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DRIFT DIRECTION CHANGES AND IMPLICATIONS FOR SEA ICE MANAGEMENT

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ABSTRACT
As the focus on hydrocarbon exploration and production in high Arctic environments increases, there is a need to develop and assess operational ice management procedures applicable to these areas. Particularly in water depths exceeding 100 m, bottom-founded structures are not a viable option and stationary floating vessels will likely be used. Ice management in the form of icebreakers is a key component for station-keeping by reducing floe sizes upstream to decrease subsequent loads on the floating vessel. Drift changes in the Beaufort Sea can be frequent and complete drift reversals can occur in only a few hours. The highly dynamic nature of ice drift can be problematic when maintaining a managed ice channel for a station-keeping vessel. This paper assesses ice drift characteristics based on an analysis of Acoustic Doppler Current Profiler and Ice Profiling Sonar data collected in the Beaufort Sea from 1990 to 2003 and identifies quantitative measures of drift direction change.

INTRODUCTION
With increased interest in hydrocarbon developments in cold ocean environments there comes a need for improved standards regulating practice in these areas. Ice management in support of these offshore operations has become an attractive option and its capability proven through various projects including production operations in Sakhalin (Keinonen et al., 2006a), the Arctic Coring Expedition (Keinonen et al., 2006b), and past expeditions to the Beaufort Sea such as the Kulluk station-keeping operations (Wright, 1999). The new ISO 19906 (2010) arctic structures standard allows the use of operational procedures, including ice management, for mitigating ice actions. The onus is on the user of the standard to demonstrate that the necessary operational procedures are in place so the floating structure is only exposed to ice conditions it can withstand safely. With regards to ISO 19906, the quantification of ice management success can help to demonstrate the safety of the system. A first step in the quantification of ice management success is the characterization of the ice environment in which the system will be deployed.

A floating structure will need to be designed for particular loading criteria and the ice management system should ensure that ice features interacting with the structure are consistent with these criteria. For example, the ice management system will be successful if ice features interacting with the structure are smaller than the design floe size. For successful ice management to occur, the rate at which ice is managed in the vicinity of the floating structure should be consistent with the speed at which new ice features are drifting onto site.

Ice drift patterns can be quite complex and are mainly driven by drag forces exerted by ocean currents and wind, pack ice mechanics and Coriolis forces. As wind is a significant driving force for sea ice, sudden changes in wind direction can cause sea ice to change trajectory.

Over large distances the Coriolis force causes inertial oscillations and can result in loop and cusp movements in the drift trajectory which can result in high angular velocity changes. Ocean currents, including diurnal and semi-diurnal tidal currents, also have an effect on drift trajectory and drift direction change. Pack ice mechanics is very important and can cause considerable variability in ice drift. During periods of high ice concentration the internal ice stresses of the pack can cause a dampening effect in ice motion causing tighter inertial oscillation trajectories. During instances when the ice pack is pressurized there exists the possibility of rapid changes in ice motion due to the unloading when failure of ice sheets occur. The integration of these various components generates a highly dynamic environment which influences the performance of the ice management system and therefore necessitates evaluation.

The focus of this study is to analyse available Acoustic Doppler Current Profiler (ADCP) and Ice Profiling Sonar (IPS) data and quantify important aspects of ice motion. Having a set of metrics containing information on the regional ice environment will provide an efficient means of developing appropriate ice management strategies.

BEAUFORT SEA ICE DATA SET

Sea ice data collection in the eastern Beaufort Sea, supported by the Department of Fisheries and Oceans Canada (Melling and Riedel, 2004), has provided invaluable information on the nature of ice draft and ice movement in this region. The sea ice draft was measured using an IPS and the ice drift velocity was measured using an ADCP. Draft and drift records were obtained for the period of 1990 to 2004 for ten mooring sites (Figure 1). The spatial coverage of the mooring sites is 70.08°N and 74.15°N latitude and 125.58°W to 133.83°W longitude. The temporal coverage of this data set is from April 4th, 1990 to September 30, 2003. An overview of this study, data analysis procedures, and statistical measurements are described by Melling and Riedel (2004). The processed data is made available by the National Snow and Ice Data Center (NSIDC) and contains information on ice drift speed, ice drift direction, and ice thickness. Ice velocity data is available in 30 minute intervals and ice thickness data in four minute intervals, with some year-to-year variation.

