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Advances in Marine Ice Profiling for Oil and Gas Applications

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ABSTRACT

Upward-looking sonar (ULS) is a primary source of data for measurements of ice thickness. Self-contained units now have the data capacity and accuracy/resolution sufficient for unattended operation over periods of months to years. Recent technological advances have now led to the next generation of ice-profiling sonar (IPS), incorporating much expanded on-board data storage capacity (69 Mbytes to 8 Gbytes) and powerful onboard real-time firmware. The enlarged data storage of the newest ice profilers enables collection of ocean wave data during periods of open water in summer. Semi-automated detection of open water in the form of short duration occurrences of ice leads is now possible. The capability to derive acoustic returns from a range of levels in the water column and the lower part of the ice cover hold promise for improving understanding of processes occurring during the initial freeze-up and early consolidation phases of sea ice growth and for detection of ice properties in the keels of consolidated ice.

KEY WORDS: ice keels, acoustics, sonar, waves, thickness

INTRODUCTION

Since initial developments in the mid 1970's, advances in acoustic profiling technologies have allowed ever more accurate and information-rich extraction of data on the draft, undersurface topography and immediately adjacent water column environment of polar and other marine and freshwater ice covers. The initial motivation for such developments was to replace and improve upon other, often inconvenient, expensive and/or otherwise unsatisfactory methodologies. Such methodologies originally included the use of upward looking sonar sounders mounted on U.S. and British submarines as well as deployments of airborne- sensors such as laser profilometers and electromagnetic induction instrumentation. These airborne measurement approaches still involved considerable logistical costs and efforts and yet were characterized by intrinsic limitations in accuracy and scale which significant degraded data quality relative to that obtainable from submarine-based acoustic sounders.

The more modern acoustic profiling technologies were based upon instrumentation designed to be deployed 25 to 50 m below the air water interface from sea floor based moorings (Figure 1) or, in shallower water, from bottom-mounted platforms. In its most extensively productive form (Melling et al., 1995) the instrument operated by emitting and detecting surface returns from frequent short pulses (pings) of acoustic energy concentrated in narrow beams (less than 2° at half power). Precise measurements of the delay times between ping emission and reception were converted into ranges separating the instrument's transducer and the ice undersurface. Contemporary data from the instrument's on-board pressure sensor were then combined with atmospheric surface pressure data and estimates of the mean sound speed in the upper water column (obtained from data collected during absences of ice above the instrument) to derive estimates of ice draft from each emitted ping.

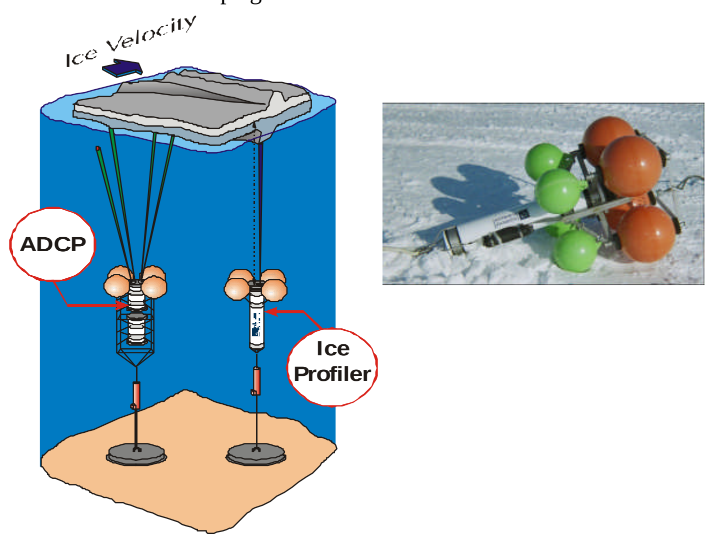

Figure 1. A typical deployment arrangement of an ice profiler and ADCP ice velocity measuring instruments on separate, sea floor-based, moorings.

