an 8- or 16-bit digital representation of transducer voltages generated by backscattered acoustic returns. For frazil targets these returns arise from individual scatterers in a volume, ΔV, given by:

$$\Delta V = (c\tau/2)\Delta\Psi\, R^2\,, \qquad [1]$$

In this expression c is the speed of sound in water, τ is the duration of the pinging pulse, $\Delta\Psi$ is the solid angle of the acoustic beam and R is the range separating the target volume and the transducer. The voltage itself is a function of SWIPS system parameters as well as, of course, the effectiveness of the insonified targets in backscattering acoustic energy. The SWIPS system incorporates a time-varying gain which compensates for the falloff of signal strength with range due to spreading and attenuation effects: offering outputs which should be proportional to backscattering effectiveness at any range. Connections of the SWIPS signals, S(R), to particle concentrations arise through the detected acoustic return intensity, $I(R) = S^2(R)$ which is linked to particle concentrations in multiple categories (i) associated with different size-dependent backscattering properties through:

$$I(R) = \alpha\, [\textstyle\sum_i N_i(R)\, \sigma_{bsi}]\,, \qquad [2]$$

The factor α in this expression is a known function of input voltage and SWIPS instrument parameters and σ_{bsi} represents the backscattering cross section of particles in category i. These cross sections are defined as the fraction of the incident acoustic energy intensity which is scattered directly back toward the transmitting/receiving SWIPS transducer by each particle. [The validity of this expression is limited to overall total particle concentrations low enough to exclude multiple scattering and significant interference between individual returns.] The quantity in the square brackets contains all information on the particle targets accessible to SWIPS measurements and, when multiplied by ΔV, yields the volume backscattering strength of the insonified volume. Knowledge of the SWIPS system parameters incorporated into the factor α allows extraction of target strengths from measured acoustic intensities I(R). The technical challenge is to separately estimate the concentration and cross section parameters included in the sum over particle categories. Knowledge of the cross section/particle size relationship is essential to effecting this separation with an ease which is sensitive to both the size of the particles and the extent of detail required (i.e. the number of classification categories). Potential tools for addressing this problem are considered in the following Section (2) prior to exploration of a primitive but promising methodology with existing SWIPS data sets. Requirements for advancing beyond the considered approach are discussed in a concluding Section 3.

2. Options for Particle Parameter Separation and Exploration of a Simple Methodology

The Rayleigh Scattering Law provides an obvious foundation for extracting frazil particle population information from SWIPS-measured target strengths. Useful features of this Law are its strong dependences on frequency (fourth power) and particle size (a sixth power dependence on spherical particle radius, a). (It will be assumed, throughout, that the behavior of tumbling, disk-shaped frazil particles can be approximated with a spherical particle assumption.) These dependences are depicted in Figure 3 in terms of the cross section (divided by πa^2) of a rigid sphere plotted as a function of ka where $k = 2\pi a\nu/c$ and ν is the acoustic frequency. The strong power law regime, represented by the steep linear portion of the plot, means that, for size/frequency combinations satisfying $ka \leq 1$, the particle cross section dependences greatly weight returns from larger particles at any given acoustic frequency. For combinations satisfying $ka > 1$, on the other hand, the scattering relationship shows negligible frequency dependence (the indicated oscillations are undetectable in realistic particle distributions) and the cross section dependence on particle radius is reduced to quadratic. In both cases, SWIPS returns are weighted toward larger diameter particles, as is the fractional occupied volume. Nevertheless, differences relative to the cubic radius dependence of the latter quantity complicates data interpretation when substantial portions of particle populations have radii both above and below the Rayleigh threshold value. The strong frequency dependence of the small particle/low frequency (low ka) regime offers advantages in this respect in that consistent interpretations of data recorded on the same frazil population but at different acoustic frequencies can give separate measures of $N_i(R)$ and σ_{bsi} for a small but potentially useful number of categories i of idealized spherical particles having different ranges of diameters. Although very achievable in principle, to date, simultaneous measurements at multiple frequencies have only been successfully made in a small number of instances and, then, utilizing just two acoustic frequencies (235 kHz and 546 kHz), one of which (235 kHz) was relatively insensitive to smaller frazil particles. Nevertheless, such comparisons, made only in the absence of an ice cover, confirmed a fourth power, Rayleigh Law, frequency dependence consistent with target particle diameters below the 0.8 mm Rayleigh threshold at 546 kHz.