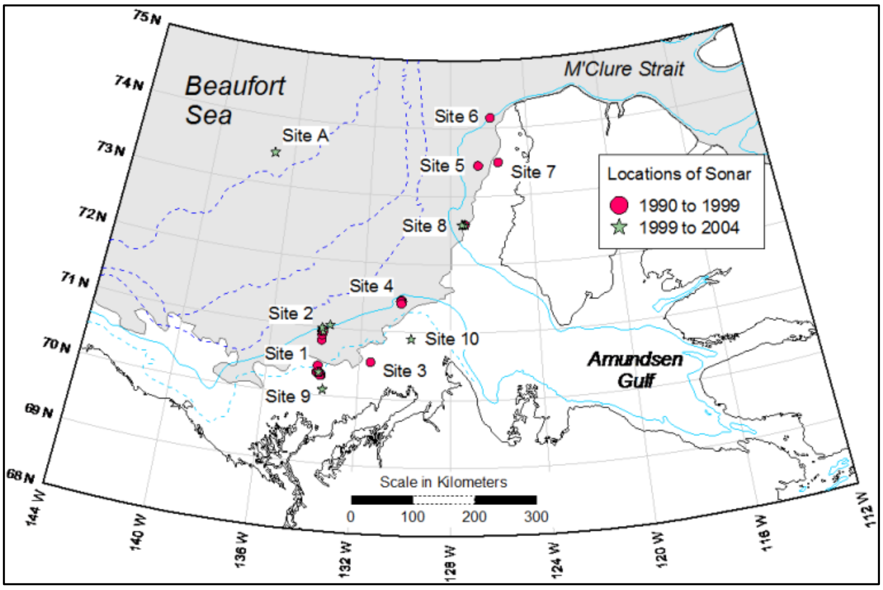

Figure 1. Beaufort Sea mooring sites (from Melling and Riedel, 2004)

Examination of this data set yielded information about the regional ice environment including: monthly ice concentration, multi-year and extreme ice features, drift rate, and drift direction. Further analysis can reveal dominant drift direction, occurrence of significant drift direction changes, rate of drift direction change and relationships between drift and ice concentration on a per region basis.

SEA ICE MANAGEMENT AND ICE DRIFT

The ultimate goal of an ice management system is to maintain the station keeping vessel in the channel of managed ice as long as possible. This can become problematic when encountering large multi-year ice features that cannot be handled by the ice management system and the stationary vessel must be disconnected and moved off site. Ice drift and ice drift direction change must also be considered as a negative factor that can contribute to the failure of the ice management system. If ice management cannot keep up with the incoming ice drift the stationary vessel will fall outside the managed ice channel (McKenna and Wright, 2012). Furthermore, in addition to the icebreaking vessels, consideration must be given to the stationary vessel which also needs to keep up with the change in drift direction so that its heading is always aligned with the major drift direction.

Hamilton et al. (2011) examined the performance of a two stage icebreaking system and found that significant drift direction change can be problematic for maintaining the station keeping vessel in the managed ice channel. A sound understanding of the ice environment coupled with a near-real-time ice monitoring system can minimize the unpredictability of ice drift and improve ice management operations.

EXAMPLE ANALYSIS

Ice Environment Characteristics to Consider

As mentioned in the previous section, there are numerous characteristics of the ice environment that need to be considered when protecting stationary vessels in the Arctic. The focus of this paper is to quantify the ice environment in terms of ice drift characteristics which could potentially be used for selection of ice management strategies. These characteristics include drift rate, rate of drift direction change, and curvature of the drift track.

Sea Ice Drift Example

Figure 2 illustrates typical direction changes occurring in the Beaufort Sea, for ice moving over ADCP/IPS mooring site 2 (see Figure 1). The trajectory of the ice is the result of drag forces, contact forces and an inertial component (Coriolis force) which is responsible for the loops and cusps observed. The Coriolis force acts perpendicular to the ice velocity and tends to push the ice to the right in the Northern Hemisphere. The inertial oscillations occur at a frequency (f_o, in day^{-1}) of

$$f_o = 2\sin\theta \qquad (1)$$

where θ is the latitude and is equal to 71°N, for site 2, which gives a frequency of 1.89 cycles/day. Figure 3 shows the frequency spectrum of the drift speed, which has a large amplitude at the inertial frequency. The -1.89 cycles/day in Figure 3 represents the clockwise rotation of the ice that occurs in the Northern hemisphere. In the Southern Hemisphere the inertial frequency would be described by a positive value.

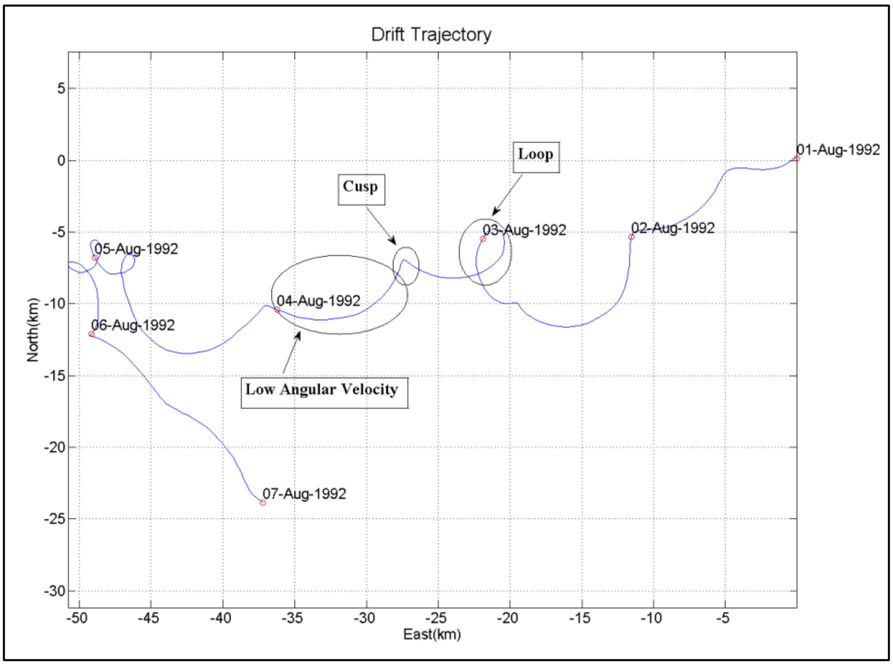

Figure 2. Site 2 Drift trajectory illustration for August 1st to August 7th, 1992