When deployed under moving ice fields with adjacent upward-looking ADCP (Acoustic Doppler Current Profiler) instruments (Figure1) with capabilities for extracting of ice drift velocity, the obtained data could be used to construct two dimensional cross-sections of the ice cover (Figure 2), designated as quasi-spatial profiles. With careful processing these products could depict detailed variations in the depth of the lower ice surface with a horizontal resolution of about 1 m and an accuracy in the vertical of 5-10 cm. Keys to the utility of the technique were its on-board data storage capacity and capabilities for reliable long term un-attended operation in the hostile environments usually associated with ice covered waters. Until recently, principal users of this technology have been polar ocean scientists with interests and concerns regarding climate change and, increasingly, international oil and gas producers with deployments throughout the Arctic Ocean and in sub-polar seas (Figure 3)

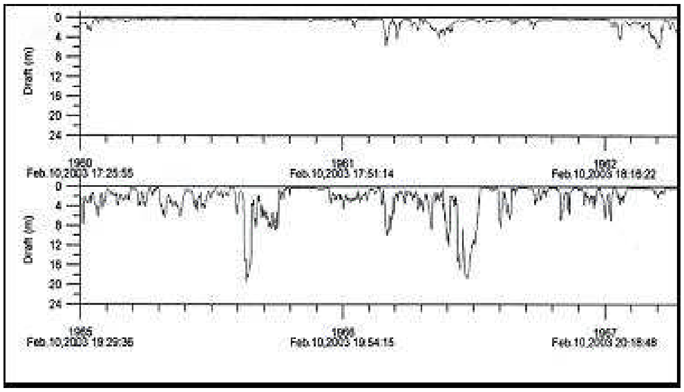

Figure 2. A quasi-spatial profile of an ice cover produced by combining time series draft and ice speed data to produce a product equivalent to the profile of the ice undersurface along a line traced out by all points on the ice which move over the ice profiler instrument during the measurement period. The abscissa is in kilometers, annotated with time of observation.

Ice science studies have largely been centered on collecting draft data over areas of sufficient extent and duration to be able to understand ice-cover processes and to identify trends and their relationships to key driving environmental factors. To date, major deployments of multiple instruments over periods up to and beyond a decade have been made in key areas such as the Beaufort Sea, and Fram Strait. The Beaufort Sea data have been productively used in understanding how ice cover evolves in response to dynamic and thermodynamic forcing. It is interesting that monthly ice-draft anomalies, or deviations from the 12-year monthly mean, (Figure 4) for annual pack ice in this area reveal no evidence of consistent change during 1991-2003, a period associated with atmospheric warming and decreasing ice volume in the Arctic Ocean overall.

There is much interest in further developments of the profiling technology which would allow similar simultaneous study of less accessible Arctic Ocean regions such as north of the Canadian Arctic Islands and in the Ocean's deep basins. Progress in these regards will require developments in profiler capability (i.e. increased data storage capacity, lower power consumption, "smarter" on-board systems) and in deployment and data recovery technologies (i.e. means for remote downloading of data from temporarily inaccessible instruments) and adaptation to dedicated mobile data collecting platforms such as submerged drifters, AUVs etc.