While further exploitation of the multifrequency approach holds considerable promise, our efforts, thus far, have been restricted to use of a cruder but simpler alternative for extracting particle population data. This treatment drew upon an early suggestion (Carstens,1966) that water column frazil could be considered in terms of an inverted suspended sediment model in which turbulent flow drives positively buoyant ice particles away from a reservoir at or close to an ice cover undersurface. This basic idea was invoked recently (Jasek and Marko, 2008,) to qualitatively account for post-stabilization frazil variability. As well, Morse and Richard (2008) applied the same concept with Rouse’s (1937) suspended sediment model to estimate rise velocities (Gosink and Osterkamp,1984) from SWIPS-like data recorded beneath moving, highly variable, ice fields. In our view, the latter application was problematic for several reasons including the use of rise velocities extracted by curve-fitting to individual, widely time-separated, stochastic ping returns and the underlying assumption of proportionality between return signals and particle concentration. Additionally, applications should be compatible with the core assumption of the method which is that particle concentration profiles are representative of equilibria between flow turbulence, and particle buoyancy forces. Profiles are, thus, sensitive to the assumed eddy viscosity vs. height relationship and to the requirement that individual particles behave as inert tracers characterized by momentum diffusivities proportional to this viscosity. This last restriction precludes applications to situations associated with active frazil particle growth: limiting valid river use to post-stabilization periods when such growth is largely absent and immobile ice covers provide convenient frazil reservoirs.

Our explorations of this approach with Peace River SWIPS data employed the simplest form of a basic Rouse theory (Rouse, 1937), which, like the cited Rayleigh scattering theory, confined considerations to a uniformly-sized distribution of spherical ice particles and a parabolic dependence of eddy viscosity coefficients on water column height, y. (measured from the face of the SWIPS transducer). These assumptions allow the ratio of the concentration, $N(y)$, of the buoyant frazil particles at a height, y, relative to the concentration, $N(y_0)$ at a reference height, y_0, to be written as:

$$N(y)/N(y_0) = [(y/(h-y))((h-y_0)/y_0)]^{Z}, \qquad [3]$$

where h denotes the river depth and Z, sometimes designated as the Rouse Number, is defined in terms of w, the "rise velocity" and u*, the friction velocity as:

$$Z = w/(\beta\kappa u^*). \qquad [4]$$

The coefficient $\kappa \approx 0.41$ is the von Karman constant, while the parameter β, represents the ratio of ice particle momentum diffusivity to water eddy viscosity, with values $0.2 < \beta < 1.5$. The friction velocity was assumed to be given by a 0.05 m/s value derived for a 5 m deep channel with a 20 m hydraulic diameter and a roughness of 0.1m The critical rise velocity parameter, w, was then related to the particle diameter, d, with Ashton's (1983) formulation:

$$w = (gd^2/18\, K_F\, \nu)\, (\Delta\rho/\rho_w), \qquad [5]$$

where: g denotes the gravitational acceleration; K_F is a resistance coefficient with a value approximately equal to 2; ν is the kinematic or eddy viscosity and $\Delta\rho = \rho-\rho_w$, where ρ and ρ_w are the mass density of the ice particle and the river water, respectively.

The effectiveness of any model is, of course, determined by the degree to which its formulations duplicate the vertical particle concentration profiles inferred from SWIPS data. We assessed this correspondence, using the simplest assumption, namely, that frazil populations were composed of spherical particles of common radius and cross section, σ_{bs}. This step allowed direct comparisons between Eq.3 and the corresponding ratio of SWIPS intensities since in that case:

$$I(y)/I(y_0) = \sum_i N_i(y)\, \sigma_{bsi} / \sum_i N_i(y_0)\, \sigma_{bsi} = N(y)/N(y_0). \qquad [6]$$

Comparisons utilized 546 kHz SWIPS data from the March periods of 2006 and 2008 which were characterized by, respectively, thinner and thicker than normal ice over the monitoring sites. In each case, the SWIPS intensity or concentration ratios (Eq. 6) were compared with corresponding concentration ratios calculated from Eq. 3 using values of Z chosen to optimize agreement with the intensity ratios at both high and low y values. The compared SWIPS data were averaged over returns from 1 Hz-separated pings as accumulated over 4 hour time periods using a common reference height, y_0, selected to correspond to the highest points in the water column where SWIPS frazil signals were distinguishable from saturated ice cover returns. The 2006 results (Figures 4 and 5) were found to be less consistently of the Rouse form than the 2008 results (Figure 6) which very closely tracked expectations in terms of (Eq. 3). However, the 2006 deviations were largely confined to a, roughly, 10 day period in the middle portion of the one month long stable ice season when "excess" returns were clearly evident from the middle portion of the water column.