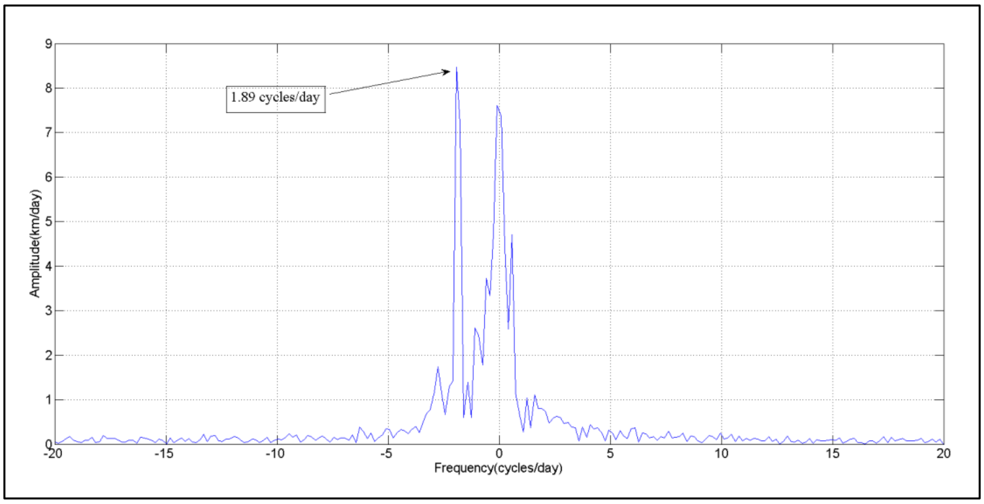

Figure 3. Frequency plot of ice speed at Site 2 for August 1st to August 7th, 1992

To better understand ice drift patterns and to characterize the various components related to ice drift, time series plots of (a) ice drift speed; (b) angular velocity; (c) drift curvature; and (d) ice drift direction are shown for a few days in Figure 4. Angular velocity was calculated by taking the change in drift angle between two points and dividing this by the time step between the two points. The angular velocity has both positive (counter clockwise rotation, CCW) and negative values (clockwise rotation, CW). The angle of drift direction is calculated with respect to true north. The CCW rotation occurs at the cusps seen in Figure 2. These cusps have high angular velocities but low drift speeds (near zero) associated with them. The peaks in the negative values of angular velocity are associated with the loops seen in Figure 2. These loops also have a low drift speed incorporated with them that is slightly higher than the drift speed seen for the cusps. High drift speeds and low negative angular velocities are associated with the straighter segments of the trajectory. From this initial assessment of ice drift, it can be seen that although the ice can rapidly change direction it has a low drift speed associated with this rapid change. This relationship is better illustrated in Figure 5. Figure 5 shows the magnitude of the angular velocity as a function of ice drift speed. An exponential type decay of the magnitude of the angular velocity is seen with increasing drift speed.

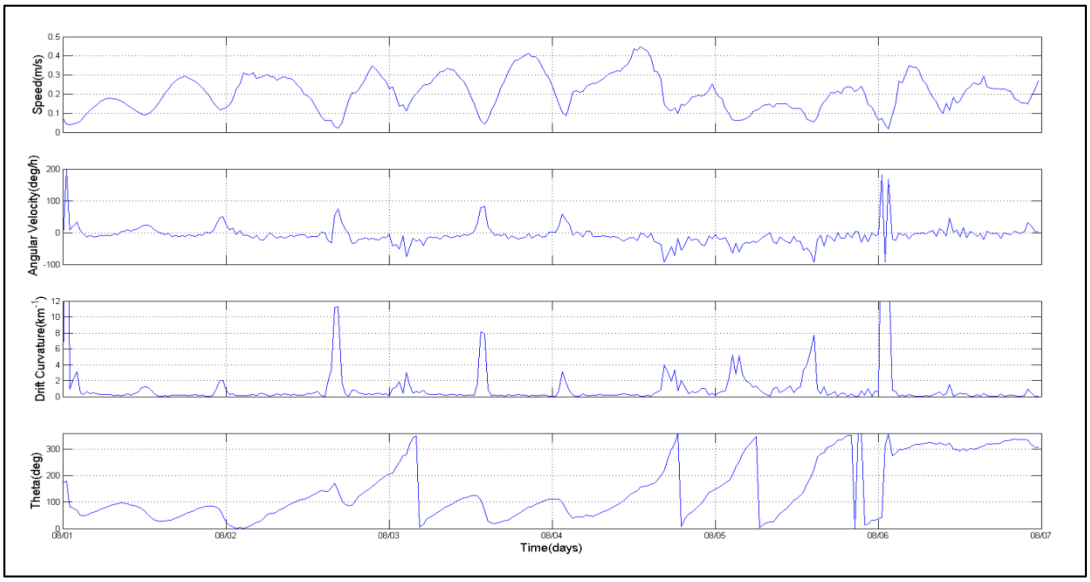

Figure 4. Time series plots of (a) ice drift speed; (b) angular velocity; (c) drift curvature; and (d) ice drift direction for August 1st to August 7th, 1992