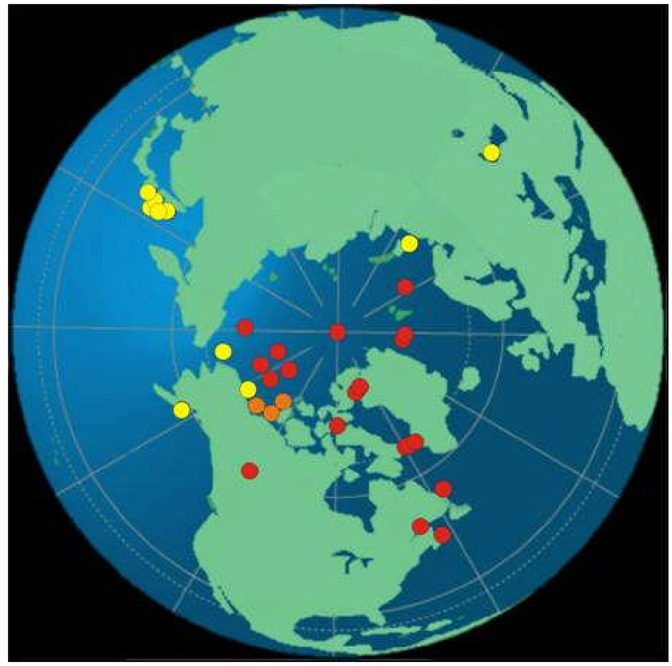

Figure 3. Locations of marine moored ice profiler deployments in the Northern Hemisphere from 1996 to the present. Ice profiler locations for scientific applications are shown by red and orange symbols while oil and gas locations are shown by yellow symbols. The orange symbols designate the locations of long term ice profiler measurements in the Beaufort Sea of the Dept. of Fisheries and Oceans (Dr. H. Melling) which have been used by oil and gas companies.

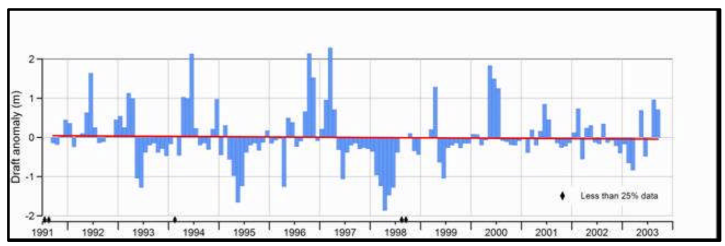

Figure 4. Anomalies in mean monthly ice drafts as measured in the southern Beaufort Sea over the period 1991-2003. The red line is the linear trend, statistically indistinguishable from zero.

Oil and gas applications of acoustic profiling have usually been more constricted in time and space, focusing upon getting as accurate as possible characterizations of the ice cover in a particular exploration region and season of interest. Larger scale issues such as trends in behavior in adjacent areas and over timescales larger than a decade or so tend to be considered as uncertainties which will eventually be resolved by the more scientifically-directed studies outlined above. It is implicitly recognized that the scientific results may force later modifications of conclusions drawn from the industry-sponsored smaller scale studies and expectations are that the general sense of such changes (i.e. improving or worsening conditions) will have become apparent by the time the smaller scale results are integrated into planning and design actions.

In the following we outline the nature of the issues addressed in past oil and gas related ice profiling studies, concentrating on identifying the key items of interest and the remaining uncertainties in the derived products. It will be noted that essentially all of the data gathered in this regard was obtained with "first generation" profiling instrumentation of the type initially introduced by Melling and coworkers (1995). The additional features of a recently introduced (by ASL Environmental Sciences Inc.) "next generation" IPS5 (Ice Profiling Sonar) instrument will then be briefly described prior to discussion of the observed and potential benefits offered in oil and gas related applications.

MARINE ICE PROFILING RELATED TO OIL AND GAS APPLICATIONS

Oil and gas requirements for ice data from sonar are associated with draft/thickness, the detailed underwater topography of ice keels and the simultaneous measurement of ice velocity. Other ice characteristics, such as ice type and strength are of great interest but have thus far proven to be problematic via acoustic remote sensing. Measurement via manual drilling and on-ice inspection remains the state of the art for such parameters.

In the first category of needs, first generation profilers such as ASL's IPS4 instrument (Figure 2) have shown capabilities for 95% recoveries of instrument and data in all major global marine environments (Figure 3) including the now more than a decade's use in areas east of Sakhalin Island, and in more recent and ongoing programs off in the Canadian and Alaskan Beaufort Seas, in Cook Inlet, in the Caspian and Pechora Seas as well as in the shipping routes of the Northwest Passage, the St. Lawrence Seaway and Northumberland Strait.

Processing and analysis of the Ice Profiling Sonar and Acoustic Doppler Current Profilers (ADCP) instruments (Birch et al., 2000) are carried out, first separately, and then combined to provide quasi-spatial profile records such as depicted in Figure 2.

Ice Profiler Data Products Presently Used for Oil and Gas Applications

Since the inception of the modern ice profilers, in the form of the ASL model IPS4 Ice Profiler introduced in the mid-1990's, methodologies have been developed to provide specific data products for application to offshore oil and gas activities. Prior to, and during oil and gas exploration activities in ice infested waters, the IPS and ADCP sonars are operated over successive ice years to provide input data useful for establishing design criteria for production platforms in specific exploration lease areas and for selection and design of operational methods and approaches for exploration and production activities.