Restricting ouselves to optimal Rouse Number (Z) values derived from the 2008 data and the portions of the 2006 period showing similarly good Rouse Law compliance, we used Eqs. 3 and 5 to obtain estimates of particle diameters for specific individual time intervals (Table 1). These estimates suggest that the more constricted water column associated with the thicker local 2008 ice cover favoured particle sizes larger than those observed under the 2006 ice cover.. More importantly, however, the results from both annual data sets indicated that particle diameters were generally below or, at worst, close to the 0.8 mm threshold (at 546 kHz) associated with the upper limit of applicability for the steep Rayleigh concentration and size dependences. This circumstance offered a means for direct estimating particle concentrations by matching the observed return intensities, I(y), with expectations in terms of Eq. 2. The matching process involved only insertion of system parameters into the factor α of the simplified (a single term in the summation) form of the latter equation, and use of a single cross section, σ_{bs}, calculated from the Rayleigh scattering expression for particles with the corresponding diameter value inferred from the Rouse Law comparisons. This process was applied to obtain concentrations, N(y), of idealized particles at specific values of y during the two different time intervals corresponding to, respectively, the light frazil conditions which followed associated with the early portion of the 2006 post-stabilization period and a period approximately coincident with peak 2008 frazil intensities. The results for these two periods are given in Figure 7 and and Table 2, in terms of the frazil particle concentrations and fractional volumes occupied at each height. The uncertainties in the estimates may easily be as larg as 50% in particle diameter and a factor of two in concentration, largely on the basis of imprecise knowledge of numerical calculation parameters and differences between the actual and manufacturer-supplied values of transducer sensitivity and beam parameters. Additional but very small errors may be attributable to the use of the spherical particle assumption. Overall, the results, with concentrations ranging between, roughly, 10^5/ m^3 to 10^7 /m^3 and maximum fraction volumes reaching about 0.5%, were consistent with past estimates (Daly, 1994) although we have no evidence that the comparison data were obtained in environments closely resembling those at our Peace River monitoring site.

Nevertheless, the, weakly corroborated, but apparent successes of the tested method are consistent with the dominance of larger particles as determinants of both fractional frazil ice volume and SWIPS returns from particles small enough to be in the Rayleigh Law scattering regime. The noted failures in our tests, largely confined to the mid-March, 2006 period, are believed to be related to breakdowns in the relationships linking water column frazil to the lower ice cover. Evidence for such a breakdown may be available in low frequency 2005 SWIPS data (Figure 8) which showed evidence for equivalently anomalous water column targets in a similar mid-March period which was both preceded and followed by extensve periods in which such targets were NOT detected. These results and accompanying 2005 video data are consistent with episodic inputs of larger particles from the deteriorating ice cover which briefly overwhelm returns from the smaller particles which are dominant at other points in the season and are usually only detectable at higher SWIPS frequencies. In this view, the occurrence of similar breakdown events in 2006 would have produced the anomalous elevations of relative intensity noted in Figures 4 and 5.

3. Conclusions and Next Steps

The results presented above require detailed verification but appear to point the way toward quantitative SWIPS monitoring of river-suspended frazil in terms directly relevant to understanding, modelling and controlling freezing rivers. Further progress is likely to require fuller use of multifrequency SWIPS instruments and, possibly, other techniques for both verification and developing methodological refinements which offer population descriptions which go beyond the mean particle diameter and concentration profile outputs obtainable with our single frequency approach. More fundamentally, data are required relevant to the origins of the breakdown of this method in the mid-March, 2006 period. Progress in this direction is likely to require nothing less than understanding the dynamics of the lower ice cover which probably control the dramatic sensitivity of suspended frazil SWIPS returns to environmental parameters (Figure 2). The data (Figure 7) suggest that the great bulk of the ice transport beneath a stabilized ice cover takes place within 1 m of the nominal ice/water interface. SWIPS monitoring at high and low (ice-penetrating) frequencies, aided, in some cases, by simultaneous current and ice movement profiling, is likely to be required to provide the data on frazil particle properties and movements close to and, probably, beyond the latter interface needed to quantify this transport.

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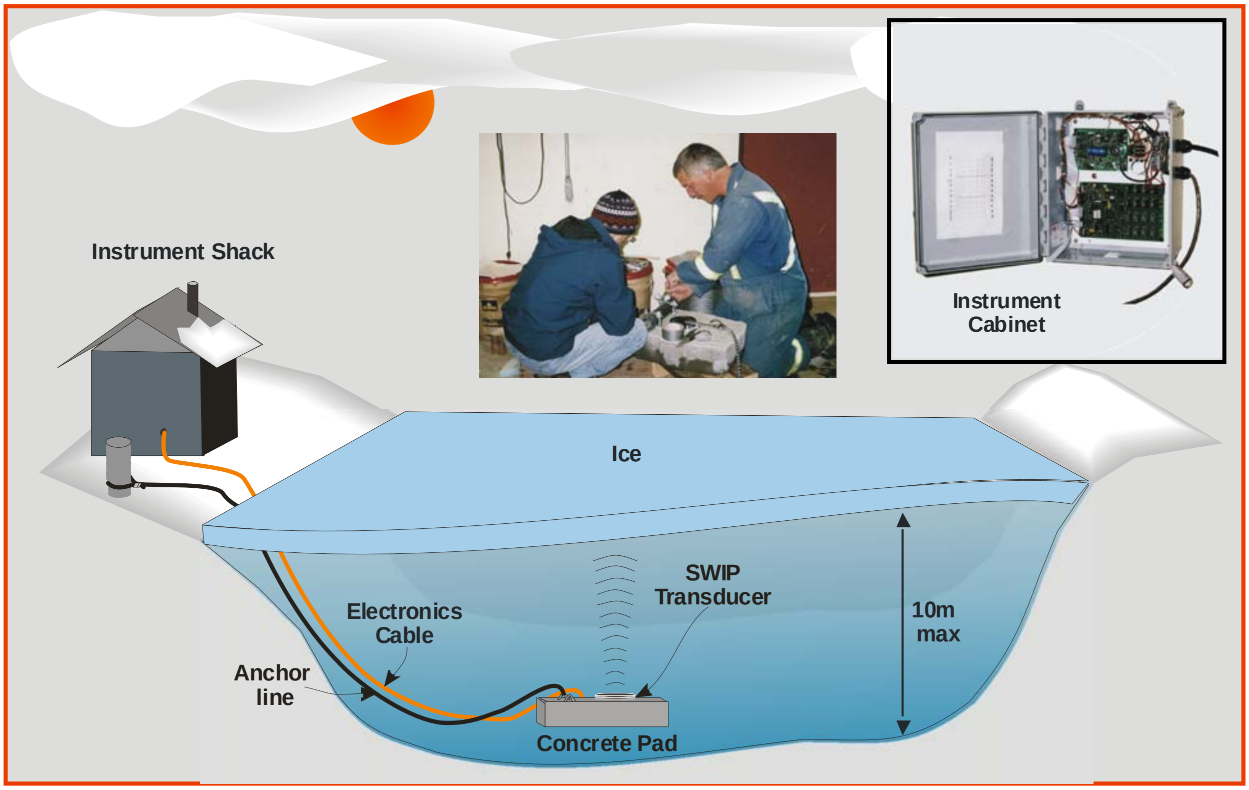