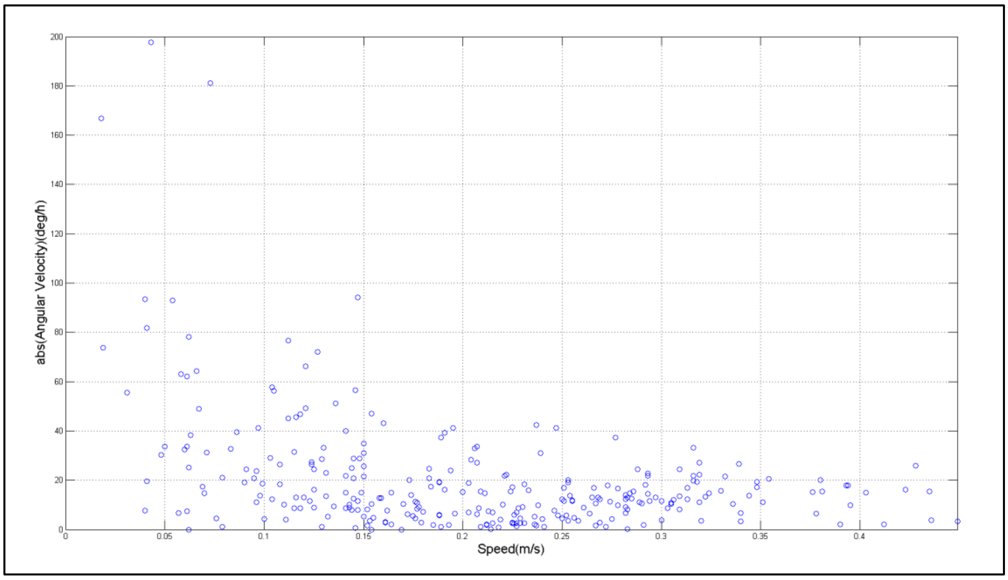

Figure 5. Magnitude of the angular velocity as a function of drift speed for August 1st to August 7th, 1992

Event Analysis

From an ice management perspective, the highest angular velocities may not pose a threat to the ice management system as they are coupled with a low drift speed; however, further assessment is needed. To better understand the characteristics of ice drift the authors looked at individual events: a loop, a cusp, and a low angular velocity event. In this study a loop is described as a negative angular velocity event that results in the ice drift path crossing itself (Figure 2). This is accompanied by an increase in the angular velocity of the ice. A cusp is associated with a positive angular velocity. The angular velocity of a cusp can be very high and cause the drift trajectory to change course. A low angular velocity event has a negative direction change coupled with a relatively high drift speed. These events were assumed to be potentially harmful to an ice management system.

Figure 6 gives time traces associated with the highlighted loop in Figure 2. The speed decreases to a minimum at about the half point of a full rotation, which is associated with a maximum CCW angular velocity. The angle of drift direction with respect to true north, theta, is approximately 280° at this point. The sharp decrease in θ is due to the transition through the 360° angle. Average values of speed, angular velocity, and radius of curvature for this segment are 0.25m/s, 24.6deg/h, and 0.607km^{-1}, respectively. The curvature of 0.607km^{-1} gives a radius of 1.65km (3.3km diameter). The duration of this segment is approximately 12 hours (corresponding to a frequency of 2 cycles/day), which is close to the inertial frequency of 1.89 cycles/day.