The data analysis products for oil and gas applications are derived from the detailed time- and quasi-spatial- series of underwater ice topography, having typical resolutions of 1-5 seconds in time and 0.5 - 2.5 m in horizontal resolution. These data products include:

(a) Statistical Distributions of Ice Drafts: Given the very large size and high resolution inherent in the ice draft data sets, statistical distributions of the ice drafts over monthly, seasonal, yearly or multiple yearly intervals are derived. These distributions are very useful in characterizing the local and regional ice regimes for engineering design purposes.

(b) Statistical Distributions of Ice Velocities: Statistical distributions of the ice speeds and directions over monthly, seasonal, yearly or multiple-yearly intervals are very useful in characterizing the local and regional ice regimes for engineering design purposes.

(c) Frequency of Occurrence of Very Large Ice Draft Features: Using specialized software, ice keel features having maximum ice drafts exceeding user-specified values (e.g. 5, 8 and 11 m) are identified and stored in a database. In the mobile ice of the Arctic Ocean, several thousand such ice keels are typically identified within any given year (Figure 5). Statistical summaries of the identified ice keel features are then compiled and presented for the parameters such as: numbers of ice keels; average and maximum ice drafts; average and maximum ice keel lengths; total distances occupied by ice keel features; and number of occurrences of and total distance occupied by open water and very thin ice.

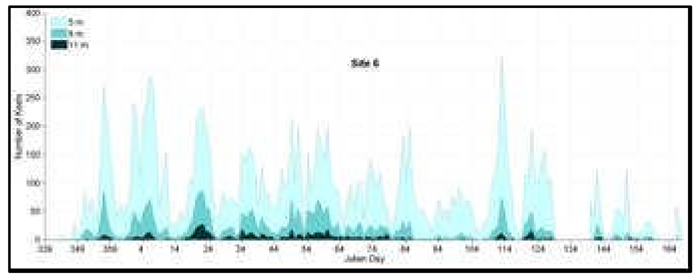

Figure 5: A plot of the number of keels each day, one of many parameters in the large ice keel database that can be automatically computed from over winter Ice Profiler data sets.

(d) Statistical Distributions of Extremal Ice Draft Features: Using the database of the very large ice draft features and the applicable probability distributions, as described above, estimates are derived for the extreme value of ice keel drafts for long-duration recurrence intervals, typically once every 10, 25, 50 and 100 years. As the duration of the database of Ice Profiler keel features increases, the confidence levels in the estimates of extremal ice draft values over very long recurrence intervals is improved and uncertainty levels are correspondingly reduced.

(e) Characterizations of the Geometry of Ice Keel Features: For very large individual ice keel features, the actual keel shapes are fitted to idealized keel geometries (Figure 6) involving simple symmetrical shapes about the maximum keel draft. The distributions of the keel geometric parameters are useful for input to engineering loading models of individual ice keels with platforms.

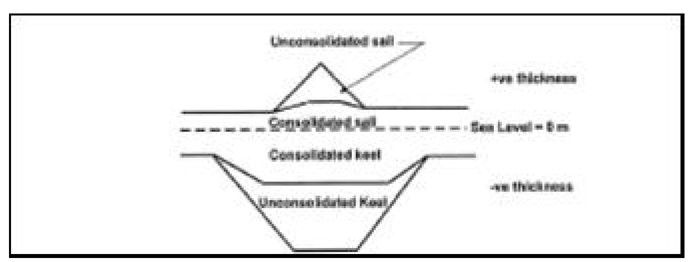

Figure 6: Actual Ice Profiler keel features, such as those shown in Figure 2, can be fitted to idealized geometry with characteristics as shown.

(f) Properties and Statistics of Hummocky and Rubble Ice Features: Statistical characterizations have been developed to distinguish between "hummocky" and "ridged" portions of the ice cover. Distinctions between these two categories are not easy to establish and are based on the underlying deformation mechanism for each ice type: with hummocky ice originating primarily from compressive events which force adjacent floes to ride up or slide over each other while ridged ice tends to arise from more drastic events in which floes are crushed and turned so that their original planes are oriented well off the vertical direction to produce more linear and more localized deformations which are usually more extensive in the vertical dimension.