Figure 1. Typical SWIPS unit and data logger installation.

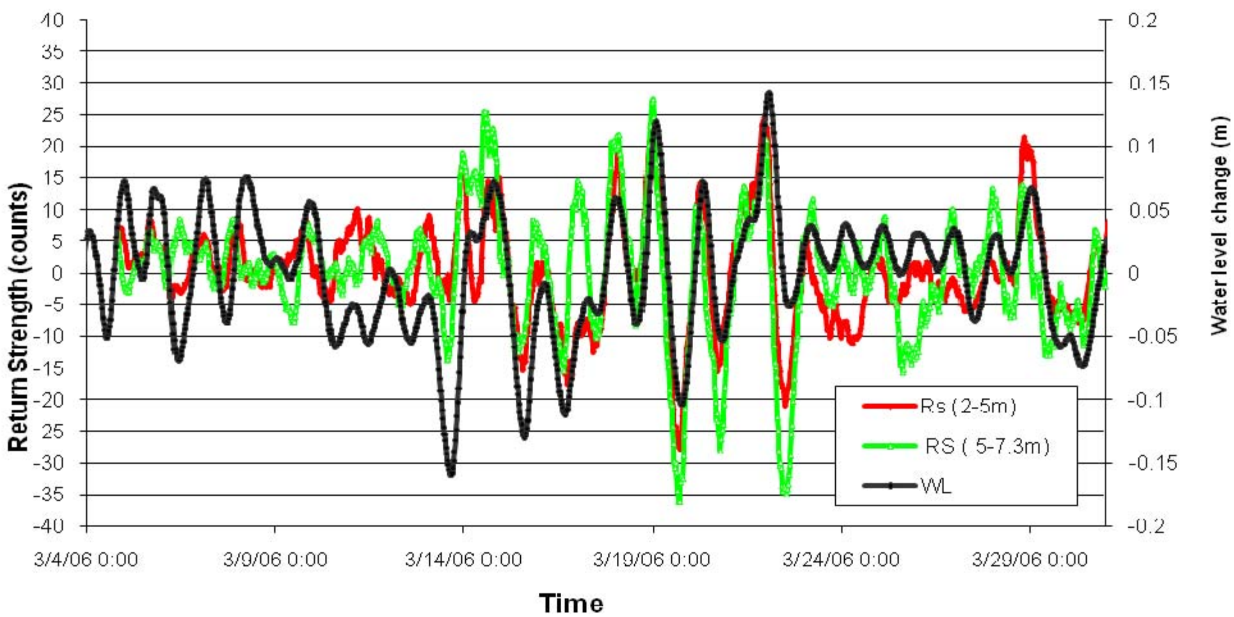

Figure 2. Time series plots of high frequency components of variability in local water level and mid- and upper-water column average return strengths.