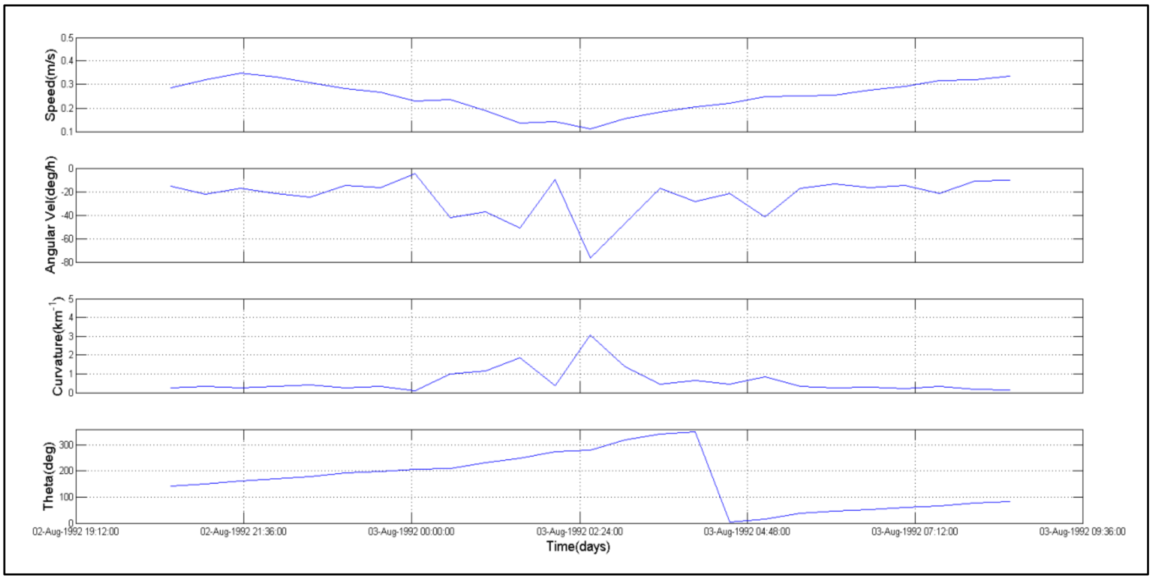

Figure 6. Time series plots for loop, August 2nd to August 3rd, 1992

Figure 7 shows time traces for the cusp and low angular velocity segment highlighted in Figure 2. The speed decreases to a minimum at the peak of the cusp, which is associated with a maximum CW angular velocity. Theta has a value of approximately 120° as the ice drift enters the cusp and has a value of approximately 20° as the ice drift exits the cusp. The cusp is defined over the period when angular velocity has a positive value. Average values of speed, angular velocity, and radius of curvature for this segment are 0.11m/s, 28.6deg/h, and 2.43km^{-1} (0.41km), respectively. The duration of this segment is approximately 3.5 hours (corresponding to a frequency of about 7 cycles/day).

For the low angular velocity segment the ice drift has a constant angular velocity with drift speed increasing to a maximum of approximately 0.4m/s. In this section theta increases from 20° to approximately 120°. This is the same change in angle associated with the cusp segment. Average values of speed, angular velocity, and radius of curvature for this segment are: 0.33m/s, 11.1deg/h, and 0.16km^{-1} (6.25km), respectively. The duration of this segment is approximately 8 hours (corresponding to a frequency of about 3 cycles/day).

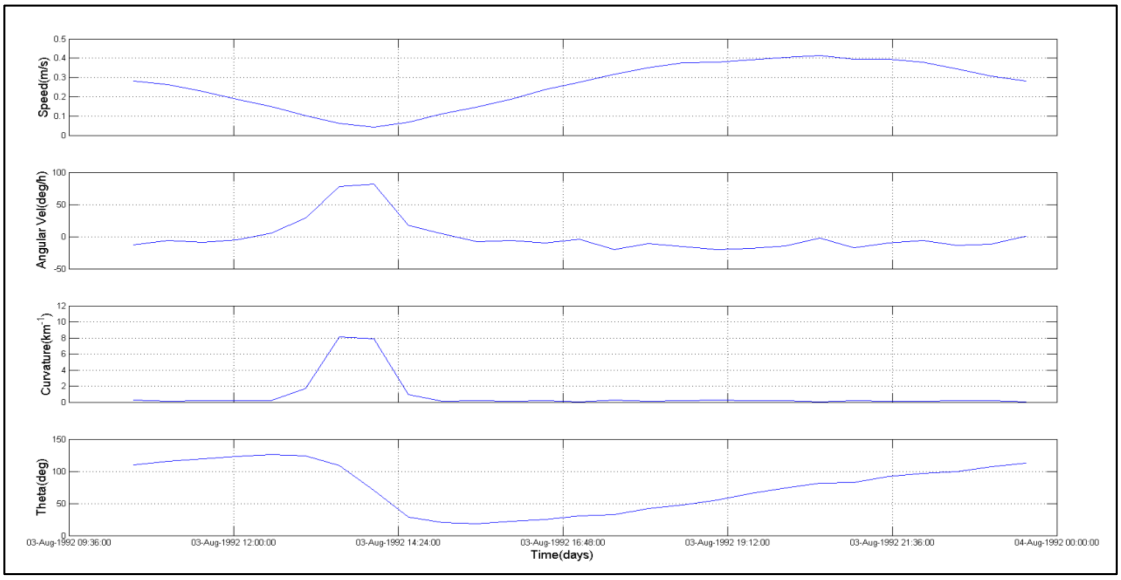

Figure 7. Time series plots for cusp and low angular velocity segment, August 1st to August 7th, 1992

Seasonal Implications on Ice Drift

There are seasonal changes in the ice environment which have an impact on ice drift. During the winter months in the Arctic, high ice concentrations are seen which affect the dynamics of ice drift. A study by Gimbert et al. (2012) suggested that there is a strong interaction between the magnitude of inertial motion and sea ice thickness and concentration, which occurs due to the dissipation of energy through the ice cover. When conducting ice management toward the end of the operating season, in contrast to the summer, a modification in ice management strategy is likely required due to the variability in the ice conditions. To illustrate the effect of ice concentration on ice drift, Figure 8 shows the drift trajectory for Site 1 in November of 1992.