The classification process was taken from earlier analyses of Sakhalin data (Marko et al., 2003) carried out to identify the potential effectiveness of Radarsat imagery in identifying regional ice types and drafts (Figure 7). In that work, a very large portion of the late winter, 1997 Sakhalin ice field was identified which was characterized by anomalous distributions of both IPS4-measured draft values and corresponding radiances on contemporary Radarsat images. This ice appeared in the outer (eastern) portion of the regional ice cover after a short period of very strong onshore winds which closed pre-existing nearshore polynyas and compressed the regional ice cover against the east coast of Sakhalin Island.

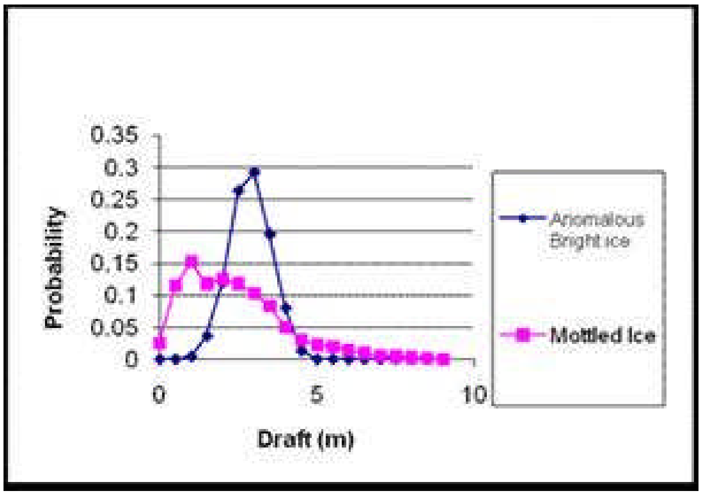

Figure 7: Examples of the Ice Profiler ice draft distributions for hummocky and rubbled ice cover off the east coast of Sakhalin (Marko et al., 2003) as used in identifying regional ice types and drafts in conjunction with Radarsat satellite imagery.

(g) Properties and Statistics of Open Water and Very Thin Ice Occurrences within the Ice Pack: Thin ice and occasionally open water can occur throughout the winter and spring, especially in marginal and seasonal ice zones. Knowledge of the frequency and duration of such occurrences is important for design and operational issues such as emergency evacuation of drilling platforms. The high resolution of the Ice Profiler time series makes these data well suited for the identification and characterization of thin ice and open water. Distinguishing between thin ice (< 10 cm and open water) emphasizes the need for very accurate characterization of the seasonally changing speed of sound in sea water; accuracy of this parameter ultimately determines the accuracy of the ice draft relative to the zero (open water) level. On average, the acoustic target strength (via scattering) of open water is considerably (up to 18 dB) larger than that of medium first-year ice. Although stochastic fluctuations in target strength are large, differences in average target strength may provide a means of distinguishing ice and open water having large (several hundred metres) extent. (The advanced features provided by the latest generation of Ice Profilers offer new capabilities for distinguishing open water from ice, as discussed below.)

(h) Occurrences and Durations of Ice Pressure Events: Ice pressure events arising from large internal ice stresses which inhibit movement of the ice pack are of considerable importance for both design inputs on structures and for operational planning. To detect possible occurrences of ice pressure events, the time-series plots of the ice drafts can be manually reviewed in conjunction with plots of the corresponding ice velocity. Time segments, having durations of at least one hour, with the following characteristics are identified:

- ice drafts with the signature of low speeds (constant or very slowly changing ice drafts over tens of minutes) and
- segments of the ice velocity time series having very low speeds (< 2 cm/s),

The time segments are then considered as candidates for pressure events by considering the degree of non movement with the underlying forcing exerted on the ice pack in the form of measured ocean currents and surface winds. From these considerations and analyses, actual ice pressure events can be identified and characterized.