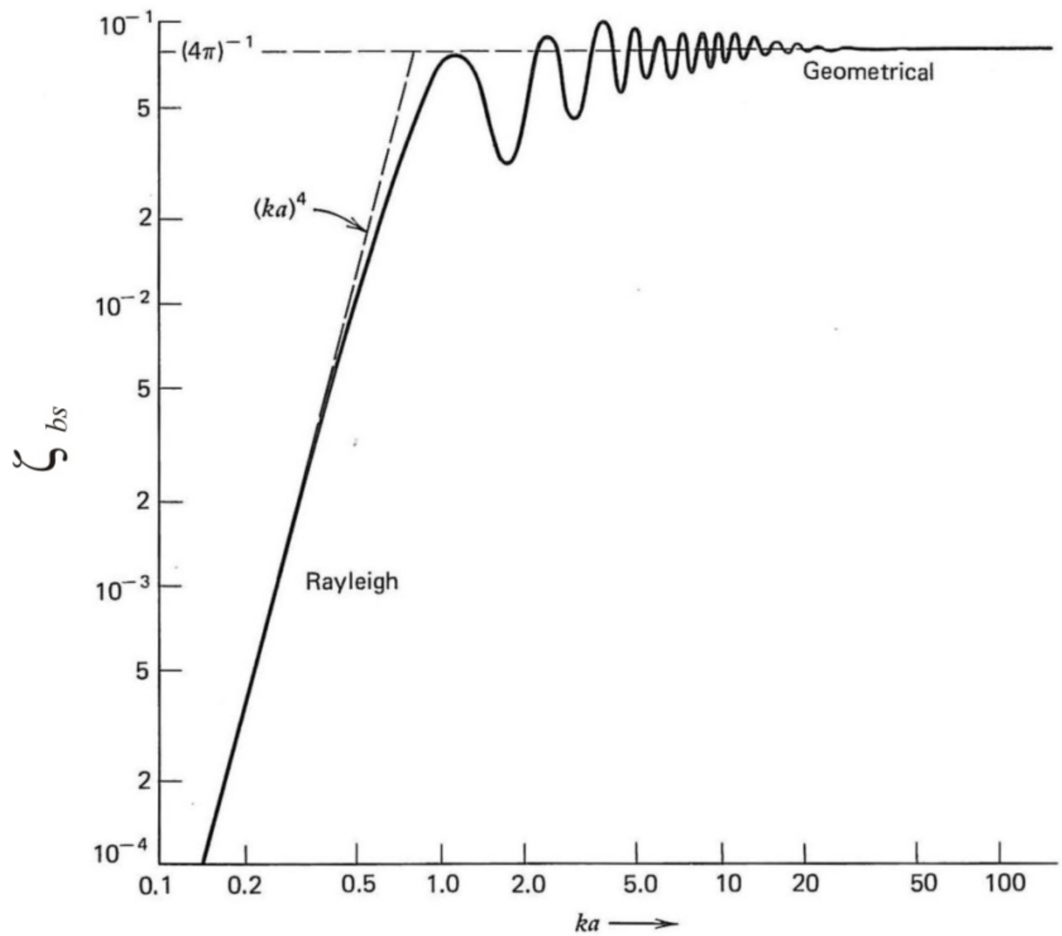

Figure 3. The backscattering function ($\zeta_{bs} = \sigma_{bs} / \pi a^2$)function of ka for a rigid sphere of radius a and an acoustic wavelength $\lambda = 2\pi/k$. (Clay and Medwin, 1977).