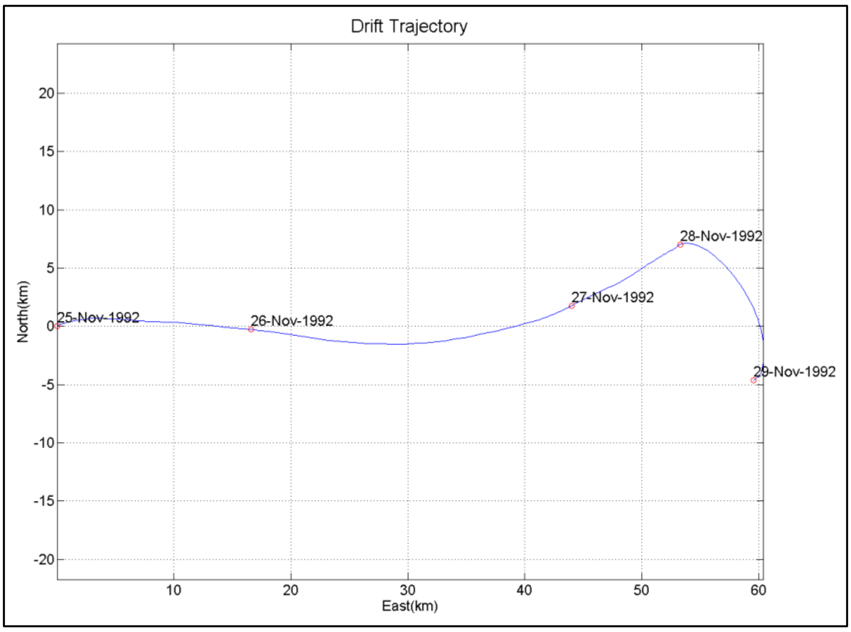

Figure 8. Site 1 Drift trajectory illustration for November 25th to November 29th, 1992

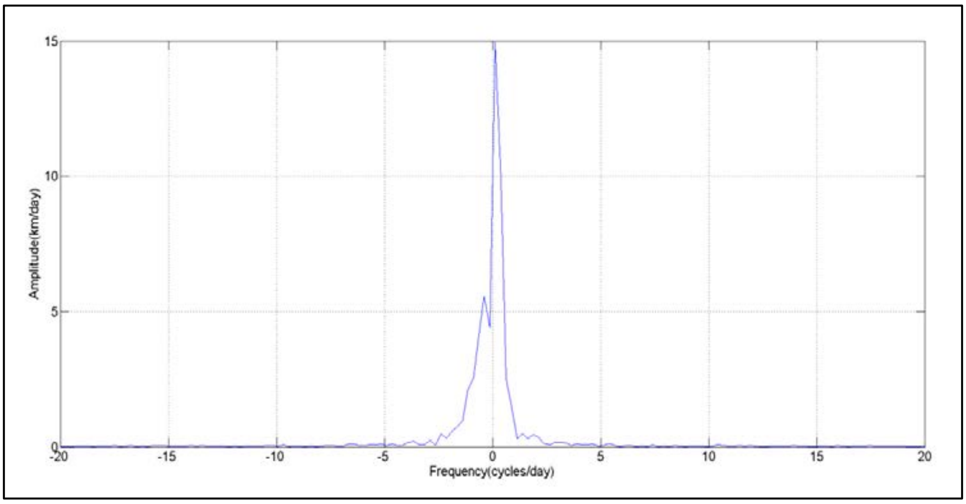

Figure 9. Frequency plot of ice speed at Site 2 for November 25th to November 29th, 1992

Comparing Figure 8 to Figure 2, it can be seen that there is a seasonal dependence on the magnitude of drift direction change, which is linked to the increased ice concentration. Also, comparing Figure 9 and Figure 3, it is seen that a smaller amplitude exists in the frequency domain at the inertial frequency. Data from the Canadian Ice Service (CIS) shows that for the period given in Figure 2 that the ice concentration was approximately 5.5/10th while for the period given in Figure 8 the ice concentrations was 9+/10th. These plots are representative of the seasonal changes of ice drift and the ability of the stress in the ice field due to increased ice concentration to damp out motion such as inertial oscillations.

SITE ANALYSIS

Site 2 contains the most available data from ADCP/IPS and therefore was chosen for this analysis. The purpose of this site analysis is to examine ice environment information that can be derived from ADCP/IPS data and hopefully reveal useful information when determining an appropriate ice management system.

Data from 1991 was used as an example to illustrate the ice drift events that can occur in the Beaufort Sea and to characterize their significance through various metrics such as event duration, mean and max angular velocity, mean and max speed, velocity at max angular velocity, and mean and max radius of curvature. Significant drift events were categorized into three groups: positive direction change (CCW), negative direction change (CW), and inertial loops. Positive direction change events include cusps that were described in the Event Analysis section of this paper.

The histogram plots given in Figure 10 illustrate the event duration time for the three kinds of events described above. Positive rate of change events have the highest frequency occurring in the range of three to four and five to six hours. The lower range represents mostly inertial cusps. Loop events have the highest proportion of the data occurring in the range of four to ten hours while negative rate of change events have the highest proportion of the data occurring between five and eight hours.