(i) Occurrences, Durations and Statistical Properties of Wave Motion of Sea Ice: Ocean waves are an important feature of the seasonal ice pack especially in the early and later portions of the ice season and in the peripheral areas of the ice pack throughout the ice season. The Ice Profiler data can be analyzed to characterize wave motion both in open water and in pack ice. For these events, the wave spectra and non-spectral wave parameters (significant ice wave height and peak period) can be determined. The draft of the sea ice itself is also determined for wave-in-ice events. The principal effect of sea ice hosting propagating ice-ocean gravity waves is generally observed in attenuation of the higher frequency (shorter wavelength) modes of the wave spectra.

(j) Development of Ice Velocity Empirical Models due to wind and ocean current forcing: The Ice Profiler and ADCP data sets, along with nearby wind measurements provide the basis for development of empirical models of ice velocity response due to ocean current and wind forcing. The uppermost bins of the ADCP current profiles provide simultaneous measurements of the near surface ocean currents while the local winds are also an important driving force for ice movements. Based on seasonal ice, ocean current and wind velocity data sets, optimal weighting factors of the wind and near-surface ocean currents on the ice velocities can be computed (Figure 8). The ocean currents can be partitioned into the predicted tidal currents and the non-tidal currents. The latter currents can be separated into direct wind driven currents and the residual currents. From the optimal coefficients derived empirically from the seasonal data sets, it is possible to develop empirical approaches to forecasting ice velocities based on tidal current predictions and now- and fore-cast winds. The unpredictable non-tidal and wind driven currents, as well as the variations in the fitted parameters, represent the uncertainties in the forecasted ice velocities.

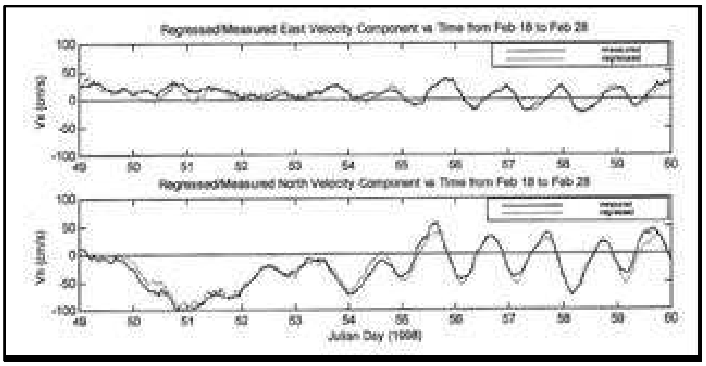

Figure 8: A hindcast representation of ice velocity as derived from regression computed from wind and ocean current measurements made simultaneously with ice velocities.

The Upgraded Ice Profiler: New Features Provided Extended Capabilities for Oil and Gas Applications

Expanded use of ice-profiler data is possible with the new generation instrument developed by ASL Environmental Sciences. Applications extend well beyond the basic capabilities noted above for obtaining detailed, accurate, draft data. The new instrument, the IPS5 Ice Profiler, was designed in response to recommendations developed at an Arctic Climate Systems Study (ACSYS) sponsored Workshop on Ice Thickness Data Thickness Measurement and Data Processing convened in Tromso, Norway in 2002. The recommendations of the Workshop emphasized needs for continued high frequency sampling, larger data storage capacities and retention of data on ice backscatter intensity additional to the previously retained target amplitude, persistence and time delay parameters .

The IPS5's 16-bit data resolution, low power consumption and up to 8-Gbyte memory capacity now permit multiple mode operation in which information on up to 5 separate targets can be measured and stored for each ping. This capability allows for the measurement of occasional "false" non-ice targets (e.g. from zooplankton or fish) while also establishing ranges to the ice targets of interest for individual pings.

Also, the echoes from separately programmed "bursts" of pings can be recorded from the entire water column above the instrument with a vertical resolution of 2 cm. These innovations greatly expand the versatility of the IPS technology and permit the collection of data from the upper ocean which significantly augment data gathered from the ice cover itself.

By allowing better target characterization of floating ice, alone, these new capabilities offer promise to simplify important and time-consuming stages of data processing. Improved accuracy in extracted ice draft values can be expected as a consequence of more confident identification of the zero-draft targets which are used to determine the time varying average speed of sound in the upper water column.