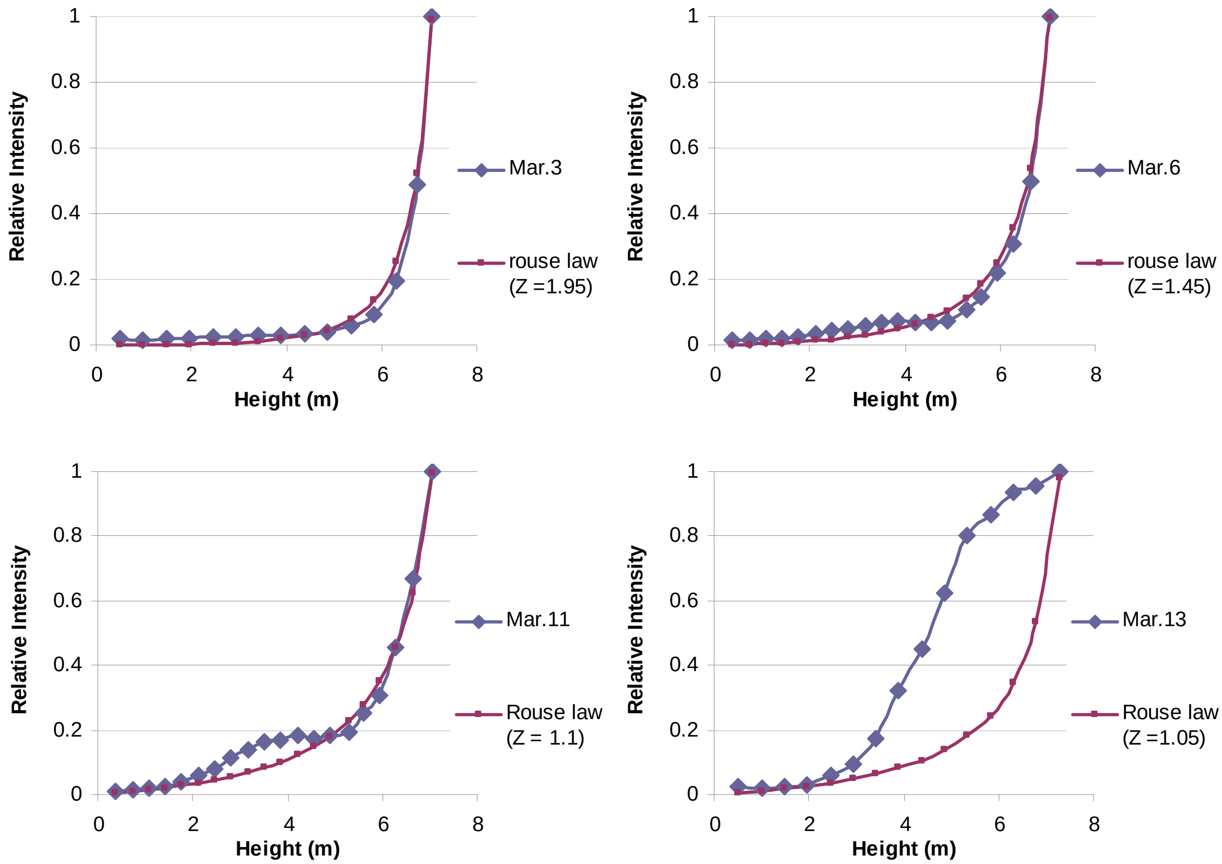

Figure 4. Observed relative return intensity as a function of height in the water column compared with relative particle concentrations as modelled with the Rouse Relationship (Eq. 1) for 4-hour periods in the first half of March, 2006 (March 3, 6, 11 and 13).

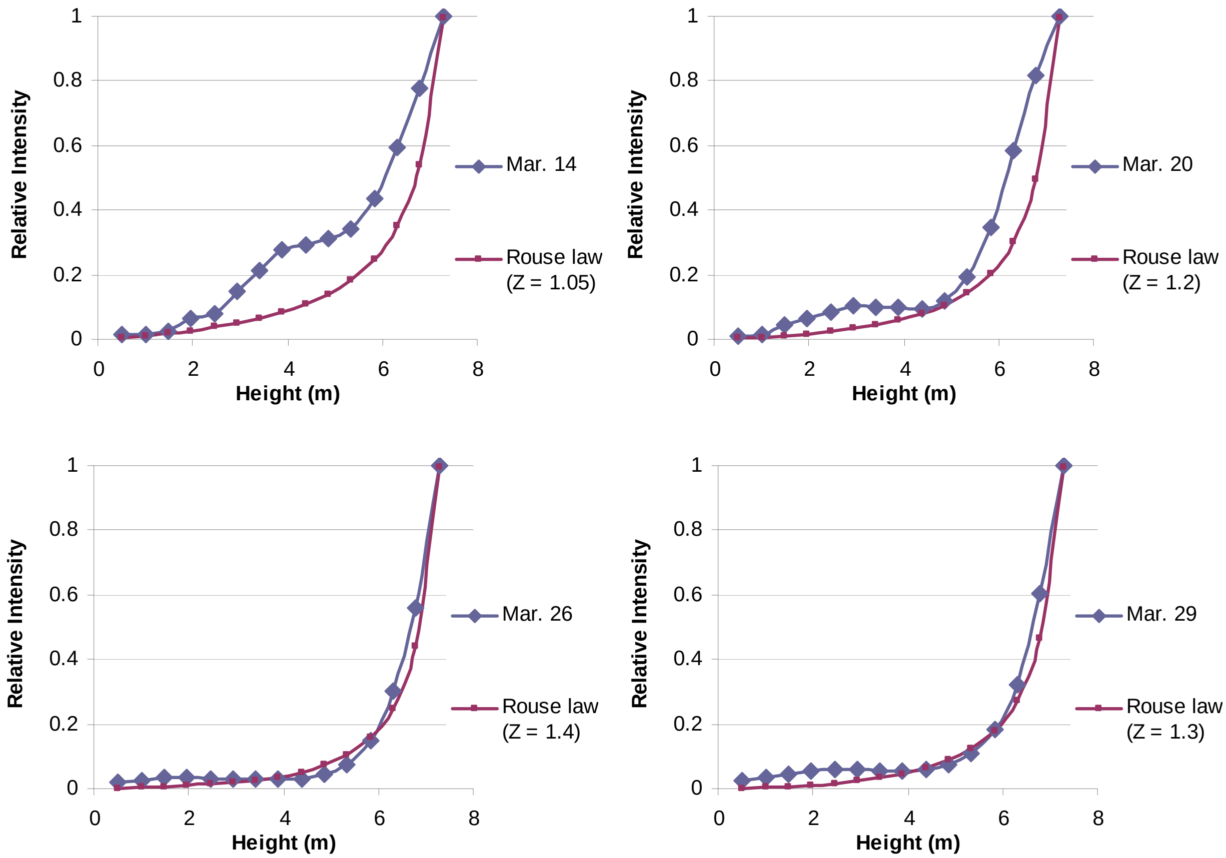

Figure 5. Observed relative return intensity as a function of height in the water column compared with relative particle concentrations as modelled with the Rouse Relationship (Eq. 1) for 4-hour periods in the latter half of March, 2006 (March 14, 20, 26, 29).