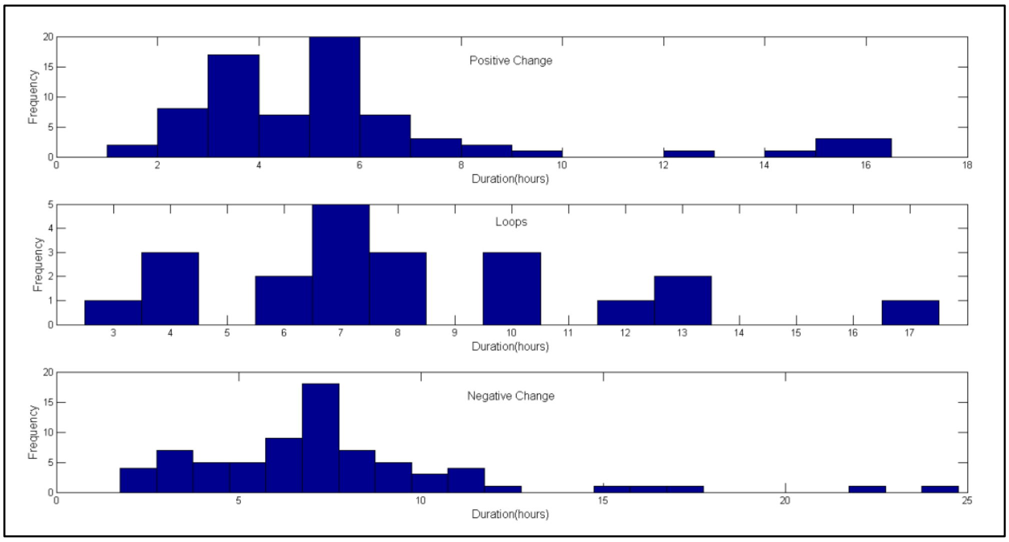

Figure 10. Event duration histogram for all events that have occurred in 1991 at Site 2

Some events occur over a short time period and evidently are associated with a high rate of direction change. This is seen in Figure 11 where a decreasing trend is noticeable for loop (red 'x') and positive rate of change (blue 'o') events. From Figure 11 there is no apparent relationship seen for negative rate of change (green '+' symbols) events for these values.

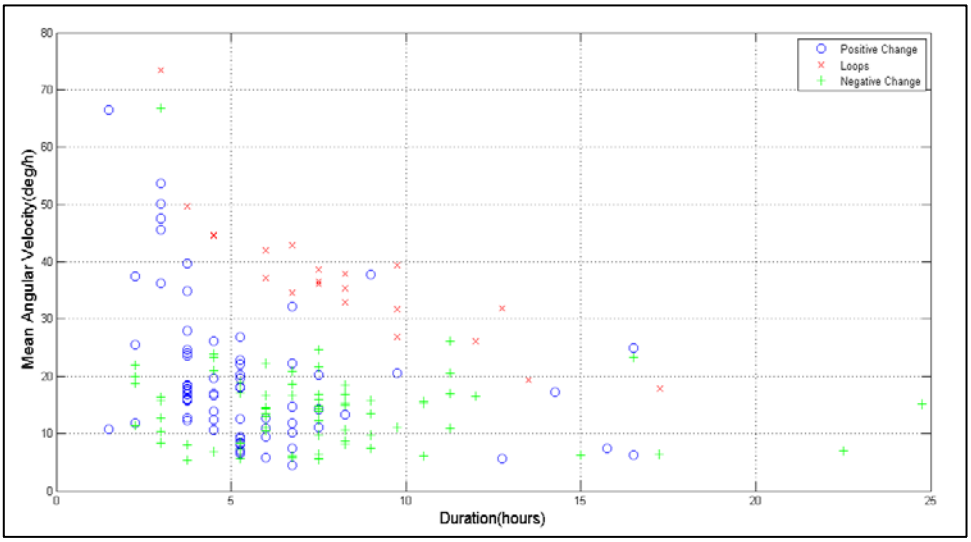

Figure 11. Angular velocity vs. Duration

Figure 12 shows angular velocity plotted against drift speed and an apparent negative exponential relationship exists. In Figure 12 (a) the mean angular velocity and mean speed given are averaged over the entire event. In Figure 12 (b) the maximum value of angular velocity is taken over the event and is plotted against the drift speed occurring at the instant of maximum angular velocity. High rates of direction change are associated with low near zero linear velocities and high linear velocities are associated with low rates of direction change. This is a positive relationship for ice management purposes as the challenging rates of direction change are occurring when the ice is near zero speed. However, some intermediate rates of direction change can still occur at more significant drift speeds. These events are mainly observed when analysing negative drift direction changes. Reducing the amount of events that cause side loading on the stationary vessel is an important goal of the ice management system. With the aid of plots similar to those in Figure 12 appropriate management strategies can be implemented to alleviate this concern.

