Suspended frazil ice detection using multi-frequency underwater acoustic devices

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Active frazil ice forms in large quantities during winter months on the St. Lawrence River. The paper reports of an intensive field sampling campaign at the Port of Québec during February and March 2009. Three underwater acoustic instruments are used at different frequencies to detect frazil ice in the water column. They include an Ice Profiling Sonar at 420 kHz, a High Definition Imaging Sonar at 900 kHz, and an Acoustic Doppler Current Profiler at 1200 kHz. The latter also provides water velocity profiles. Water temperature sensors, underwater cameras and a water conductivity sensor are also deployed on a platform on the bottom of the river. An underwater Remote Operated Vehicle (ROV) is used to obtain images of suspended frazil ice in the flow. Field sampling of the ice particles is also attempted using a custom made pumping system. This paper presents the instrumentation, the methodology and some preliminary results.
1. Introduction
The St. Lawrence River, near Québec City, experiences frequent active frazil ice formation during winter months. Beginning the winter of 2005-2006, this is Laval University’s third winter field instrumentation program aimed at studying suspended frazil ice. Field detection of frazil ice is very difficult but the use of acoustic instrumentations has recently proved very promising. This paper presents and describes the 2008-2009 field campaign and some preliminary results. The primary objective of the paper is to discuss the detection and quantification of frazil ice.

2. Study site
Figure 1 shows the previous and new study sites within the reach of the St. Lawrence River near Québec City. In 2009, the underwater instruments were deployed on the river bottom, 6 m from the Port de Québec dock no. 25, located on the river’s left bank. The water depth ranged from 12 to 17 meters during the study period. The Gulf of St. Lawrence is located some 550 km downstream of the study site. During flood tide, currents are totally reversed. At high tide, there is a salt wedge, normally considered to end approximately 40 km downstream of the site.

3. Instruments
Underwater instruments were mounted on a steel platform (1.5 x 1.5 x 1.1 -m) that was deposited on the bottom of the river on February 4th, 2009. It was recovered on March 19th 2009, giving a total of 43 days of data. The platform and its instruments are presented on Figure 2. Water temperature was measured at 5 minute intervals by 6 independent and different types of sensors. As the accuracy wanted to detect supercooling was within the order of a hundredth of a degree, redundancy is very useful to corroborate sensor measurement. The most accurate sensors used were thermistors that have an accuracy thought to be between 0.005 to 0.01 °C. Also, a multi-parameter probe provided water electrical conductivity (in addition to water temperature).

Two different acoustic profilers were deployed at the bottom of the river on the platform (Figure 2). The first instrument described here is the Upward-looking Ice Profiling Sonar (IPS4). This profiler operates at a frequency of 420 kHz. The particular instrument used has the capability to record vertical profiles of acoustic echo intensities. The second acoustic instrument used was a Broadband Acoustic Doppler Current Profiler (ADCP) that operates at a frequency of 1228.8 kHz, which is much higher than the IPS4. Although the main function of the ADCP is to measure local current profiles, the instrument can also record echoed amplitudes profiles and is capable of detecting interfaces at the surface (water/ice and water/air). The two instruments’ configurations are given in Table 1.

On March 13th 2009, a field measurement trip was made on an ice canoe. It was intended to obtain real time optical and acoustical images of frazil ice particles within the flow (using the ROV equipped with strong lights, camera and the high definition imaging sonar) and to pump those particles using a custom-made frazil ice pumping system. The sonar used operates at 900 kHz, which value is within those of the two other acoustic instruments previously presented. Figure 3 shows the ice canoe, the ROV and the pumping system. Although the sonar is not visible in Figure 3, it is mounted on the bottom of the ROV.

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1 The underwater camera mentioned on Figure 2 was an attempt to obtain images of frazil ice to compare to the acoustic backscattering, but the camera experienced a malfunction and no images have been recovered.
4. Background on underwater acoustics

Frazil ice can be efficiently detected by acoustic waves (e.g., Jasek and Marko, 2007; Morse and Richard, 2009). Further, the simultaneous use of multiple frequencies could also provide estimations of the size distribution of the particles, as well as their concentration. Volume backscattering strength (noted $S_v$ and expressed in dB) is the logarithm in base 10 of the ratio of the intensity of sound scattered to the incident sound intensity for suspended matters. Computation of this parameter requires knowledge of a certain number of parameters related to the equipment, the medium and the target. These are related together by the well known sonar equation:

$$ EL = SL - 2TL + TS $$

in which $EL$ is the received echo level, $SL$ is the source level, $TL$ are the transmission losses and $TS$ is the target strength. For the purposes of this study, parameters specified by the manufacturers are assumed to be sufficiently accurate and realistic estimates. Based on [1], two different equations were used for the IPS4 and the ADCP because their equipment are different. For the ADCP, a very detailed procedure is described (and was used) in Deines (1999) to convert $EL$ to $S_v$. On the other hand, the IPS4 recorded echo intensity were converted to $S_v$ using the equation proposed by Lemon et al. (2008). The specific parameters for both the ADCP and the IPS4 were obtained from their respective manufacturers.