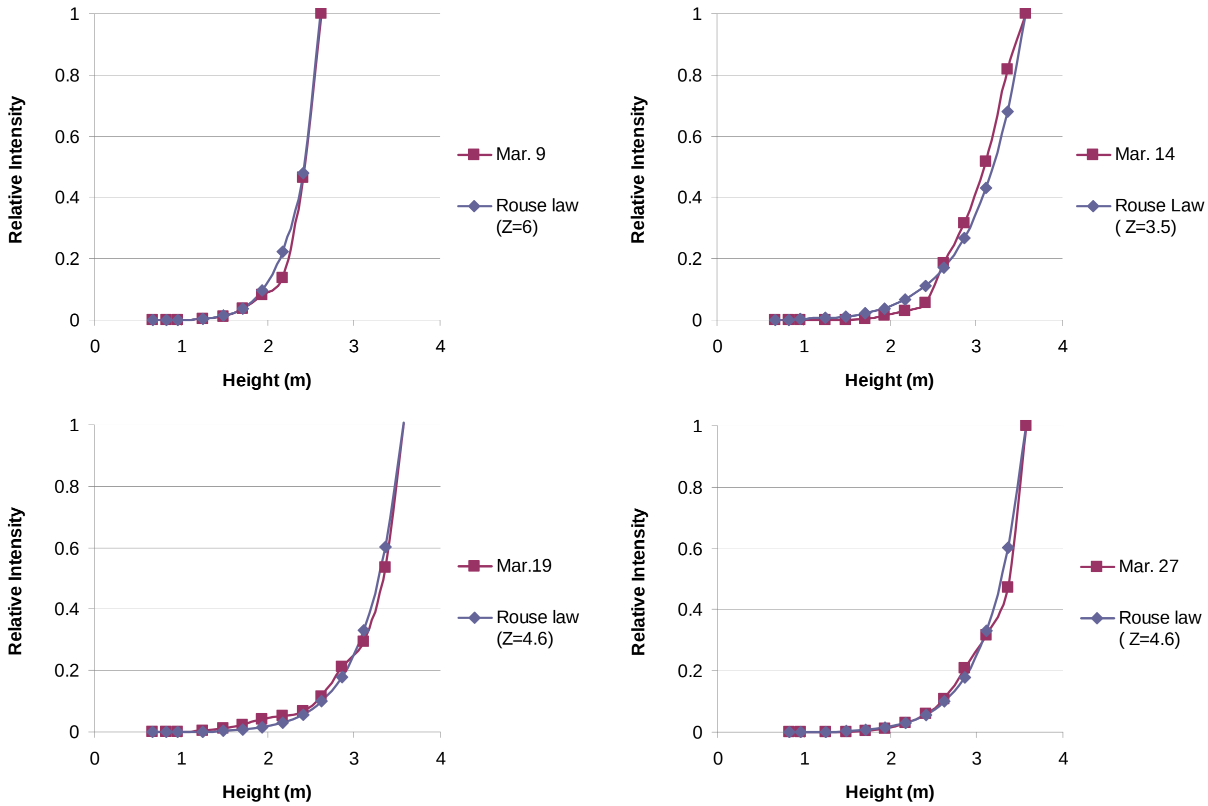

Figure 6. Observed relative return intensity as a function of height in the water column compared with relative particle concentrations as modelled with the Rouse Relationship (Eq.1) for 4-hour periods in March, 2008 (March 9, 14, 19 and 27).

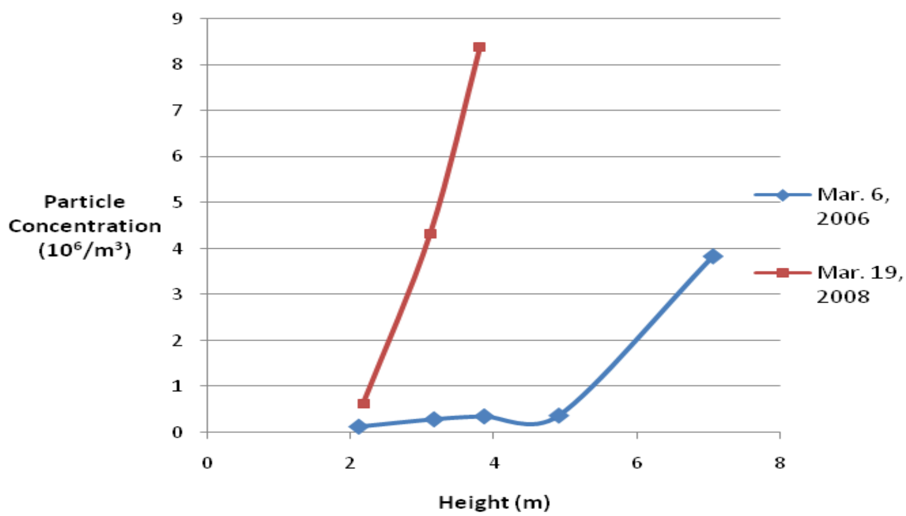

Figure 7. Estimates of frazil particle concentrations in units of $10^4/m^3$ at selected heights in on March 6, 2006 and March 19, 2008.