Additional target selection capabilities and, particularly, the capacity to gather full profile data allow the IPS5 to open new possibilities for studies of ice processes in rivers and lakes where frazil ice (Wadhams, 2000) suspended in the water column and in viscous clouds beneath consolidated ice covers (Marko et al., 2006) is of considerable scientific and practical interest (Figure 9).

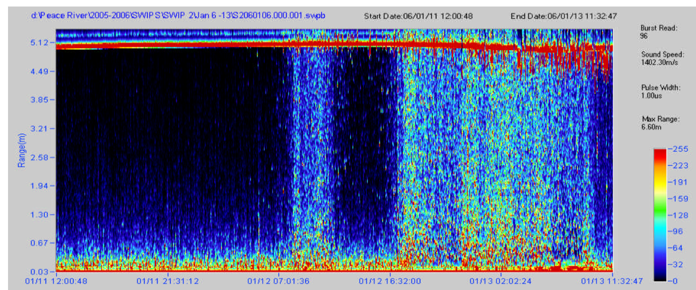

Figure 9. Acoustic target strength profiles gathered over a 2 day period in about 5 m of water in the Peace River during an interval which included two major intervals of frazil ice production by extreme atmospheric cooling. The downward-extending strong (Red) target strengths at the upper ends of the profiles in the latter half of the record correspond to returns from ice floes drifting downstream over the monitoring site.

More recently these capabilities have been applied (Fissel et al., 2007) to resolve ambiguities (Belliveau et al., 2001 ; Hayden et al., 2002) in ice draft data collected in Northumberland Strait where ice fragments created by floe failure at nearby bridge piers are drawn down to depths of 10-15 m by pier-generated turbulence (Figure 10).

An important additional feature of the new IPS5 instrument is that the full echoes can be recorded at intervals which are selectable multiples of the basic target-detecting pinging intervals (usually 1 s) for later processing in a variety of ways. For the first time, this new capability provides an opportunity to simulate the performance of the ice-detection algorithms used by the IPS4 predecessor and by other upward-looking sonars (e.g. models made by the Applied Physics Laboratory of the University of Washington and by Christian Michelsen Research Norway) which have generally utilized sampling intervals much longer than 1 s. Such simulations facilitate thorough inter-comparisons among data obtained with different instruments and at various times and locations. These inter-comparisons can provide a basis for integrated use of all collected data sets, maximizing the confidence and value of resulting assessments of climate trends and variations.

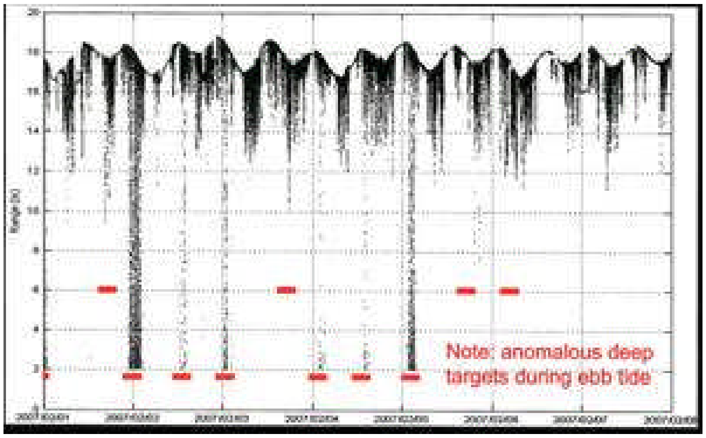

Figure 10. Raw ranges of "first targets" detected over a week-long monitoring period with the IPS5 instrument in Northumberland Strait (from Fissel et al., 2007).

Another important new feature of the Ice Profiler is the addition of a "wave measurement" mode to provide expanded capabilities to measure ocean waves when ice is either not present in the area or occurs mostly in the form of scattered ice floes under low concentration, open pack ice conditions. In the new wave mode sampling feature, the instrument samples surface targets at 2 Hz over user selected burst durations within each burst period (e.g. 17.06 minutes or 34.12 minutes each hour). While operating in the wave mode, the instrument will also continuously sample for surface targets at a user-selected ping rate in order to detect ice floes, if present, and the instrument can provide full water column profiles when not sampling at 2 Hz.