5. Results

5.1 General overview of the data

Significant supercooling events were measured 6 times during the 43 days of deployment. As previously mentioned, it is important to note that, as the river is subject to tidal fluctuations from the Gulf of St. Lawrence, a salt wedge is present and generally assumed to be located almost 40 km downstream of the instruments. Given the importance in the present study of knowing accurately the freezing temperature of the water, water electrical conductivity was measured and used to compute the local water salinity. Water salinity computed at the site varied between 0.12 and 0.15 ‰ depending on the tidal state. With the computed salinity values, albeit rather low, this could yield to a drift in the freezing point estimated to be at the worst 0.008 °C below zero.

Although active frazil ice occurred only a few times during the deployment, the ADCP and the IPS4 data detected at least six additional events when water temperature was not supercooled. It was also observed that both instruments do not always detect particles simultaneously, that is, one instrument could be “virtually” blind while the other is not. Minimum detectable particle size depends upon the acoustic frequency used. Normally, the scattering strength is at a maximum when the radius ($r$) of the particle is at least equal to the inverse of the acoustic wave number (that is, $r = \lambda / 2\pi$, where $\lambda$ is the wavelength). For particles having a smaller radius, the scattering strength decreases very rapidly ($\propto r^6$ assuming Rayleigh’s law). A rough estimate of the critical particle dimensions for the acoustic frequencies used in this study would be that the minimum nominal detectable diameters are approximately 1.1 mm and 0.4 mm for frequencies of 420 kHz and 1228.8 kHz respectively. The sonar, at 900 kHz, would be in between, with diameters approximately of 0.5 mm.
5.2 Selected frazil ice event

The strongest active frazil ice event will be presented and briefly discussed. The event occurred on the evening of February 9th 2009. Figure 4 presents the important parameters that were measured during that event. The first subplot shows the water level (blue line) and the ice/water interface (black line) as computed from the IPS4 acoustic return travel time and backscattering strength. The event occurred during the ebb tide with virtually ice-free surface, as did all others.

The second subplot shows the actual degree of supercooling (\(\Delta T_w\)) reached by the water. The maximum supercooling reached is approximately \(\Delta T_w = -0.025^\circ C\). This value is small compared to values obtain in the laboratory; nevertheless, it is somewhat typical of values observed in the St. Lawrence River (Richard and Morse, 2008).

The third subplot depicts the water velocity measured by the ADCP within the water column. Velocities having negative values mean that the current is actually directed upstream (thus during the flood tide), whereas positive values mean that the current is directed downstream, during ebb tide. The strong currents along with cold air temperature (between -14.5 and -17.2 \(^\circ C\)) and strong winds at that time were likely indications of probable supercooling.

The fourth subplot shows the volume backscattering strength of the ADCP (\(S_{v,1228 \text{ kHz}}\)) computed from the echo intensity. It seems that the instrument measured significant backscattering intensity prior to the event for approximately 30-40 minutes. Note that this occurred when the currents were at their maximum. When water became supercooled, the intensity rose somewhere between -15 and -20 dB. As the water current slowed down, \(S_{v,1228 \text{ kHz}}\) decreased, especially near the bottom, although it seems to decrease near the surface also, but not as much. This could be explained by the rise of the particles towards the surface. Reduced water currents, along with low supercooling, may also significantly reduce the frazil ice production rate. There was also a short period when the backscattering intensity was very low after which the water temperature dropped sharply towards its minimum (maybe as a result of the reduced production rate of frazil that causes less heat transfer to the water) and the backscattering intensity peaked up again through the entire vertical profile. Significant intensity stopped being detected when the water temperature started to rise from its minimum value.

Finally, the last subplot depicts the volume backscattering strength of the IPS4 (\(S_{v,420 \text{ kHz}}\)) computed from the echo intensity. What is the most startling, when looking at this subplot, is that the backscatter intensity was nowhere as significant as that of the ADCP. However, as was previously discussed, the IPS4 did respond well in other times throughout the deployment and during those times, the backscatter was significant. It is not thought that the instrument experienced a malfunction. This suggests that particles were mostly smaller than the minimal nominal size detectable by the IPS4 at 420 kHz.

5.3 Frazil ice detection by the ROV and the sonar (900 kHz)

The 900 kHz sonar could not have been deployed along with the two other instruments as it is not designed to do so. However, it was mounted on the ROV to compare both optical images from its cameras and the acoustical echoes from the sonar. Figure 5 shows images of frazil ice that were taken by one of the ROV’s camera and its equivalent sonar image. The ROV was
manoeuvred in the flow, in the middle of the river, into what is thought to be passive frazil ice. On the bottom sonar image, some return signals are seen but they seem simply to be noise².