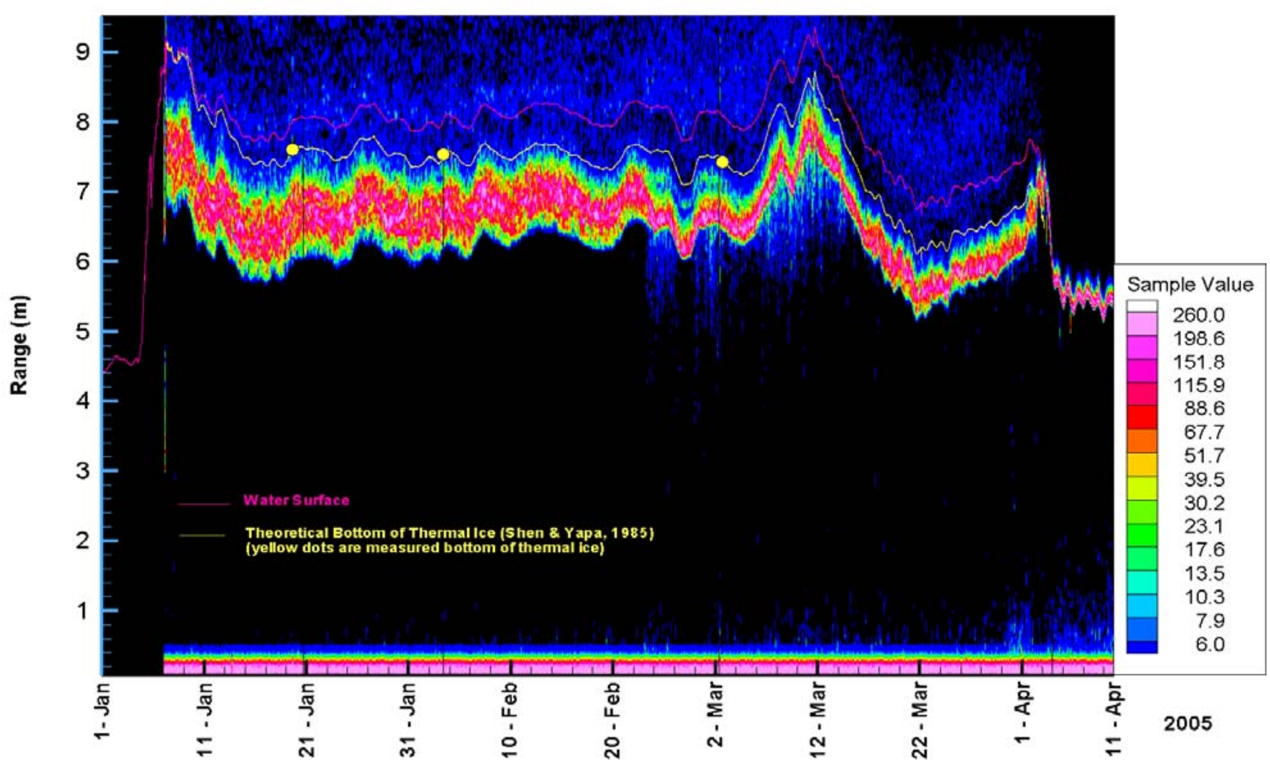

Figure 8. Two-hour-averaged (low (235 kHz) frequency) SWIPS profiles under January-April, 2005 stationary ice cover with water levels and estimated/modelled thermal ice boundary ranges.

Table 1. Rouse Numbers and corresponding calculated (from Eqs. 2 and 4) particle diameters for optimal Rouse matches to 2006 and 2008 relative return intensity vs. height data.

Date	Z (Rouse Number)	Diameter (mm)
March 3, 2006	1.95	0.49
March 6, 2006	1.45	0.42
March 11, 2006	1.1	0.36
March 26, 2006	1.4	0.41
March 29, 2006	1.3	0.40
March 9, 2008	6.0	0.86
March 14, 2008	3.5	0.66
March 19, 2008	4.6	0.75
March 27, 2008	4.6	0.75

Table 2. Estimates of fractional volume occupied by frazil particles at the indicated water column levels for the two indicated interval analyzed time intervals.

Date	Height(m)	Fractional Volume Occupied by Frazil (%)
March 6, 2006	4.9	0.004
March 6, 2006	7.05	0.04
March 19, 2008	2.18	0.04
March 19, 2008	3.11	0. 28
March 19, 2008	3.8	0.56