The new IPS5 can now be programmed for up to 12 (previously 8) individual measurement "phases" in which the sampling parameters can be changed between ice and wave measurement modes and for subsampling full water column profiles, at specific dates selected by the user. These features allow use of sampling strategies optimized for full year or multi-year deployments, such as high resolution measurement of under-ice topography from late autumn through early summer and measurement of ocean waves in the summer and early autumn periods.

Opportunities for Development of Additional Capabilities

The new capabilities of the IPS5 instrument open possibilities for further research and development to extend measurement capabilities into new areas of ice type recognition.

With the water column profiling feature, early stages of ice formation can be characterized through the backscattered acoustic returns from suspended sea ice crystals in the upper portion of the water column associated with the formation of frazil, grease and other early stages of ice growth. The profiling of acoustic backscatter amplitude returns also allow for measurement of the amplitudes and attenuation of the acoustic backscatter returns in the underside of the sea ice. While the penetration of acoustic energy is typically attenuated over distances of the order of 10-15 cm when entering consolidated ice, the better than 2 cm resolution of the acoustic returns will allow for examination of the possibility of detecting different ice types based upon the amplitudes of returns off the underside of the sea ice.

Combination of Ice Profiler and All-Weather Radar Imagery for Identifying Key Ice Parameters

It is difficult to see how the apparently critical role of the polar marine regions in the overall progress of climate change could be monitored and understood without a continuing and accelerating primary reliance on sub-surface upward-looking sonar for measuring ice draft/thickness and other parameters descriptive of the vertical distribution of ice in the ocean. It would appear that more than a decade of development has brought capabilities to an advanced level of performance of use, particularly when employed in a coordinated manner and in conjunction with other technologies, for tracking change and for studying physical processes in the marine cryosphere. The greatest remaining monitoring challenges would appear to involve developing techniques for effective and affordable data retrieval from the stationary and mobile platforms which are central to wider deployments of this technology.

Remote Data Access for Ice Profilers in Multi-Year Mooring Operations

Ice Profilers have been operated for up to three years with year-round data acquisition in the past, and the much expanded data capacity, along with extended battery capacity presently under development, will support expanded levels of multi-year operation.

In areas within the interior of the permanent Arctic Ocean pack ice, access to the moorings by ship is very expensive and, in some years, difficult or impossible to achieve. Under such conditions there is a need to access the data from the Ice Profilers and other moored instruments without having to affect full recoveries of the moorings. Prospects for accessing the data from the moored instruments in ice pack conditions include the use of acoustic modems, or the remotely activated release of small "data pods" as well as possible applicability of electromagnetic modem links in conjunction with ROV/AUV-based data recovery tools. Such capabilities and low instrument power consumption would enable the cost and effort savings characteristic of longer term deployment without the inevitable uncertainties and inconvenience associated with long delays in conventional instrument recoveries.

SUMMARY AND CONCLUSIONS

Since the inception of the modern ice profilers, in the form of the ASL model IPS4 Ice Profiler introduced in the mid-1990's, profiling instruments have been widely used in support of oil and gas exploration activities in ice infested waters. Typically, the IPS and ADCP sonars are operated over successive ice years to provide input data useful for establishing design criteria for production platforms in the specific exploration lease areas and for selection and design of operational methods and approaches for the both the exploration and production activities.

Extended and new capabilities were provided with the launch of the next generation version of the Ice Profiler. These new features will allow for improved resolution and coverage of the detailed under-ice topography, as well as better characterization of the early stages of sea-ice formation and improved capabilities for measurement of ocean waves, during periods without any significant sea ice or when ocean waves propagate within the loose ice pack.

The next generation of the Ice Profiler also sets the stage for research and development into the measurement of new ice parameters, the combination of information from Ice Profilers and all-weather radar satellite systems, and the possibility of remote access to the Ice Profiler data from multi-year moorings located well within the main Arctic Ocean ice pack.

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