5.4 Theoretical frazil ice particle number densities from volume backscattering strength

Theoretical frameworks exist that could allow a crude estimation of the relation between particle number densities and the volume backscattering strength, without in-situ calibration. Let us estimate particle number densities from the ADCP data showed in Figure 4. For volume and incoherent backscattering, the backscattering strength arithmetically adds up for every scatterer, and, so, the target strength ($TS$) is closely related to mass concentration. The number of particles ($N_v$) within the ensonified volume of a cell ($V$) can be computed using equation [1] (when using specific values for the acoustic instrument – here, the ADCP) when replacing the target strength by (Tessier et al., 2007):

$$TS = 10 \log_{10} \left( \sigma_{bs} N_v V \right)$$  

[2]

into which $\sigma_{bs}$ is the mean backscattering cross-section of frazil ice particles (in m$^2$). A theoretical cylinder approximation George and Bahl (1995) is assumed $\sigma_{bs} = rt^2 / 2\lambda$ where $r$ is the radius and $t$ is the length of the cylinder. The ensonified volume ($V$) depends upon the instrument used. The particle number density of frazil ice in natural freshwater is expected to be in the order of $10^6$ particles per m$^3$ (Daly, 1994). Figure 6 shows computed values of $N_v$ assuming three different mean particle diameters (respectively 1, 2 and 3.15 mm) and assuming a constant diameter to thickness ratio of 15. Results seem to be within the same range with values between $1 \times 10^7$ and $5 \times 10^7$ m$^{-3}$, depending upon the assumed diameter. The analysis could be improved and refined in a lot of ways but nevertheless, this approach could be promising.

6. Discussion

Acoustic instruments offer very good possibilities in frazil ice detection, and the use of multi-frequencies could greatly help in assessing the size distribution of the crystals. Data that could be extracted from such instrumentation could really provide a comprehensive insight on frazil ice dynamics. The ADCP used at 1228.8 kHz offers numerous advantages: (1) it measures the water velocity; (2) it measures the echo of the acoustic pulse; (3) it can profile depth with a good definition; (4) it has four beams to offer redundancy and assure the best correlation within the measures; (5) it can detect particles as small as roughly 0.4 mm because and (6) it can measure the ice thickness (although not as accurate as the IPS4) and surface ice velocities. Operating at a higher frequency however limits the operating range to depths less than say, 20 meters. The IPS4 (at 420 kHz) also offers most of those possibilities, yet the lower frequencies allow the instrument a larger depth of operation should they be needed. On the other hand, it does not detect particles as small as those detected by the ADCP. The use of only one or the other of those instruments is interesting, but somehow restricting. Generally, the more frequencies used, the best estimate of the size distribution of the scatterers might be.

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² This is deduced by comparison with the measured intensities when the sonar was not submerged.
Acoustic instruments combined with a good field sampling program to obtain valid and accurate field calibration with frazil ice crystals could yield major advances in frazil ice detection. The main difficulty is to assess how to efficiently sample frazil ice and obtain non-destructive measurements. Doing that might require that the measurements are done very rapidly on-site (or even better, in the water) as when crystals are exposed to cold air, they transform rapidly.

7. Conclusions
Acoustic devices can detect frazil ice efficiently. When using a single frequency, it is suggested to use the maximum frequency possible (depending on the maximum local water depth) in order to “see” particles as small as possible. Also, using multiple frequencies in combination with accurate water temperature measurements could provide valuable insights on frazil ice evolution, size distribution and vertical concentrations in natural water bodies. The use of underwater cameras (such as the ones on the ROV) could be efficient to obtain field optical image of frazil. Theoretical frameworks can also provide interesting ways of analyzing the data. However, it is thought that good and accurate field sampling would be of inestimable value for calibrating the acoustic response to frazil ice of different size at different frequencies.

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References


Table 1. Acoustic Instruments configurations.

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<th>IPS4</th>
<th>ADCP</th>
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<td>1 ping ensemble every minute</td>
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<td>Transmit pulse length (µs)</td>
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<td>143</td>
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</table>
Figure 1. Study site within the Québec City area (images from Google Earth™).
Figure 2. Platform and the instruments deployed underwater.
Figure 3. The ice canoe and part of the team (top left); the ROV and the sonar being prepared to dive (top right); the custom made frazil ice pumping system (bottom left) and a view of the surroundings of the ice floe with the Québec bridge in the background (bottom right).
Figure 4. Overview of the February 9th event.
Figure 5. Frazil ice particles within the flow caught by one of the ROV camera (top left) and by the sonar mounted on the ROV (top right) and comparison of equivalent images when no frazil ice is present in the water column (bottom left and right).
Figure 6. Theoretical particle number densities (for the same event as Figure 4) computed from the volume backscattering strength of the ADCP (colorbar units are number of particles per m$^3$) for: (top) an assumed mean crystal diameter of 1 mm (maximum densities in the order of $5 \times 10^7$ particles per m$^3$); (middle) an assumed mean crystal diameter of 2 mm (maximum densities in the order of $2 \times 10^7$ particles per m$^3$) and (bottom) an assumed mean crystal diameter of 3.15 mm as reported in Morse and Richard (2009) (maximum densities in the order of $1.1 \times 10^7$ particles per m$^3$).