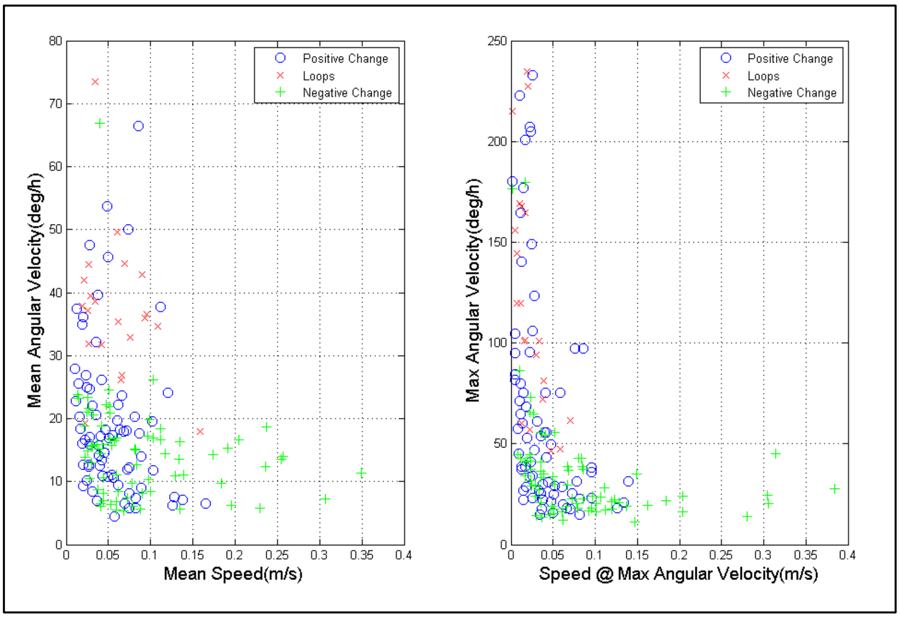

Figure 12. (a) Mean angular velocity as a function of mean speed; and (b) event maximum angular velocity as a function of event maximum speed

Another important metric to consider is ice drift curvature which is given in *Figure **13*** as a function of mean ice drift speed. This can aid in determining which swath width of the managed ice channel to maintain. The small radii of curvature might require special management tactics to avoid having the vessel extend beyond the managed track.

For curvature approaching zero, the ice is drifting in a straight line and usually at a relatively high drift speed. Drift trajectories with large values of curvature are associated with low linear velocities and sometimes signify a large drift direction change. These near zero velocities allow the ice management vessels to retreat to the stationary vessel to wait for the drift direction change. Figure 11 to *Figure **13*** can be beneficial for selection of an ice management system.

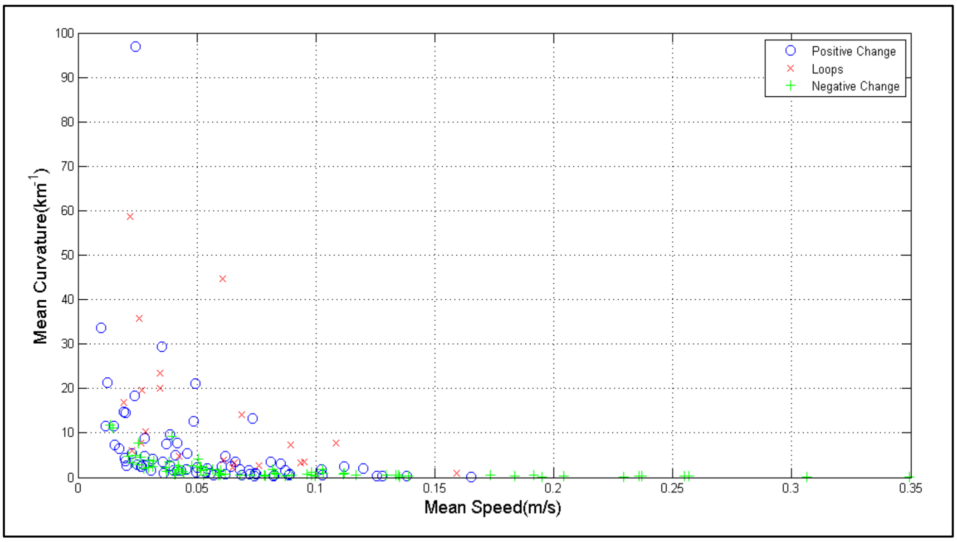

Figure 13. Mean curvature as a function of mean speed

CONCLUSIONS

The preliminary analysis of ice drift data from the Beaufort Sea has aimed to identify important characteristics of sea ice drift that are essential for the selection of an ice management system. By identifying these key parameters a more informed selection process can be established.

This study has characterized three types of drift change and illustrated the relationships of various factors. Significant drift changes that have a large angular velocity occur when the ice drift stalls and then starts again. These large angular velocities are usually associated with cusps and can have a change in drift direction of 120° and occur over a few hours. However, these events have a low associated drift speed and are likely not the limiting factor of the ice management system from a drift direction change perspective. Events that threaten the ice management system are likely those that occur at intermediate values of speed and angular velocity. Further research needs to be conducted to develop criteria for selecting such events and should include looking at the various sites and years in the dataset to verify the trends observed here.

In addition, further research in this topic will incorporate a more in depth analysis of the metrics outlined in the previous sections. This will include further analysing the sea ice drift data set to identify seasonal and spatial characteristics and a more refined study that includes applying threshold criteria to the various parameters to identify “significant drift changes.” Ice concentration should also be incorporated in the analysis to observe possible trends with ice drift. This will be done by looking at the various sites and years for ADCP/IPS data collection.

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